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Effects of fibre length on tensile strength of carbon/glass fibre hybrid composites

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The tensile strength of epoxy resin reinforced with random-planar orientation of short carbon and glass fibres increased as the length of the reinforcing fibres increased, and the increase in tensile strength remained almost unchanged after the fibre length reached a certain level. The tensile strength of composites at any fibre length could be estimated by taking the strain rate and temperature dependence of both the yield shear strength at the fibre–matrix interphase and the mean critical fibre length into consideration. The tensile strength of the hybrid composite could be estimated by the additive rule of hybrid mixtures, using the tensile strength of both composites.

1. Introduction

As is well known, loads working on the short fibre-reinforced composites are transmitted to the fibre through shear at the fibre–matrix interface. Consequently, mechanical properties of the composites are greatly influenced by the shear strength at the fibre–matrix interface or the critical fibre length, which is dependent on interfacial shear strength. Hence, in discontinuous fibre-reinforced resins, precise determination of shear strength at the interface or critical fibre length is of great importance.

We have reported two methods for directly measuring yield shear strength at the fibre–matrix interphase or critical fibre length. Namely, if a sufficiently long fibre is embedded in the resin matrix and the system is elongated, the fibre eventually breaks into many pieces. By measuring lengths of the broken pieces, the interfacial yield shear strength for the system can be estimated in the case where the tensile strength of the fibres is assumed to be uniform [1], and where it is assumed to be variable [2, 3]. According to the latter method, we were able to clearly explain the strain rate and temperature dependence of both the yield shear strength at the interphase and the critical fibre length [3–5].

Until now, there have been a considerable number of investigations [6–13] carried out regarding the mechanical properties of discontinuous random planar composites. In particular, Lees [6] discussed the tensile strength of a composite experimentally and theoretically. However, it was assumed that the tensile strength of the reinforcing fibre was uniform in these investigations. Furthermore, most investigations [14–19] have investigated hybrid composites which have been reinforced with unidirectionally oriented continuous fibres or cloths composed of carbon, aramid and/or glass. Few studies have been conducted on hybrid composites reinforced with a random-planar orientation of discontinuous fibres. The effect of fibre length on mechanical properties of composites reinforced with short fibres has been experimentally examined for injection-moulded composites. Only Sanadi and Piggott [20] have discussed theoretically and experimentally the fibre-length dependence of tensile strength and Young's modulus for epoxy resin reinforced with a random-planar orientation of short carbon fibres. They reported that the fibre–matrix interaction should be considered for the fibre-length dependence of mechanical properties. Ibarra and Chamorro [21] and Gupta *et al.* [22] showed the important role of the fibre–matrix interface for study of the effect of fibre length on the mechanical properties of composites.

In this work, hybrid composites reinforced with a random-planar orientation of short fibres were prepared from carbon and glass fibres and epoxy resin, and the effect of fibre length on the tensile strength of the hybrid composites was investigated. Furthermore, the strain rate and temperature dependence of the yield shear strength and the critical fibre length previously encountered were applied to the hybrid composites system.

2. Experimental procedure

The reinforcing fibres and resin used here were the same as those used in the previous paper [1, 2, 4, 5, 23, 24], and the composites reinforced with a random-planar orientation of short fibres were prepared as reported elsewhere [2, 23, 24]. The fibres used were carbon fibre (Pyrofil, T1, 7.81 μm diameter, Mitsubishi Rayon) and "E" glass fibre (R2220, MA859, XL16, 12.73 μm diameter, Asahi Fiber Glass), and the matrix material was a bisphenol A type epoxy resin (Epikote 828, Yuka Shell Epoxy). Carbon fibre was oxidized electrolytically and the surface of the carbon fibre was sized with bisphenol A type epoxy oligomer, while the surface of E glass fibre was treated with silane coupling agent (A-1100, U.C.C.). The properties of these materials are shown in Table I.

