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Fatigue behaviour of hybrid composites

Part 2 *Carbon–glass hybrids*

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A study has been made of the fatigue behaviour in repeated tension of unidirectional and $[(\pm 45, 0, 0)_2]_s$ hybrid laminates composed of XAS carbon fibres and E-glass fibres in the same 913 epoxy resin. The ordinary mechanical properties of these composites are close to those predicted by simple, conventional models of hybrid behaviour. For the unidirectional materials, the fatigue stress for a given life is not a linear function of composition, showing a substantial positive deviation from the rule of mixtures. This behaviour closely mirrors that of unidirectional carbon–Kevlar hybrids reported in Part 1 of this work. In terms of strain–life comparisons, results for all hybrid compositions and plain carbon fibre reinforced plastic fall within a single scatter-band. These features are also reflected in the fatigue behaviour of the more complex hybrid laminate.

1. Introduction

The work to be presented in this paper is the second part of a wider programme of research on the fatigue behaviour of hybrid composite laminates. In Part 1 [1] we discuss the results for carbon–Kevlar-49 hybrids, including unidirectional composites and laminates of more complex construction. The purpose of that work was twofold. The first intention was to examine the effect of including an increasing proportion of aromatic polyamide (Aramid) fibres into a carbon fibre reinforced plastic (CFRP) of high fatigue resistance, given that the fatigue response of composites reinforced with Kevlar-49 fibres (KFRP) is intrinsically poorer than that of CFRP [2]. The second objective was to investigate the effect of introducing an increasingly large compressive component into the fatigue cycle, given that Aramid fibre composites are usually considered to be unreliable under conditions involving bending or compression forces. In the course of that work we were able to show that in unidirectional composites the KFRP component led to no unexpected deterioration in performance, the fatigue response of the hybrids being determined simply by composition as a rule-of-mixtures interpolation from the behaviour of the two single-fibre CFRP and KFRP components. However, the tensile strengths of the unidirectional CFRP–KFRP hybrids did not vary linearly with composition, being instead close to the predictions of the simple failure strain model [3]. Consequently, the fatigue ratio (fatigue stress for a life of 10^5 or 10^6 cycles divided by the monotonic tensile strength) also did not vary linearly with composition (rule of mixtures) but showed a strong positive synergistic effect. Furthermore, the behaviour of the hybrid mixtures was not adversely affected by the application of a fatigue cycle containing large compressive components except in the sense that all fibre composites are weaker in compression than in tension (CFRP included): the fatigue performance of any given laminate (single-fibre or hybrid) was reduced by compression loading more or less in proportion to the reduction of its monotonic tensile load-bearing ability.

The more complex composite, a laminate of $[(\pm 45,0_2)_2]_s$ structure containing equal proportions of CFRP and KFRP, behaved similarly at high stress levels, the fatigue stress for a given life being only marginally below a mixture-rule interpolation between the S–log N curves for the plain CFRP and KFRP laminates. However, this holds true only up to the point where the established S–log N curve for the KFRP laminate (and also for the unidirectional composite) shows a marked downward turn, beyond about 10^4 to 10^5 cycles, where the hybrid curve also deviates increasingly from the average.

In this part of the work we extend the study to a consideration of carbon–glass–epoxy hybrids. The most significant differences between the CFRP–KFRP and the CFRP–GRP systems (GRP = glass reinforced plastic) relate, naturally, to the qualities of the second fibre species, glass being structureless and therefore free of the weaknesses normally associated with the fibrillar sub-structure of the Aramid fibre. And whereas the failure strains of the plain CFRP and KFRP composites were similar, that of GRP is substantially greater than that of CFRP.

2. Experimental details

Materials were supplied by Ciba-Geigy as zero-bleed prepregs of XAS carbon fibre and E-glass in the same

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TABLE I Lay-up geometries for unidirectional study

CFRP (%)	Lay-ups*
25	$(GGCG)_s$
50	$(GCGC)_s$, $(CGCG)_s$
75	$(GCCC)_s$, $(CGCC)_s$, $(CCGC)_s$

*G = GRP, *C* = CFRP.

BSL 913 epoxy resin. Prepregs were laid up on a vacuum-assisted laying-up table according to predetermined compositions and stacking sequences, and were either autoclaved at the Royal Aircraft Establishment, Farnborough, or hot-pressed at Westland Helicopters, Yeovil, following the manufacturer's recommendations, to a nominal fibre volume fraction of 0.60.

