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Rate-dependent fatigue of aramid-fibre/carbon-fibre hybrids

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A previously observed hybrid effect in the flexural fatigue behaviour of aramid-fibre (A)/carbon-fibre (C) reinforced hybrid is re-examined as far as this effect can be attributed to the loading-rate dependence of the hybrids. This research comprises an investigation of the fatigue behaviour of composites distinguished by its combination of experimental conditions, including the materials, loading mode and rate of loading. Unidirectional carbon-fibre/aramid-fibre reinforced hybrids were tested in flexure under a range of strain rates, in order to investigate the hybridization effect on the rate dependent fatigue behaviour. The ACA sandwich hybrid, whose fatigue performance is far better than that of the CAC hybrid, and which exhibits an improvement even with respect to the aramid parent composite, exhibits a clear strain-rate dependence. The different performances of the two hybrids are ascribed to the different rate dependences of the compressive and tensile strength of the parent C and A composites.

1. Introduction

This paper presents a study of the fatigue behaviour of composites, distinguished by its combination of experimental conditions, including the materials, loading mode and rate of loading. Unidirectional carbon-fibre/aramid-fibre (C/A) reinforced hybrids were tested in flexure under a range of strain rates, in order to investigate the hybridization effect on the rate-dependent fatigue behaviour discovered earlier [1].

The fatigue performance of a composite material is determined in general by a combination of two elements. These are the static strength of the material and its rate of degradation under cyclic loading, manifested respectively by the intercept and the slope of the S-log N fatigue curve. A study of the effect of the rate of stress application (RSA) on the fatigue behaviour must, therefore, be resolved into two analyses, evaluating separately the RSA effect on the static strength and on the degradation rate. Because the RSA, the test frequency and the magnitude of the applied stress are interrelated, as explained in ref. [2], an RSA effect can be simply transposed with a frequency effect.

A number of fatigue studies have examined RSA or frequency effects on the behaviour of different composite materials. In general, improved fatigue behaviour is reported for higher strain rates or frequencies. Sun and Chan [3] have shown that the tension–tension fatigue behaviour of $[\pm 45°]_{2S}$ graphite/epoxy laminates were highly frequency- (and temperature-) dependent, with higher frequencies tending to increase the fatigue life. The results were explained in terms of a theory of crack growth in a viscoelastic medium. This was later replaced by a damage accumulation model, explaining similar empirical results [4]. However, the frequency-dependent fatigue life increase has been observed over a range of relatively low frequencies, from 0.05 to 10 Hz, with a subsequent fall above 10 Hz [3, 4]. In an earlier work, Dally and Broutman [5] found a small fall in the fatigue life of crossply and isotropic glass-fibre-reinforced composites, when the test frequency was increased from 1 to 40 Hz. It was later pointed out [2] that they had ignored a possible initial increase of the fatigue life up to a frequency of 10 Hz, and that the subsequent fall above 10 Hz was a temperature effect at the higher frequencies. Thus it has been suggested [2] that the frequency effect in Dally and Broutman's work was camouflaged by a temperature effect.

The effect of the RSA or the frequency could be associated with the rate effects in the constituents and with rate effects on the static strength of the composite. It has been shown, for example, that the static strength of glass-fibre-reinforced composites increases significantly with RSA [6], hence the increased fatigue life could be related to this property. A further example of this effect is given in [7]. There the previous finding that the tensile strength of 0°/90° carbon-fibre and of aramid-fibre-reinforced composites were independent of testing rate [8] was implemented in choosing a test programme that incorporated varying loading

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rates, as the RSA effect on fatigue was expected to be negligible. Sims and Gladman present this point effectively in their paper on the fatigue behaviour of glass fabric reinforced composites [2]. They show that the RSA effect on the fatigue behaviour of the laminate was merely a reflection on the dependence of the ultimate tensile strength on the RSA.

Flexural fatigue produces simultaneous tension–tension and compression–compression cycling, and it is a crucial testing mode for assessing structural beams that are subjected to flexural loading (see ref. [9]). The flexural fatigue performance of fibre-reinforced composites is usually worse than the pure tension–tension fatigue performance, which is ascribed to the weakness of composites on the compression side [10]. This phenomenon is also observed under interlaminar shear flexural fatigue [11]. In general, a linear S–log N dependence is also observed under flexure, as reported for unidirectional glass fibre reinforced composites [8, 12].