Fibres in roving form were bundled and cut into short fibres of uniform length by a constant-length

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TABLE I Properties of materials (at 20 °C)

Materials	Tensile strength (GPa)	Young's modulus (GPa)	Poisson's ratio	Thermal expansion coefficient ($°C^{-1}$)
Carbon fibre	1.69[a]	216.7[a]	0.39	9.5×10^{-6} [b]
Glass fibre	2.25[a]	87.5[a]	0.21	6.6×10^{-6}
Epoxy resin	0.069	1.9	0.30	5.9×10^{-5}

[a] Test length = 100 mm.
[b] Perpendicular direction to fibre axis.

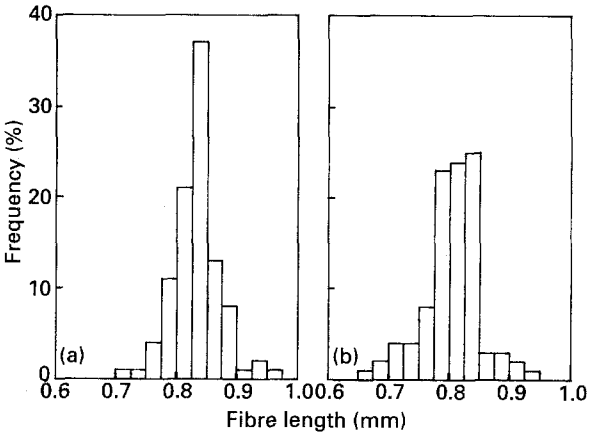

Figure 1 Frequency distribution of fibre length. (a) Carbon fibre, $\bar{L} = 0.83$ mm; (b) glass fibre, $\bar{L} = 0.80$ mm.

cutter. In order to study the effect of fibre length on the tensile strength of hybrid composites, five fibre lengths in the range 0.15–4.00 mm were used as reinforcement. After cutting, the ratio of carbon fibres to glass fibres was weighed. Both fibres were suspended in a large amount of distilled water and stirred well so that they could be distributed uniformly. After the water was rapidly drained out of the bottom of the vessel, both kinds of fibres were allowed to settle on a filter cloth placed at the bottom. The water was removed by pressing at a suitable pressure. The fibre mats were then dried at 90 °C for 24 h. In this manner it was possible to obtain a mat in which both short fibres were oriented random-planarly and yet distributed uniformly.

The damage of fibres in the mixed mat after cutting was examined. The typical fibre length distributions of the carbon and glass fibres extracted randomly from the mixed mat which has received several treatments after cutting, are shown in Fig. 1. Both reinforcing fibres have been cut sufficiently uniformly and suffered virtually no damage in the subsequent treatments. The mean fibre lengths, $\bar{L}$, standard deviation and coefficient of variation, are shown in Table II. The coefficient of variation in the case where the mean fibre length is 0.5 mm, is the largest (about 20%), but in other cases it is less than 10% and is almost the same. Accordingly, the mean fibre lengths were hereafter used as the fibre length.

The resin mixtures were prepared and defoamed under the same conditions as reported in the preceding papers [1, 2, 4, 5, 23, 24]. Namely, the epoxy resin and hardening agent (S-Cure 661, Kayaku Akzo) were defoamed under vacuum for about 1 h. 100 parts epoxy resin and 10 parts hardening agent were mixed and agitated thoroughly, and the mixture was then defoamed under vacuum for about 20 min.

The fibre mats were put into an impregnation apparatus and then evacuated thoroughly to remove entrapped air in the fibre mats. The resin mixture was poured into the apparatus so that the mats could be fully impregnated. Thereafter, atmospheric pressure was gradually applied to expedite the impregnation of the resin mixture. Finally, the impregnated mats were cured at 65 °C for 17 h and post-cured at 140 °C for 5 h, and then cooled to room temperature.

