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Strain rate and temperature dependence of tensile strength for carbon/glass fibre hybrid composites

MINORU MIWA and NAOKI HORIBA
Faculty of Engineering, Gifu University, Yanagido 1-1, Gifu, Japan 501-11

The tensile strength of epoxy resin reinforced with a random planar orientation of short carbon and glass fibres increased as the strain rate increased, and the increase in tensile strength became slightly remarkable with increasing temperature. The strain rate–temperature superposition was held for each composite. The strain rate and temperature dependence of tensile strength of composites could be estimated based on the dependence of the mechanical properties of the matrix resin, the interfacial yield shear strength and the critical fibre length. The strain rate and temperature dependence of the tensile strength of the hybrid composite could be estimated by the additive rule of hybrid mixtures, using the strain rate and temperature dependence of the tensile strength of both composites. The experimental values at a higher rate were lower than the calculated values. It was hypothesized that this may have been caused by the ineffective fibres formed during preparation of the specimen.

1. Introduction

The strain rate and temperature dependence of the mechanical properties of fibre-reinforced resins based on the mechanical properties of the resins serving as a matrix have been experimentally examined [1–11].

As is well known, the mechanical properties of short fibre-reinforced composites are greatly influenced by the shear strength at the fibre–matrix interface or by critical fibre length, which is dependent on interfacial shear strength. It therefore appears appropriate to study strain rate and temperature dependence of the tensile strength of the composites in conjunction with interfacial shear strength and critical fibre length.

Until now, most investigations 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, and strain rate and temperature dependence of their mechanical properties have also not been experimentally examined [12–14].

The carbon and glass fibres and epoxy resin used in this investigation are the same as those used in the preceding papers [15–18]. The hybrid composites reinforced with a random planar orientation of short fibres were prepared as reported elsewhere [17, 18] and the strain rate and temperature dependence of the tensile strength were 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 previous papers [15–18] and the composites reinforced with a random planar orientation of short fibres were prepared as reported elsewhere [17, 18]. The fibres used were carbon fibre (Pyrofil, T1, 7.81 μm in diameter, Mitsubishi Rayon) and 'E' glass fibre (R2220, MA859, XL16, 12.73 μm in diameter, Asahi Fiber Glass), and the matrix material was a bisphenol A type epoxy resin (Epikote 828, Yuka Shell Epoxy).

Fibres in roving form were bundled and cut into short fibres of uniform length by a constant-length cutter. In this experiment, mean fibre length L for both carbon and glass was 1.01 mm. After cutting, the ratio of carbon fibres to glass fibres was determined by weighing. Both fibres were suspended in a large amount of distilled water and well stirred so that they would 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.

The resin mixtures were prepared and defoamed under the same conditions as reported in previous papers [15–18]. Namely, the epoxy resin and hardening agent (S-Cure 661, Kayaku Akzo) were each defoamed under vacuum for about 1 h. The 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

0022–2461

entrapped air in them. 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 down to room temperature.

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 10%. Three hybrid ratios [1.0:0, 0.5:0.5, 0:1.0 by volume] of carbon fibres to glass fibres were also prepared, in consideration of the results obtained in a previous study [17].

The test specimens were cut from these hybrid composites in accordance with JIS K 6767 and subjected to tensile tests with the aid of a Tensilon UTM-I-2500 (Orientec). Measurements were made at intervals of 20 °C from 20 to 100 °C. Four test speeds were selected from 5.9×10^{-3} mm/mm/min to 5.9 mm/mm/min. Ten to fifteen specimens were tested for each test condition.

3. Results and discussion

The relationship between strain rate and tensile strength at various temperatures for the carbon fibre-reinforced composites (CFRP) and glass fibre-reinforced composites (GFRP) is shown in Fig. 1. For comparison, the tensile strength of epoxy resin serving as a matrix is also plotted in Fig. 2. With these composites, the tensile strength increases as the strain rate increases, and the increase in tensile strength becomes slightly remarkable with increasing temperature.

We showed in preceding papers [19, 20] that the tensile strength $\sigma_{C,L}$ of a composite in which short fibres are arranged in a random planar orientation depends strongly on the yield shear strength τ at the fibre–matrix interphase and is written as

$$\sigma_{C,L} = \frac{2\tau}{\pi}\left[2 + \ln\left\{\frac{(1 - l_c/2L)\cdot\sigma_f\cdot\sigma_m\cdot V_f + \sigma_m\cdot\sigma_m'\cdot V_m)}{\tau^2}\right\}\right] - [\sigma_r]_T \quad L \geqq l_c$$

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

where L is the fibre length, d is 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 the following equation

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

where α is the thermal expansion coefficient, E is Young's modulus, ν is 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 [15, 16], we also showed that the yield shear strength $\tau_{\dot{\varepsilon},T}$ at the fibre–matrix interphase at a given strain rate $\dot{\varepsilon}$ and temperature T for the carbon fibre–epoxy resin and glass fibre–epoxy resin systems was given as

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

where a_T is the shift factor and 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.