2.1. Compositions and lay-ups

Two main lay-up geometries have been studied, the first group of materials being unidirectional, to provide, as for the earlier carbon–Kevlar investigation, a baseline of fibre-dominated performance for the various hybrids, and the second being $[(\pm 45, 0_2)_2]_s$ laminates. For the unidirectional study, a sequence of 8-ply plates of compositions 25, 50 and 75% carbon was prepared with lay-up sequences as in Table I.

Plain CFRP and plain GRP materials completed the unidirectional set. The stacking sequence for the $[(\pm 45, 0_2)_2]_s$ laminate, which was determined by the composition rather than by normal structural considerations, was

$$[(\pm 45)\ G,\ 0C,\ 0G,\ (\pm 45)\ C,\ 0G,\ 0C]_s$$

The GRP was always used for the outer plies, and the plies were arranged so that all interfaces (except the $+45/-45$ interfaces) were carbon–glass interfaces.

The standard, autoclaved or pressed 1.0 m × 0.3 m plates were C-scanned after manufacture, following which they were dried and bagged to await use. The cutting of test samples by a water-cooled diamond saw was carried out in such a manner as to avoid the use of plate edges and those areas that were indicated as defective by the ultrasonic scanning.

2.2. Environmental conditioning

We have previously studied the effects of environmental conditioning on the fatigue response of glass, carbon and Kevlar-49 reinforced epoxy resin composites [2] and have shown that, except under grossly exaggerated pre-treatment conditions, the fatigue characteristics of the composites were not sensitive to the effects of hydrothermal treatment. For the current work, therefore, a standard conditioning routine was used to bring all materials to a moisture content of approximately 1% by room-temperature treatment in a 65% RH (relative humidity) enclosure.

It will be appreciated that differential thermal contraction, following cooling from the cure temperature, will lead to residual thermal strains in hybrid laminates. However, a simple composite beam theory analysis, based on the known elastic and thermal properties of CFRP and GRP, leads to the result that in a 50–50 carbon–glass unidirectional hybrid the maximum possible level of compressive thermal stress in the CFRP plies would be of the order of only 1 MPa.

2.3. Fatigue testing

The fatigue results to be presented in this paper were all obtained in repeated tension, at an *R* ratio ($\sigma_{min}/\sigma_{max}$) of 0.1. The fatigue tests were carried out in a pair of Instron 1332 servohydraulic machines operating under load control. In our previous work [2] we emphasized the need to ensure comparability of results for different composites by allowing for the strain-rate sensitivity of the strength of our three different types of material. This concern over testing rates had largely been related to the known strain-rate sensitivity of the tensile strength, and therefore also of the fatigue response, of GRP, as discussed by Sims and Gladman [4, 5]. This sensitivity arises, apparently, from the environmental sensitivity of the strength of the glass fibres [2] but its effect seems to be eliminated in a hybrid composite in which carbon fibres are also present. This is shown in Fig. 1 where it can be seen that the strength of a unidirectional 50–50 CFRP–GRP hybrid composite shows no sign of the rate-dependence demonstrated by the plain glass composites. We have not therefore been constrained to run all tests at the same rate of load application (RLA), as in our previous programme, and although the majority of tests were carried out at an RLA of approximately 200 kN sec^{-1}, we increased the rate to 500 kN sec^{-1} where necessary to achieve a reasonable testing rate. In the results which follow, however, where values of monotonic tensile strengths appear on the extreme left of fatigue curves they have been measured at the same rate of loading as that used in the cyclic testing.

All fatigue tests have been carried out on straight-sided (unwaisted) coupons, with their edges polished to remove the most serious cutting marks, and with soft aluminium end-tabs bonded on to prevent grip damage. These end-tabs were glued to the specimen surfaces, following shot-blasting of the aluminium and abrasion of the sample surface, with Redux 403 resin cured for 10 h at 45° C under light load.

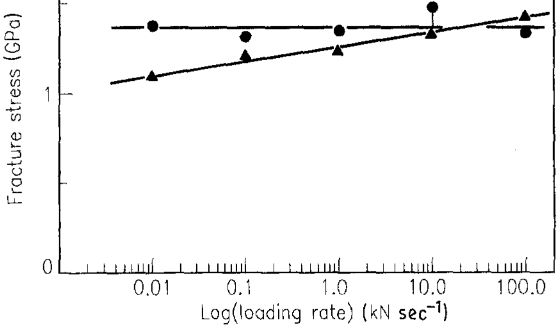


Figure 1 Loading rate sensitivity of the tensile strength of (▲) a plain GRP composite and (●) a GRP/CFRP hybrid (unidirectional laminates; 913 resin, E-glass and XAS fibres).