Regarding the effect of hybridization on fatigue performance, the common approach has been to investigate the result of replacing the inferior fibre by the superior one. For example, it is reported that the fatigue life of hybrids is longer than that of the glass fibre control and increases markedly with the carbon fibre content [13]. In general, the tension–tension fatigue performance of hybrids is reported to fall close to the rule of mixtures prediction [14]. In a recent work on tension and compression–tension fatigue of carbon/Kevlar hybrids a positive hybrid effect was reported for the unidirectional hybrids [7]. This effect became apparent when the fatigue ratio (being the fatigue stress for a given life divided by the monotonic tensile strength) was plotted as a function of hybrid composition. It was clear that increasing the concentration of the aramid fibres in the hybrid did not exert a weakening effect on the fatigue response of the hybrids. Based on fractographic evidence it was explained that the hybrid effect resulted from a change in the fracture mechanism of the aramid fibres in the hybrid, where the typical fibre splitting was suppressed, and replaced by planar failure as of the carbon fibre. A similar hybridization-related change in fracture mechanism was observed previously in glass/carbon hybrids, where the pull-out lengths of the two fibres varied with the hybridization composition [15].

2. Experimental procedures

2.1. Materials

The experimental programme was carried out with a set of unidirectional materials, comprising the parent aramid-fibre- (A) and carbon-fibre- (C) reinforced composites and sandwich hybrids of aramid/carbon/aramid (ACA) and carbon/aramid/carbon (CAC) with different ratios between skin and core thicknesses.

Unidirectional prepregs were prepared by winding aramid fibres (Kevlar 49, Du Pont) or carbon fibres (ACIF–HT, Afikim Carbon Fibers, Israel) on a drum of a filament winding machine. The fibres were impregnated with epoxy resin (Araldite MY 750 and HT-972 hardener, both from Ciba–Geigy) diluted with acetone. After impregnation the solvent was evaporated and the epoxy resin B-staged. The prepreg layers were cut to the required size and arranged in a mould according to the desired final structure of the composite (see Table I). The mould was placed in a press, heated to 160° C, and pressed for 20 min after removal of air and surplus resin to its final thickness. Specimens were machined with a SiC cut-off wheel at 2000 r.p.m., and then post-cured for 2 h at 180° C.

TABLE I Materials for fatigue tests

Material designation	Layup	Fibre volume fraction		
		Total	A	C
Aramid (A)	8A	0.65	0.65	–
Carbon (C)	8C	0.68	–	0.68
ACA	2A/4C/2A	0.67	0.29	0.38
CAC	2C/4A/2C	0.67	0.29	0.38

2.2. Testing

Testing was performed in three-point bending on servo-hydraulic MTS and Schenk machines at relatively high loading span to specimen depth ratios, designated to produce tensile/compressive failures, rather than shear. The span to depth ratio was 13.7 to 17.7 (the loading span was 40 mm, and the loading ratio varied with the depth of the specimen in the range 2.9 to 2.2 mm). The reason why the specimen depth varied was to maintain a constant fibre volume fraction (see Table I). Fixed steel loading rollers, 10 mm in diameter, were used.

Fatigue behaviour was studied by cyclic loading at relatively high stress amplitudes, varying from a minimum of 7 to 10% to a maximum of 70 to 100% of the static strength, the minimum stress/maximum stress ratio, R, being 0.1. The specimens were fatigued at linear loading rates (ramp function) ranging from 1.0 to 200.0 cm min^{-1}, and the cycling frequencies varied with stress (see [2]) in the range 0.03 to 10.0 Hz. The strain rates were calculated from the machine cross-head speed (the slope of the ramp function) according to Equation 1.

$$\dot{\varepsilon} = (6h/L^2)\dot{D} \tag{1}$$

where $\dot{\varepsilon}$ is the strain rate, $\dot{D}$ is the cross-head speed, h is the specimen thickness and L is the loading span.

3. Results and discussion

The basic results of the fatigue behaviour of the C and A parent composites, and of the CAC and ACA hybrids, were obtained in an earlier work [1], and are reintroduced here for clarity. Figure 1 presents the S–log N plots of these materials, tested at varying frequencies in the range 0.05 to 0.5 Hz. The symbol S in Fig. 1 designates $S_{\max}$, which is the maximum of the amplitude of the cyclic stress, and the unfilled symbols mark specimens which did not fail after the specified number of cycles. Straight lines were fitted, considering only the failed specimens, according to the function

$$S = n \log N + a \tag{2}$$

where n and a are material constants.