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

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

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

$\tau_{\dot{\varepsilon},T}$ and $(l_c)_{\dot{\varepsilon},T}$, obtained from Equations 3 and 4, respectively, at the strain rate and temperature in this experiment are shown in Figs 3 and 4.

The solid lines in Fig. 1 represent calculated values of $\sigma_{C,L}$ obtained from Equations 1 and 2 by substituting yield shear strength $\tau_{\dot{\varepsilon},T}$ (Fig. 3) and mean critical fibre length $(\bar{l}_c)_{\dot{\varepsilon},T}$ (Fig. 4) into Equation 1 for τ and l_c. In these calculations, experimental values of σ_m and σ_m' are shown in Figs 2 and 5. We have employed the mean strength $\bar{\sigma}_l$ of the links (length of link for carbon fibre is 3 mm [16] and that for glass fibre is 5 mm [15]) for $\sigma_F{:}\bar{\sigma}_l$ is 3.36 GPa for carbon fibre and 3.68 GPa for glass fibre. We have assumed that $\bar{\sigma}_l$ is constant in the strain rate and temperature range of this study. $[\sigma_r]_T$ is also shown in Table I.

With these composites, the experimental values agree approximately with the calculated values. It is therefore possible to estimate the tensile strength of composites reinforced with a random planar orientation of short fibres using Equations 1 and 2 over the entire range of experimental strain rate $\dot{\varepsilon}$ (5.9×10^{-3}–5.9 mm/mm/min), 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.

However, the tensile strength of the composites at a higher strain rate and lower temperature was considerably smaller than the calculated value. A possible cause for this was stress concentration produced by the pores at the side of the specimen formed during preparation. It is conceivable that the effect of stress concentration on the tensile strength is remarkable at a lower temperature and higher strain rate. The dumb-bell-shaped test specimens were cut in accordance with JIS. The fibres embedded in the neighbour-