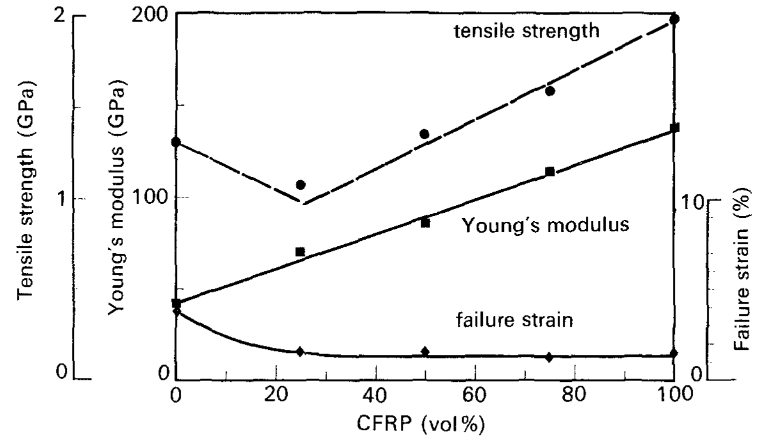


Figure 2 Effect of composition on the mechanical properties of unidirectional CFRP–GRP hybrids (913 resin, E-glass, XAS carbon). Test results are the averages of at least three values. The dashed line represents the predicted variation of strength with composition from the simple failure-strain model [3].

3. Experimental results and discussion

3.1. Unidirectional composites

The mechanical properties of the unidirectional CFRP–GRP hybrid laminates are shown as a function of composition in Fig. 2, together with the predicted strengths of the hybrids given by the simple failure strain model [3]. The elastic modulus is a linear function of composition and the strengths fall close to the predicted values. In both respects, this behaviour is identical with that of the CFRP–KFRP composites reported in Part 1 of this work [1] although the deviations of the strength values below the linear combination line are much greater for these CFRP–GRP hybrids because of the greater difference in failure strains of the two single-fibre composites. The relatively high failure strain of the plain GRP composite falls to a level characteristic of the plain CFRP laminate after the incorporation of only 25% of CFRP, just beyond the point at which the failure strain model predicts the change of failure mode. This change in failure strain with composition, with the implication that in hybrids containing less than 25% of CFRP the carbon fibre plies are failing at strain levels greater than their normal failure strain, is what is popularly referred to as the "hybrid effect" or "failure strain enhancement" [6], thereby gracing with an unnecessary and even fallacious title an effect that is not unique to hybrids, being readily observable in single-fibre composites [7], and which is simply a consequence of the statistical nature of failure of brittle filaments in a less-brittle environment, be it the plain matrix or a second composite component. The different GRP and CFRP ply distributions listed in the previous section had no effect on the static strength or stiffness.

To avoid initial confusion arising from superposition of the whole family of *S*–log *N* curves we present first the fatigue curves for the plain CFRP and plain GRP unidirectional composites in Fig. 3. The *S*–log *N* curve for the carbon composite has a slope of 100 MPa per decade of life, or about 5.7% of the static strength per decade. This rate of fall is approximately what we would have predicted, for a composite of modulus 138 GPa, from the arguments in our earlier work [2]. In that work the curves that we obtained for the 0/90 GRP laminates were not linear, by contrast with the arguments of Mandell *et al.* [8], who maintained that the slopes of *S*–log *N* curves for GRP composites of all kinds are linear and of slope approximately 10% of the fracture strength. Similarly, the curves for the 913-glass composites in Fig. 3 are also non-linear, although a crude estimate of the mean slope of that curve is 137 MPa per decade, or 9.8% of the static fracture stress, which gives a value of the factor σ_f/B, the ratio of monotonic tensile strength to the slope of the *S*–log *N* curve, of 10.4 (cf. Mandell *et al.*'s value of 10) when the strength is measured at the same rate of loading as was used for fatigue testing.

The *S*–log *N* curves for the unidirectional hybrid composites, illustrated in Fig. 4, fall into the pattern that would have been expected, given the behaviour of

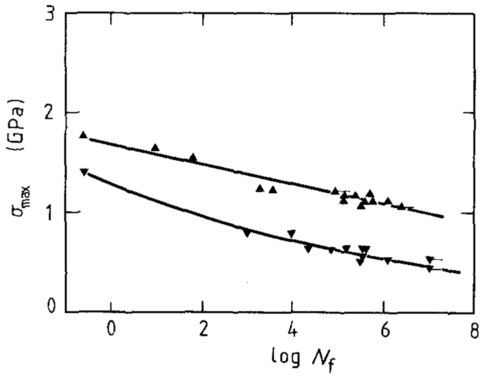


Figure 3 *S*–log *N* curves (peak stresses) for unidirectional (▲) 913-carbon and (▼) 913-glass single-fibre composites (R = 0.1).