Test pieces were cut from composites prepared in the above-mentioned manner, and their surfaces and/or cross-sections were polished to inspect the state of fibre dispersion. A random planar arrangement of fibres was confirmed by the stereological theory [25].

This procedure enabled us to prepare bubble-free hybrid composites reinforced with a random-planar orientation of both kinds of short fibres. The volume fraction of the total fibres could be controlled by pressing the mat before impregnation. In this experiment, the volume fraction of both fibres was set at 9.9%. In the preceding paper [23], we showed that a hybrid composite which is reinforced with carbon and glass fibres in a one-to-one ratio (1 : 1 by volume) has an impact fracture energy higher than a composite which is only reinforced with carbon fibres, and approximately the same tensile strength and a little lower Young's modulus of the latter composite. Accordingly, three hybrid ratios (1.0 : 0, 0.5 : 0.5, 0 : 1.0 by volume) of carbon fibres to glass fibres were prepared in this experiment.

The test specimens were cut from these hybrid composites in accordance with JIS K 6767 and subjected to tensile tests at a test speed of 0.059 mm mm^{-1} min^{-1} with the aid of a Tensilon UTM-I-2500 (Orientec). All the specimens were 3 mm thick. Measurements were made at intervals of 20 °C from 20–100 °C. Between 10 and 15 specimens were tested for each test condition.

TABLE II Statistical values of fibre length

	Carbon fibre					Glass fibre				
Mean fibre length (mm)	0.15	0.40	0.83	1.76	3.92	0.15	0.42	0.80	1.88	4.07
Standard deviation (mm)	0.028	0.039	0.038	0.088	0.189	0.036	0.039	0.057	0.093	0.254
Coefficient of variation (%)	18.7	9.7	4.6	5.0	4.8	24.0	9.3	7.1	4.9	6.1

3. Results and discussion

The relationship between fibre length and tensile strengths for the carbon fibre-reinforced composites (CFRP) and glass fibre-reinforced composites (GFRP) is shown in Fig. 2. The value when the fibre length is zero is the tensile strength of epoxy resin serving as a matrix.

With these composites, the tensile strength increases as the fibre length increases within 1 mm; however, the increase in tensile strength has remained almost unchanged after the fibre length has reached a certain level.

We showed in preceding papers [2, 24] that the tensile strength $\sigma_{C,L}$ of a composite in which short fibres are oriented random-planarly depends strongly on the yield shear strength, τ, at the fibre–matrix interphase and is written as follows in the same way as an equation derived by Lees [6]

$$\sigma_{C,L} = \frac{2\tau}{\pi}\left\{2 + \ln\left[\frac{(1 - l_c/2L)\sigma_f\sigma_m V_f + \sigma_m\sigma'_m V_m)}{\tau^2}\right]\right\} - [\sigma_r]_T \qquad L \geqslant l_c \tag{1a}$$

$$\sigma_{C,L} = \frac{2\tau}{\pi}\left\{2 + \ln\left[\frac{\tau(L/d)\sigma_m V_f + \sigma_m^2 V_m}{\tau^2}\right]\right\} - [\sigma_r]_T \qquad L < l_c \tag{1b}$$

where L is the fibre length, d the fibre diameter, l_c is the critical fibre length, σ_f is the tensile strength of the fibre, σ_m is the tensile strength of the matrix, V_f is the fibre volume fraction, V_m is the matrix volume fraction, and σ'_m is the matrix stress at the breaking strain of the fibre. $[\sigma_r]_T$ is the thermal stress produced during moulding of the composite by the difference in the thermal expansion coefficient between fibre and matrix resin, and is given by

$$[\sigma_r]_T = \frac{2(\alpha_m - \alpha_f)E_m\Delta T}{(1 + \nu_m) + (1 + \nu_f)(E_m/E_f)} \tag{2}$$

where α is the thermal expansion coefficient, E is Young's modulus, ν is the Poisson's ratio, ΔT is the difference in temperature from the moulding temperature, and subscripts m and f represent matrix and fibre, respectively.