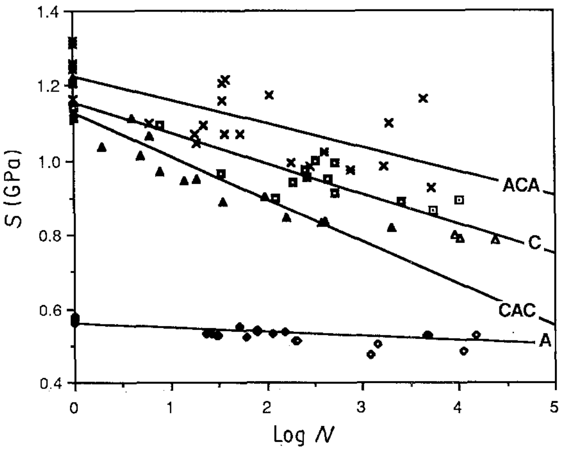

Figure 1 S–log N plots of the parent composites and of the two sandwich hybrids as presented in a previous paper [1]. ■, C; ◆, A; ▲, CAC; x, ACA.

Apart from the observation that the aramid-fibre-reinforced parent composite was the least sensitive to cyclic loading – although at much lower stress levels – it was noticed that the ACA results exhibited a bigger scatter compared with the other results, which was attributed to the extremely high strain rate sensitivity of the ACA hybrid [1]. Because at that preliminary stage both the loading rate and the frequency of the fatigue experiments varied, the two hybrids were now tested at different strain rates in order to confirm the suspected rate sensitivity of the ACA hybrid.

The results of the CAC and the ACA hybrids are presented in Figs 2 and 3, respectively. The S–log N data of the CAC hybrid do not exhibit an apparent rate dependence. Indeed, when the intercepts (equivalent to the static strength) and the slopes of the S–log N traces are plotted against strain rate in Fig. 4, no consistent trends can be identified. In contrast, the ACA data reveal a strong rate dependence, whereby at constant stress levels higher rates produce longer lives, as anticipated in the Introduction. That becomes readily evident in Fig. 5, where the intercepts (and the static strengths) and the slopes of the S–log N traces are plotted against strain rate. It is clear that the rate sensitivity prevails in the 0 to 10% $\sec^{-1}$ range of strain rate; thereafter the strain rate effect levels off.

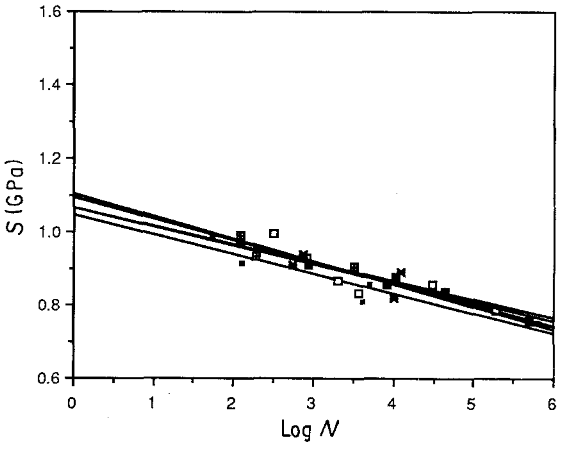

Figure 2 S–log N plots of the CAC hybrid for different strain rates (% $\sec^{-1}$): ▪, 0.8; □, 1.6; ■, 5; □, 10; ✳, 13.

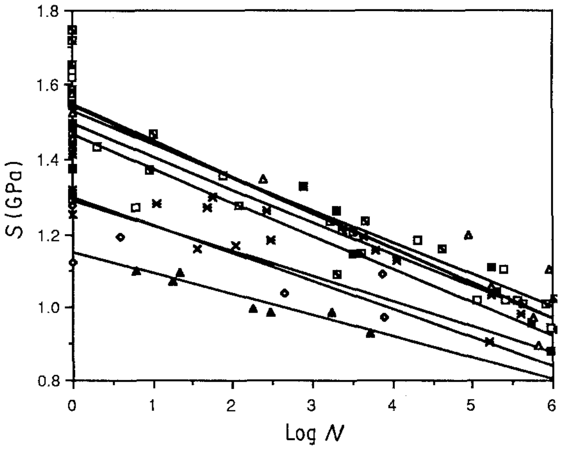

Figure 3 S–log N plots of the ACA hybrid for different strain rates (% $\sec^{-1}$): ▲, 0.16; x, 0.8; ◇, 1.6; ■, 5; □, 11; ✳, 16; □, 24; △, 32.