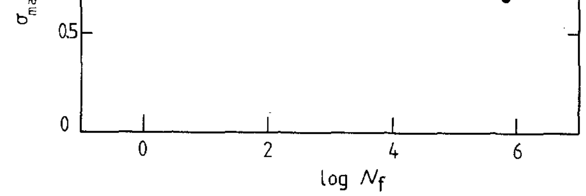


Figure 4 *S*–log *N* curves (peak stresses) for unidirectional CFRP–GRP hybrid composites (R = 0.1). GRP content (■) 25%, (▲) 50%, (●) 75%.

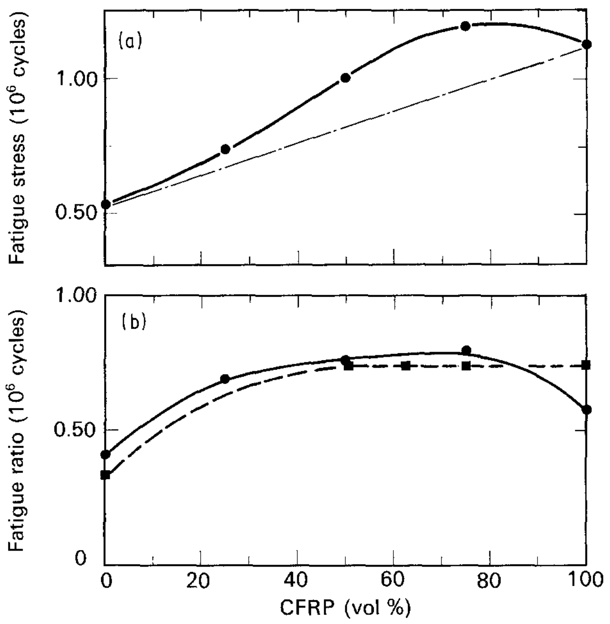


Figure 5 Effect of composition on the fatigue response for a life of 10^6 cycles for unidirectional CFRP–GRP hybrids ($R = 0.1$). (a) Plain fatigue stress. (b) Fatigue ratio (fatigue stress for a life of 10^6 cycles divided by tensile strength): (●) CFRP–GRP, (■) comparable data for carbon–Kevlar hybrids reported in Part 1 of this work [1]. Note that the resin used in the CFRP–KFRP work was 914 epoxy, whereas that for the CFRP–GRP hybrids was 913 epoxy.

the two single-fibre composites just discussed, with the overall lay of the curves modified by the fact that the curve for the 50% GRP hybrid starts from approximately the same point as the plain GRP laminate shown in Fig. 3 and that of the 25% CFRP hybrid starts below that of the plain GRP laminate, as required by the positions of their respective strength values in Fig. 2. The degree of scatter in the hybrid results is greater than that for the plain GRP and CFRP (a feature also of the earlier carbon–Kevlar work).

We note that the slopes of the hybrid *S*–log *N* curves are all roughly the same but, unexpectedly, *lower* than that of the plain CFRP laminate, so that the data for the plain carbon and for the 25% GRP composite overlap at long lives. This can be more clearly illustrated by plotting the fatigue stress for a life of 10^6 cycles as a function of composition as in Fig. 5a. By contrast with the results of Phillips [9] on carbon–glass cloth hybrids and with our own results for carbon–Kevlar hybrids [1], the relationship is non-linear, falling well above a notional linear combination line. Thus, despite the scatter that mars the individual *S*–log *N* curves, there again appears to be a positive synergistic effect. This effect is emphasized if the fatigue stresses are considered in relation to a more realistic baseline rather than the notional mixtures rule. This is done by plotting the fatigue ratio (fatigue stress for a given life divided by the monotonic tensile strength) as a function of composition, as in Fig. 5b. The implication is clear: in a stress-based comparison, all three hybrid compositions are superior in respect of their fatigue response to both of the single-fibre CFRP and GRP composites. The comparable set of results for the unidirectional carbon–Kevlar composites from Part 1 of this work [1] are also plotted in this figure, and it can be seen that although the resins are different in the two sets of composites (914 in the CFRP–KFRP and 913 in the CFRP–GRP materials) the variation of the fatigue ratio (10^6 cycles) for the two sets of materials is almost identical. The intrinsic fatigue resistance of the 914-based plain CFRP appears to be slightly better than that of the 913-based CFRP, but this superiority is not translated into the hybrids.