In the preceding papers [4, 5], we discussed the strain rate and temperature dependence of both the yield shear strength and the critical fibre length. For the carbon fibre–epoxy resin and glass fibre–epoxy resin systems, the yield shear strength, $\tau_{\dot{\varepsilon},T}$, at the fibre–matrix interphase at a given strain rate, $\dot{\varepsilon}$, and temperature, T, was given as

$$\tau_{\dot{\varepsilon},T} = K_1 + K_2 \log(\dot{\varepsilon} a_T) \tag{3}$$

where a_T is the shift factor, K_1 and K_2 are constants depending upon the materials constituting the composites, the adhesive state at the fibre–matrix interface, and the reference temperature.

The mean critical fibre length, $(\bar{l}_c)_{\dot{\varepsilon},T}$, under the same conditions, using $\tau_{\dot{\varepsilon},T}$, given by Equation 3, was given as

$$(\bar{l}_c)_{\dot{\varepsilon},T} = \frac{\bar{\sigma}_l d}{2\tau_{\dot{\varepsilon},T}} \tag{4}$$

where d is the fibre diameter, $\bar{\sigma}_l$ is the mean value of the strength of the links constituting the fibre.

$\tau_{\dot{\varepsilon},T}$ and $(\bar{l}_c)_{\dot{\varepsilon},T}$ obtained from Equations 3 and 4, respectively, at the strain rate ($= 0.059\ \text{min}^{-1}$) in this experiment, are shown in Fig. 3.

The solid lines in Fig. 2 represent calculated values of $\sigma_{C,L}$ obtained from Equations 1 and 2 by substituting yield shear strength, $\tau_{\dot{\varepsilon},T}$, and mean critical fibre length $(l_c)_{\dot{\varepsilon},T}$ (Fig. 3) into Equation 1 for τ and l_C. In these calculations, experimental values of σ'_m, E_m, α_m and ν_m at various temperatures are shown in Figs 4 and 5. We have employed the mean fibre length, $\bar{L}$, for L, the mean strength, $\bar{\sigma}_{f,L}$, of the fibre calculated from the following equation [2] for σ_f

$$\bar{\sigma}_{f,L} = \sigma_p + \left(\frac{\sigma_o}{n^{1/m}}\right)\Gamma\left(\frac{m+1}{m}\right) \tag{5}$$

where σ_o, σ_p, and m are the Weibull parameters. Γ is the complete gamma function, n is the number of links constituting the fibre, and the gauge length l divided by the length l_l of the link. σ_o, σ_p, m, and n determined in the preceding papers [2, 5] are shown in Table III. Young's modulus, E_f, of the fibre, the thermal expansion coefficient, α_f, of the fibre, and the Poisson's ratio,

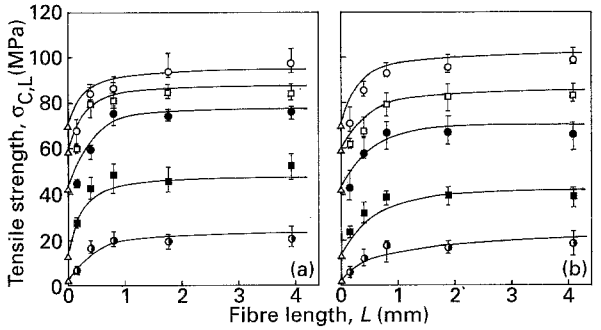

Figure 2 Relation between fibre length and tensile strength: (a) carbon fibre–epoxy resin composite; (b) glass fibre–epoxy resin composite. (○) 20 °C, (□) 40 °C, (●) 60 °C, (■) 80 °C, (○) 100 °C, (△) epoxy resin, (I) error bar, (—) value calculated from Equation 1.