As pointed out above, the rate dependence of fatigue performance could be a result of a rate effect on either or both the static strength or the rate of degradation (i.e. the slope). By eliminating one effect it would be possible to isolate the other, and examine its contribution separately. Thus the ACA data were normalized with respect to the static strengths measured at the corresponding strain rates, as suggested in [2]. This procedure, which in fact eliminated the effect of strain rate on the static strength, produced the results presented in Fig. 6. The normalized data were fitted with straight regression lines, whose slopes varied from −0.050 to −0.062 with average and standard

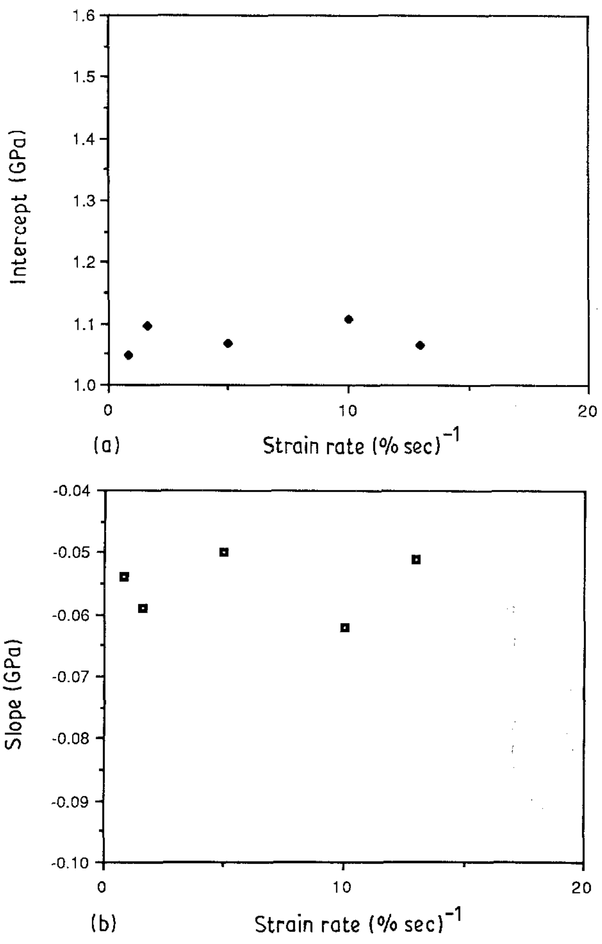

Figure 4 The parameters of the S–log N regression lines, (a) intercept and (b) slope, of the CAC hybrid as a function of strain rate.