As in the case of the CFRP–KFRP mixtures, the simple model of hybrid behaviour which adequately explains the static tensile behaviour of these composites does not, therefore, help to predict the fatigue response. Far from there being any question, here, of the carbon plies affording some degree of protection to a less fatigue-resistant GRP component, it appears that the presence of the glass is positively beneficial. It seems likely that this is because the glass plies, working as they are at relatively low strains by comparison with their failure strains, are able to act as classic crack arresters, or damage inhibitors, perhaps on both the macroscopic and microscopic scales [10, 11]. While it seems hard to imagine that a GRP ply only some 0.125 mm thick would be sufficient to stop a crack of the same length formed in one of the unidirectional CFRP plies, it should be recalled that it is indeed a feature of Zweben's statistical model [12] that crack arrest in hybrids can function at the individual fibre (or fibre bundle) level. Aveston and Sillwood [13] also demonstrated that the contribution of the carbon to the mechanical properties of a CFRP–GRP hybrid composite was preserved to much higher strains than the normal failure strains of the carbon fibres themselves, and they suggested that this was a result of the ability of intact glass fibres to suppress cracks extending from failed clusters of carbon fibres. It is this apparent increase in the failure strain of the lower-extensibility carbon fibres that is usually dubbed the "hybrid effect". Although in respect of the fatigue of our unidirectional carbon–glass hybrids we are not dealing with tensile fracture mechanisms proper, there seems no reason why similar protection arguments should not apply. Curiously, the marked synergistic effect illustrated in Fig. 5 occurs over the full range of hybrid compositions, which is in contrast to the normal observations of enhanced failure strains in hybrid tensile tests. For the CFRP–GRP system, such enhancement should occur at low carbon content when the low failure-strain carbon fibres are well surrounded by the higher failure-strain glass fibres. We conclude that the laminated composite structure modifies the behaviour in a manner not predicted by random fibre distribution models.

Direct comparison with the results of Phillips [9] is difficult because his work was for woven cloth laminates in a vinyl ester resin matrix. One would expect that in a woven cloth hybrid damage development would be more directly determined and controlled by the weave of the cloth, leaving less scope for ply-level crack stopping. We noted earlier that his results indicated that the fatigue stress for 10^5 cycles was a linear function of hybrid composition and did not therefore reflect the synergistic effect indicated by

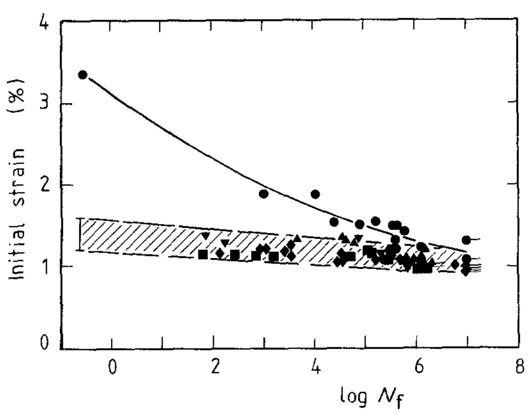


Figure 6 Fatigue results for all unidirectional CFRP–GRP hybrids and for the plain CFRP and GRP (from Figs 3 and 4) replotted in terms of initial strain against life (R = 0.1). GRP content (●) 100%, (▼) 75%, (▲) 50%, (■) 25%, (◆) 0% (all carbon).

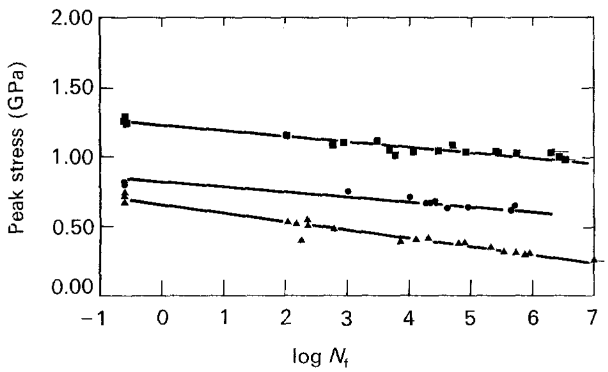


Figure 7 Peak stress S-log N curves for $[(\pm 45, 0_2)_2]_s$ (■) plain carbon, (▲) plain glass and (●) 50–50 CFRP–GRP hybrid laminates (R = 0.1).

our results (Fig. 5a). However, the strengths of his composites showed the expected non-linear variation with composition, as in our Fig. 1, and if his results are plotted as fatigue ratio against composition, therefore, they too show a strong positive synergistic effect very similar to that shown in Fig. 5b.