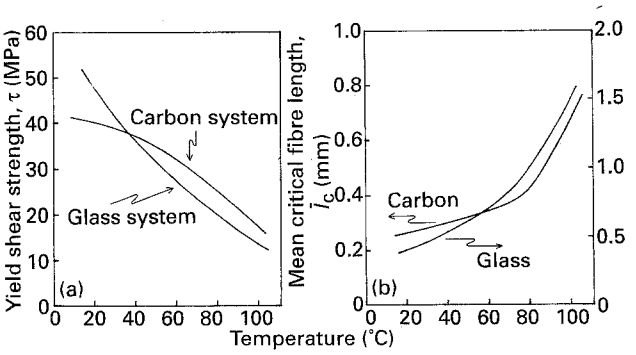

Figure 3 Temperature dependence of yield shear strength at fibre–matrix interphase and mean critical fibre length calculated from Equations 3 and 4.

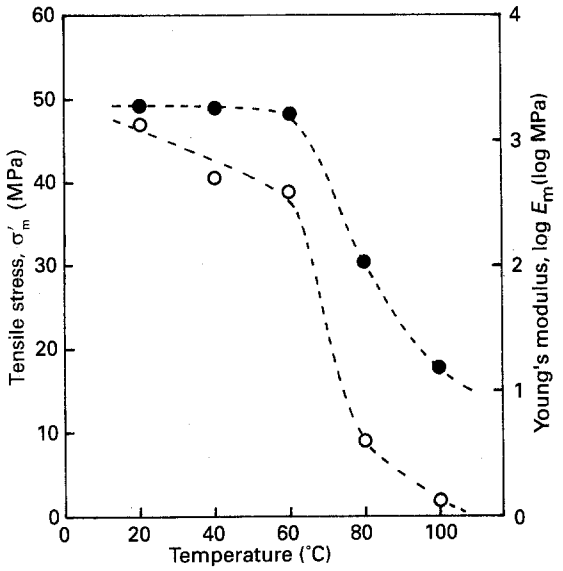

Figure 4 Temperature dependence of (○) tensile stress at fibre breaking strain and (●) Young's modulus of epoxy resin.

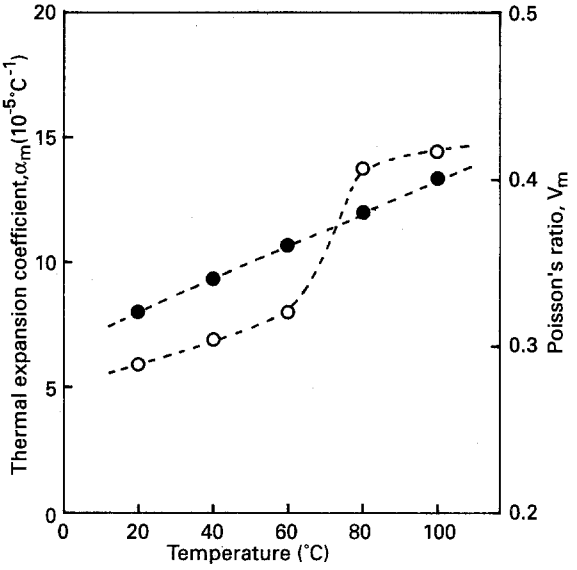

Figure 5 Temperature dependence of (○) thermal expansion coefficient and (●) Poisson's ratio of epoxy resin.

TABLE III Statistical values of tensile strength for reinforcing fibres

Fibre	Weibull parameters			Link length
	m	σ_o (GPa)	σ_p (GPa)	l_l (mm)
Carbon fibre	3.4	2.88	0.77	3.00
Glass fibre	4.3	3.71	0.30	5.00

v_f, of the fibre shown in Table I, were therefore used, and we have assumed that these values are constant in the temperature range of this experiment.