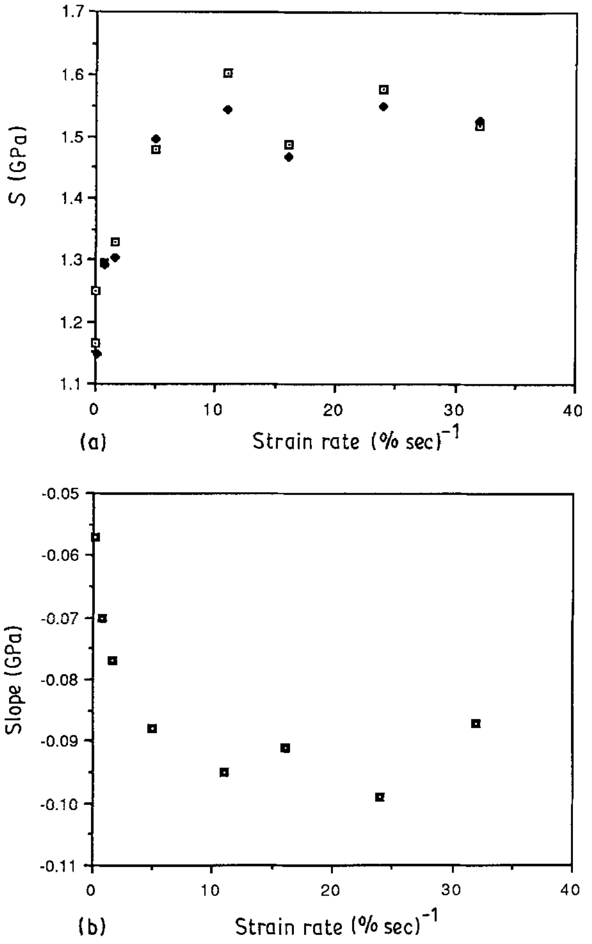

Figure 5 The parameters of the S–log N regression lines (intercept and slope) of the ACA hybrid as a function of strain rate. (a) ▣, S(GPa); ◆, intercept. (b) slope.

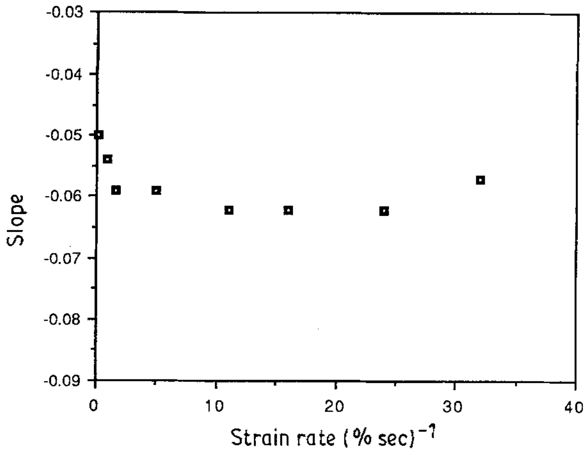

Figure 7 The slopes of the normalized ACA data as a function of strain rate.

deviation of 0.058 and 0.004, respectively, exhibiting no consistent trend, as shown in Fig. 7. This was taken as an indication that the normalized results overlapped and fell within the same band. The fact that the normalized fatigue results superimposed suggested that the rate of fatigue degradation (i.e. the slope) was RSA-independent. A similar response was observed in [2], for glass-fabric-reinforced composites in tension–tension fatigue. For comparison, the normalized S–log N results of the CAC hybrid are shown in Fig. 8; the slopes range from -0.047 to -0.056 with an average and standard deviation of 0.051 and 0.004, respectively, showing no significant difference from the ACA normalized trends.

It is proposed that the RSA-dependent fatigue performance of the ACA hybrid be analysed by the same approach that explains its improved flexural fatigue performance (the positive hybrid effect). The positive hybrid effect observed in the flexural fatigue performance of the ACA hybrid [1] was attributed to a positive hybrid effect in the static strength of this hybrid compared even with the parent C composite. The strength improvement with respect to the parent A composite was explained by the lowering of the extent of compressive yielding in flexure of the aramid fibre following its partial replacement by a carbon-fibre core. The strength improvement with respect to the parent C composite resulted from the protection provided by the aramid skin to the carbon core, thereby increasing the static strength of the latter above the value of the parent C composite.

More generally it has been shown that because flexural loading simultaneously induced tensile and compressive stresses at different zones in the beam, the flexural behaviour of sandwich hybrids reflected faithfully the lay-up sequence of the fibres and the relative thicknesses of the skins and core. This observation was in particular valid for hybrids that contained an organic fibre reinforcement such as aramid [16, 17]. The flexural behaviour of such hybrids was dominated

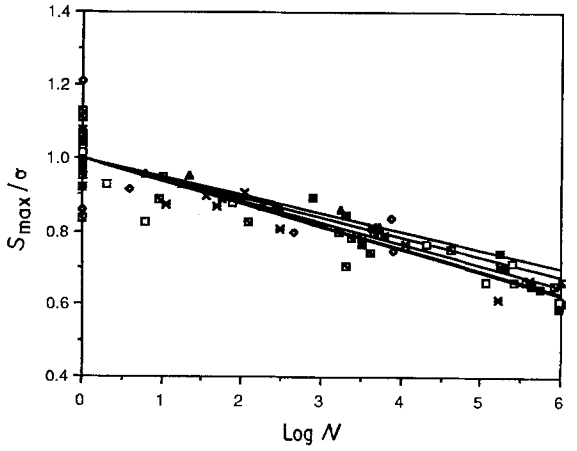

Figure 6 The normalised S–log N data of the ACA hybrids. Strain rate (% sec^{-1}), symbols as in Fig. 3.