The non-linear effects shown in Fig. 5 are also reflected in a plot of the fatigue data on a strain basis, as in Fig. 6 where the results for the whole hybrid family are superposed. In this plot, the only data which stand out from the rest are those for the plain GRP. All other results fall within a single scatter band without any clear distinction between the different hybrids and the plain carbon.

In their work on HTS–S-glass hybrids, Hofer and co-workers [14, 15] found that unidirectional laminates tested in fluctuating tension following normal manufacturing schedules exhibited "mixture rule" behaviour, but when the same composites were subjected to accelerated hygrothermal ageing they showed a positive synergistic effect similar to that illustrated in Fig. 5. Such an effect may be due to matrix plasticization or to interfacial changes, and it seems highly likely, therefore, that the choice of resin will also significantly affect the behaviour of different kinds of hybrid.

3.2. Behaviour of $[(\pm 45, 0_2)_2]_s$ laminates

The basic mechanical properties of these laminates are given in Table II.

The strength of the all-CFRP laminate is 59% and its modulus is 55% of the corresponding values for the unidirectional XAS–913 composites already discussed. Since 0° plies account for 50% of the cross-section of the laminate, the expected strength and stiffness on a crude netting analysis basis would be $\Sigma a_n \cos^4\theta$ times the unidirectional strength, a factor of 0.625 which is clearly higher than the actual CFRP laminate values. The corresponding values for the all-glass laminate are 55 and 57%, respectively, both also below the netting analysis factor. Furthermore, the carbon–glass hybrid laminate strength is only 87% of the average of the values of the plain CFRP and plain GRP laminates, although its modulus is equal to the equivalent mean.

Fig. 7 shows the S-log N curves for these three laminates for repeated tension cycling. There is relatively little scatter here, and all three sets of data fall on reasonably straight lines. When the results of Fig. 7 are plotted on a strain basis it can be seen (Fig. 8) that the 50–50 hybrid strain–life curve falls close to that for the plain CFRP laminate, as in the case of the 50–50 unidirectional hybrid.

The relative performances of the unidirectional and $[(\pm 45, 0_2)_2]_s$ laminates may also be compared by evaluating the extent to which the fatigue responses of the corresponding single-fibre composites are translated into the hybrid. If, from Fig. 7, the fatigue stress for the plain CFRP laminate for a given life, N, is taken as $(\sigma_C)_N$, and that for the plain GRP laminate is $(\sigma_G)_N$, then the mean value $(\bar{\sigma}_{G,C})_N$ is

$$(\bar{\sigma}_{G,C})_N = \frac{(\sigma_G)_N + (\sigma_C)_N}{2}$$

If the corresponding experimental value for the hybrid laminate is $(\sigma_H)_N$, then the extent to which the fatigue resistances of the separate components are translated into the hybrid, using the linear combination rule as a basis for comparison, is indicated by the ratio $[(\sigma_H)/(\bar{\sigma}_{G,C})]_N$. The value of this ratio as a function of life is given (as a percentage) in Fig. 8. Although, as discussed, the short-term behaviour (strength) of the hybrid laminate is only some 87% of the mean, this fraction rises, for increasingly long lives, towards the mean level, reaching 98% at 10^7 cycles. This reflects somewhat similar behaviour in the unidirectional

TABLE II Mechanical properties of CFRP–GRP $[(\pm 45, 0_2)_2]_s$ laminates

Composition	Tensile strength (GPa)	Failure strain (%)	Young's modulus (GPa)
Plain CFRP	1.17	1.47	76.0
CFRP–GRP hybrid (1 : 1)	0.82	1.82	51.0
Plain GRP	0.51 (slow test) 0.71 (fatigue rate)	2.11	23.9

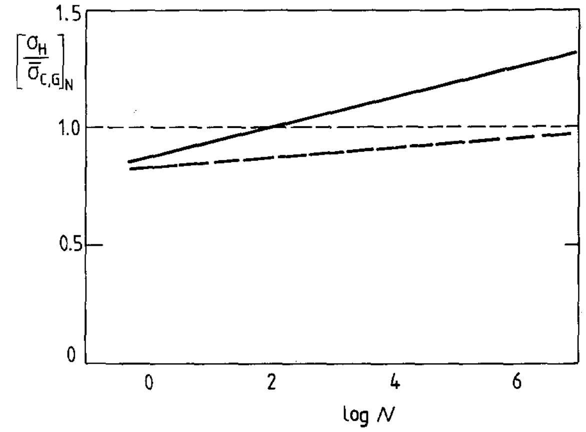


Figure 8 Fatigue behaviour of 50/50 unidirectional and $[(\pm 45, 0_2)_2]$s hybrid CFRP/GRP laminates. The points represent the hybrid fatigue stress for a given life as a fraction of the averages of the fatigue stresses for the plain CFRP and GRP laminates for the same life. The curves are based on the experimental data of Figs 3, 4 and 7 (R = 0.1).