With these composites, the experimental values agree approximately with the calculated values. It is therefore possible to estimate the tensile strength of a composite reinforced with a random-planar orientation of short fibres using Equations 1 and 2

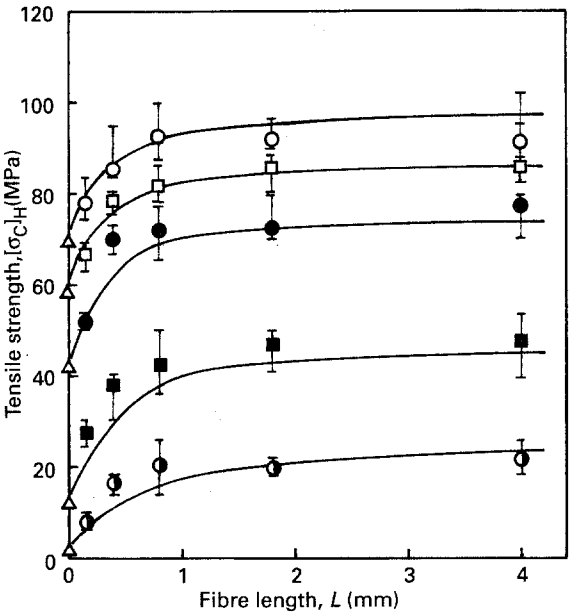

Figure 6 Relation between fibre length and tensile strength of hybrid composite: (○) 20 °C, (□) 40 °C, (●) 60 °C, (■) 80 °C, (○) 100 °C, (△) epoxy resin, (I) error bar, (—) value calculated from Equation 6.

over the entire range of experimental fibre length, $\bar{L}$(0.15–4.00 mm), by taking the strain rate and temperature dependence of both the yield shear strength at the fibre–matrix interphase and the mean critical fibre length into consideration.

The relationship between length of fibre and tensile strength for a hybrid composite, in which the hybrid ratio of carbon fibres to glass fibres is half (0.5 : 0.5), is shown in Fig. 6. In a similar manner for CFRP and GFRP (Fig. 2), the tensile strength increases rapidly as the fibre length increases; however, the increase in tensile strength remained almost unchanged after the fibre length reached a certain level.

We showed in the preceding paper [23] that the tensile strength, $[\sigma_c]_H$, of a hybrid composite is estimated by the following rule of hybrid mixtures using the tensile strength, $[\sigma_{c,f}]_c$, of CFRP and that, $[\sigma_{g,f}]_c$, of GFRP

$$[\sigma_c]_H = [\sigma_{c,f}]_c[v_{c,f}]_H + [\sigma_{g,f}]_c[v_{g,f}]_H \quad (6)$$

where $[v_{c,f}]_H$ and $[v_{g,f}]_H$ are the hybrid volume fraction of the carbon fibre and that of the glass fibre, respectively, ($[v_{c,f}]_H + [v_{g,f}]_H = 1$).

The solid lines in Fig. 6 represent calculated values of $[\sigma_c]_H$ obtained from Equation 6 by substituting the tensile strength, $[\sigma_{c,f}]_c$, of CFRP and that, $[\sigma_{g,f}]_c$, of GFRP obtained from Equation 1. The experimental values agree approximately with the calculated values. It is therefore possible to apply the rule of hybrid mixtures (Equation 6) to the tensile strength over the entire range of the experimental fibre length (0.15–4.00 mm).

4. Conclusion

Epoxy resin reinforced with a random-planar orientation of short carbon and glass fibres was prepared, and

the fibre length dependence of the tensile strength of the hydrid composites was examined.

At each temperature, the tensile strength of composites increased as the length of the reinforcing fibres increased, and the increase in tensile strength remained almost unchanged after the fibre length reached a certain level. The tensile strength of composites at any fibre length could be estimated by taking the strain rate and temperature dependence of both the yield shear strength at the fibre–matrix interphase and the mean critical fibre length into consideration.

The tensile strength of the hybrid composite could also be estimated by the additive rule of hybrid mixtures, using the tensile strength of both composites.

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