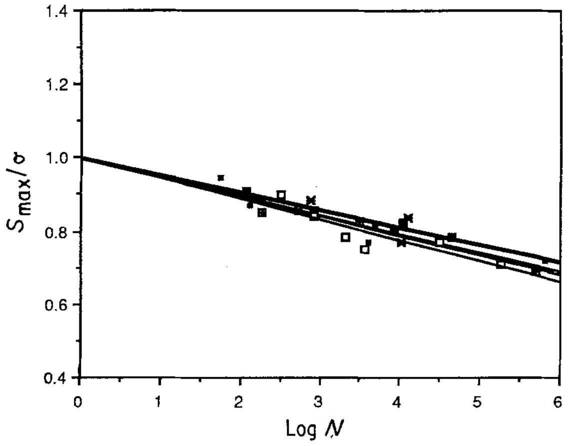

Figure 8 The normalized S–log N data of the CAC hybrids. Strain rate (% sec^{-1}), symbols as in Fig. 2.

by their premature yielding in compression at the compression side as a result of the low compressive strength of the aramid fibre. The extent of the effect of the plastic compressive yielding of the fibre depended on its placement (skin or core) in the composite and on the relative thickness of its layer.

The same approach could be used to explain the rate dependence of the fatigue performance of the ACA hybrid. For this hybrid at constant stress levels longer lives were obtained under higher fatigue rates, while in contrast the fatigue performance of the CAC hybrid was rate insensitive. The analysis of the normalized fatigue data of the ACA hybrid indicated that the rate of fatigue degradation of this hybrid was RSA independent, proving that the rate dependence of the fatigue performance was an outcome of the rate dependence of the static strength of the hybrid. According to the model of flexural behaviour of hybrid beams, this is controlled by the lay-up sequence and by the properties of the layers. Hence understanding of the RSA dependence of both the tensile and compressive strengths of the aramid-fibre and of the carbon-fibre parent composites is a prerequisite to the understanding of the flexural fatigue behaviour of the ACA and CAC hybrids. Such a study is currently under way.

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References

1. G. MAROM, H. HAREL, S. NEUMANN, K. FRIEDRICH, K. SCHULTE and H. D. WAGNER, *Composites* (in press).
2. G. D. SIMS and D. G. GLADMAN, *Plast. Rubber Mater. Appl.* **3** (1978) 41.
3. C. T. SUN and W. S. CHAN, *ASTM Special Technical Publication* **674** (1979) 418.
4. G. C. TSAI, J. F. DOYLE and C. T. SUN, *J. Compos. Mater.* **21** (1987) 2.
5. J. W. DALLY and L. J. BROUTMAN, *ibid.* **1** (1967) 424.
6. G. MAROM, N. KONIECZNY and F. R. TULER, *J. Mater. Sci.* **11** (1976) 1974.
7. G. FERNANDO, R. F. DICKSON, T. ADAM, H. REITER and B. HARRIS, *ibid.* **23** (1988) 2732.
8. C. J. JONES, R. F. DICKSON, T. ADAMS, H. REITER and B. HARRIS, *Composites* **14** (1983) 288.
9. B. D. AGARWAL and S. K. JONEJA, *Mater. Sci. Engng* **46** (1980) 63.
10. M. J. OWEN and S. MORRIS, in "Carbon Fibres: Their Composites and Applications" (Plastics Institute, London, 1971) p. 292.
11. R. B. PIPES, *ASTM Special Technical Publication* **546** (1974) 419.
12. D. G. FESKO, *Polym. Engng Sci.* **17** (1977) 242.
13. K. E. HOFFER Jr., M. STANDER and L. BENNETT, *Polym. Engng Sci.* **18** (1978) 120.
14. K. SCHULTE, E. REESE and T.-W. CHOU, in Proceedings of the International Conference on Composite Materials VI & European Conference on Composite Materials 2, Vol. 4 (Elsevier, Cambridge, 1987) p. 89.
15. G. MAROM, S. FISCHER, F. R. TULER and H. D. WAGNER, *J. Mater. Sci.* **13** (1978) 1419.
16. S. FISCHER and G. MAROM, *Compos. Sci. Tech.* **28** (1987) 291.
17. G. MAROM and E. J-H. CHEN, *Compos. Sci. Tech.* **29** (1987) 161.

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