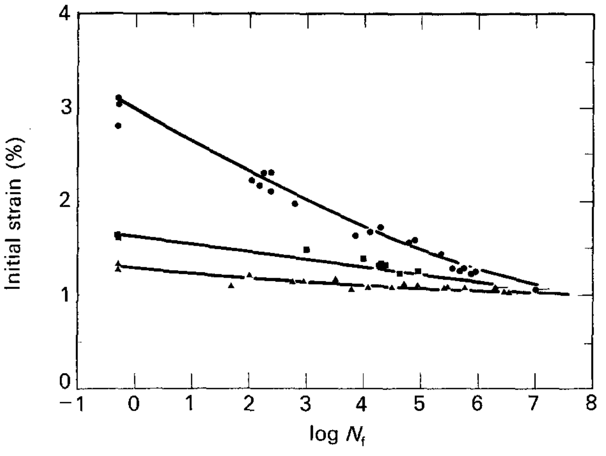
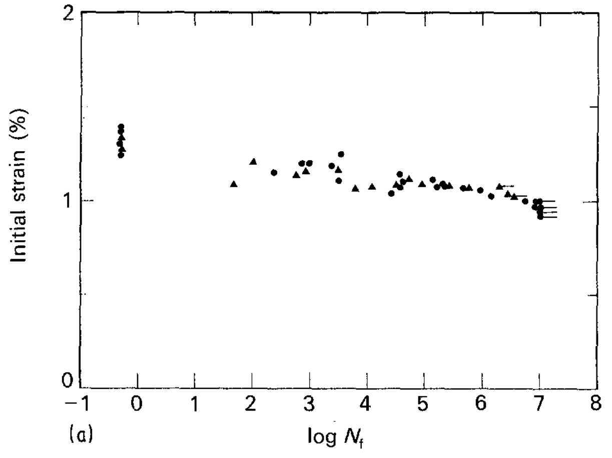


Figure 9 Fatigue results of Fig. 7 replotted in terms of initial strain against log (life) (R = 0.1). (▲) Plain carbon, (●) plain glass, (■) 50–50 CFRP–GRP hybrid laminates.

CFRP–GRP hybrids. We have already noted that the unidirectional hybrids appeared to show a synergistic effect which was at its maximum near the 50–50 composition, and this divergence between the behaviour of the two types of laminate is clearly illustrated when the results for the 50–50 unidirectional CFRP–GRP hybrid are plotted on the same diagram (Fig. 9).

Finally, in Fig. 10 we present a direct comparison of the strain–life responses of unidirectional and $[(\pm 45, 0_2)_2]_s$ laminates, for the three compositions (GRP, 50–50 hybrid, CFRP) studied. All three pairs show an analogous response, regardless of composition. The similarity of these three pairs of data, for two such dissimilar lay-ups, recalls the fundamental problem of what mode of presentation of data is most likely to be helpful in design and development. We have already remarked on the somethat confused state of opinion relating to the so-called hybrid effect. We have also referred to the use of the mixtures rule as a means of comparing the behaviour of hybrids of different composition, and have shown a marked deviation from linearity in the composition-dependence of the fatigue ratio for unidirectional hybrids of both CFRP–GRP and CFRP–KFRP, albeit without making any *a priori* assumptions about expected performance. It is clear from Fig. 10, however, that on a strain basis, increasingly regarded as a more meaningful parameter in respect of deformation-limited design, there is no recognizable difference between the fatigue behaviour of the unidirectional and $[(\pm 45, 0_2)_2]_s$ laminates even though there may be marked distinguishing features in their conventional S–log N curves. We also note that when the stress–life data of Fig. 7 are normalized relative to the tensile strengths of the laminates, the data for the plain CFRP and the 50–50 CFRP–GRP hybrid form a single population, well separated from the plain GRP laminate results, another indication of synergistic



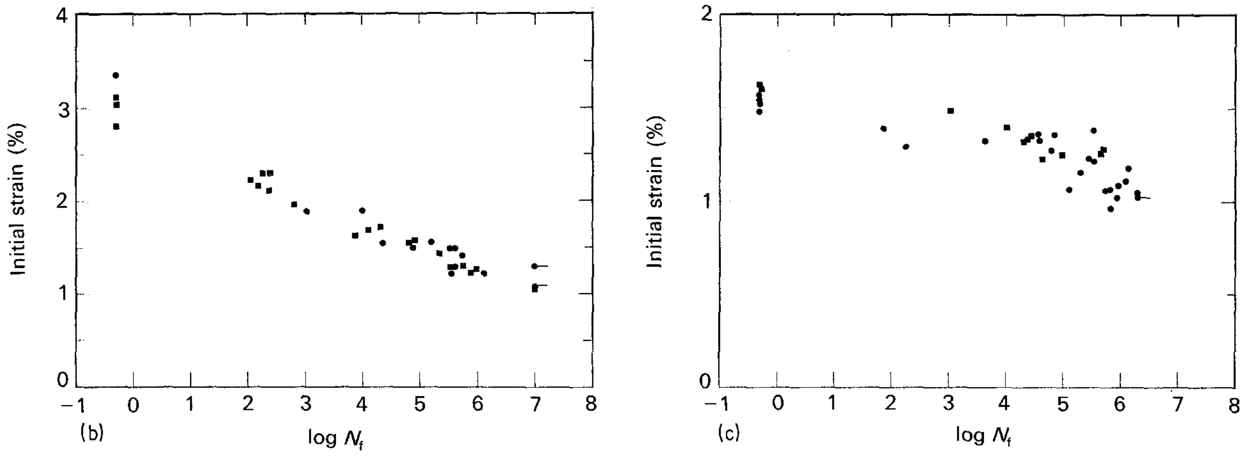


Figure 10 Comparison of fatigue behaviour of (●) unidirectional and (▲), (■) $[(\pm 45, 0_2)_2]_s$ laminates on a strain–log (life) basis: (a) 913–carbon, (b) 913–glass, (c) 913–carbon–glass hybrids (R = 0.1).

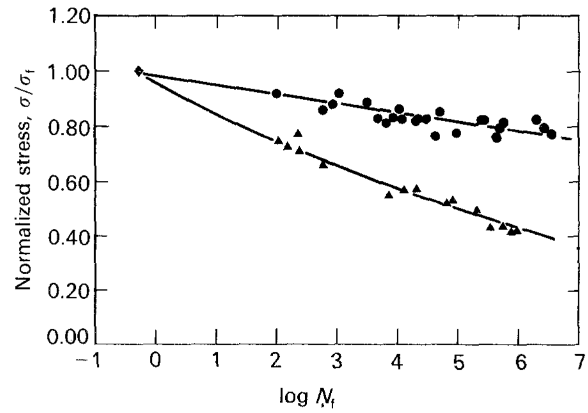


Figure 11 Comparison of fatigue results for (▲) plain GRP, (●) plain CFRP and 50–50 CFRP–GRP hybrid $[(\pm 45, 0_2)_2]_s$ laminates ($R = 0.1$). The stress levels are normalized with respect to the tensile failure stresses of the individual laminates.

behaviour (Fig. 11). Since the slopes of the normalized S-log N curves for the plain CFRP and hybrid laminates are identical, it follows that their fatigue resistances are also identical and that for a given limiting strain the hybrid will perform as well as the stronger plain carbon laminate, and at lower cost.

4. Conclusions

1. The mechanical properties of the unidirectional hybrids follow the expected forms of behaviour, the elastic modulus varying linearly with composition, the tensile strength closely following the prediction of the failure strain model, and the failure strain varying smoothly but non-linearly between the values for the two single-fibre CFRP and GRP composites.

2. The fatigue stress for a life of 10^6 cycles and the fatigue ratio vary with composition in a manner that suggests a positive synergistic effect – i.e. an upward deviation from the rule of mixtures. This effect is similar to that reported in Part 1 of this work for unidirectional carbon–Kevlar hybrids.

3. The strain–life curves for all of the hybrid compositions studied and that for the plain CFRP material fall within a single scatter-band – a further indication of the synergistic effect referred to in the conclusion above.

4. The introduction of 45° plies does not appear to affect this pattern of behaviour significantly, the effects described above being reflected in the response of the 50–50 $[(\pm 45, 0_2)_2]_s$ hybrid. The pairs of strain–life curves for the unidirectional and $[(\pm 45, 0_2)_2]_s$ laminates of the three composites studied (plain GRP, plain CFPR and the 50–50 hybrid) each superpose almost exactly.

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