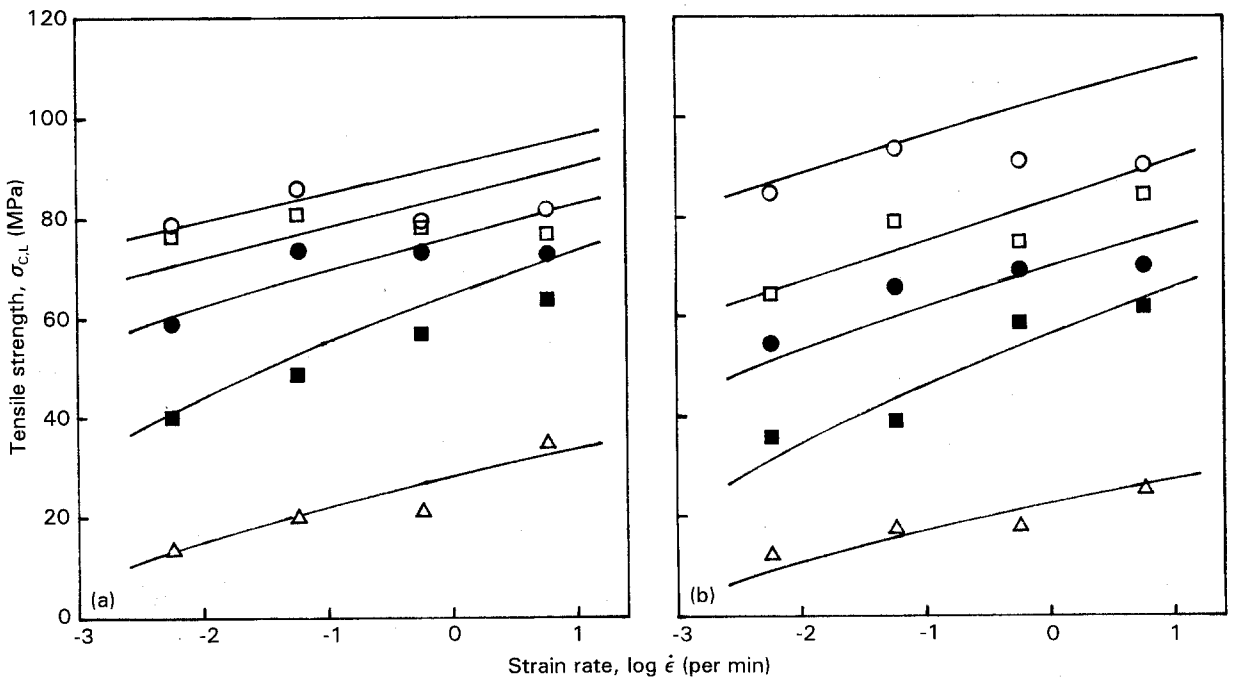

Figure 1 Relation between strain rate and tensile strength at various temperatures. (a) Carbon fibre–epoxy resin composite. (b) Glass fibre–epoxy resin composite. ○ 20 °C; □ 40 °C; ● 60 °C; ■ 80 °C; △ 100 °C; — value calculated from Equation 1.

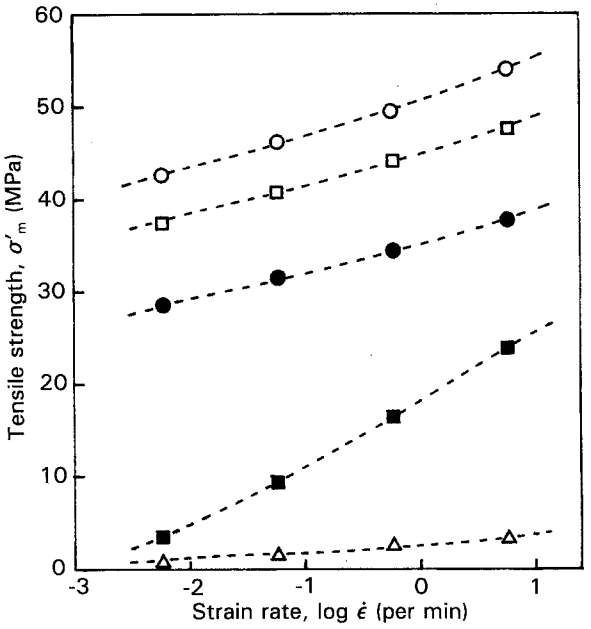

Figure 2 Relation between strain rate and tensile strength of epoxy resin at various temperatures. ○ 20 °C; □ 40 °C; ● 60 °C; ■ 80 °C; △ 100 °C.

hood of the side of the specimen were cut, which resulted in a length which was shorter than the critical fibre length. Hence, these fibres did not play any role in reinforcement. The embedded positions in such fibres acted as pores. The tensile strengths of the composites were influenced by them as if there were many cracks. The effect of the cracks on the tensile strength was larger in brittle materials. Young's modulus of epoxy resin used in this experiment at room temperature was larger by two orders of magnitude than one at a higher temperature [18], and the fracture strain and smaller. Therefore, epoxy resin exhibited a ductile fracture at a higher temperature and lower strain rate and a brittle fracture at a lower temperature and higher strain rate. As a result, crack sensibility was significant at a lower temperature and higher strain rate. It was inferred that this result could be attributed to the fact that tensile strengths expected from Equations 1 and 2 were not realized. As shown in Fig. 4, $(\bar{l}_c)_{\dot{\epsilon},T}$ of the carbon fibre–epoxy resin system at a given strain rate and temperature was shorter than that of the glass fibre–epoxy resin system. It therefore was inferred that the effect of pores on the tensile strength of carbon fibre composites was low. However, in the case where the volume fraction and length of the carbon fibres were equal to those of glass fibres, the carbon fibres were more numerous than the glass fibres, because the carbon fibre was finer. Namely, the fibres cut at the side of the specimen were numerous. For the above-mentioned reason, it was conceivable that the effect of pores on the tensile strength of carbon fibre-reinforced composites was almost the same as that of the glass fibre-reinforced composites.

The relationship between strain rate and tensile strength for a hybrid composite in which the hybrid ratio of carbon fibres to glass fibres was half (0.5 : 0.5) is shown in Fig. 6. In a similar manner to that for CFRP and GFRP (Fig. 1), the tensile strength increases as the strain rate increases and the increase in tensile strength becomes remarkable with increasing temperature.

We showed in a preceding paper [17] that the tensile strength $[\sigma_c]_H$ of a hybrid composite is estimated by the following rule of hybrid mixtures using the tensile strengths $[\sigma_{C,f}]_c$ of CFRP and $[\sigma_{g,f}]_c$ of GFRP

$$[\sigma_c]_H = [\sigma_{C,f}]_c \cdot [V_{C,f}]_H + [\sigma_{g,f}]_c \cdot [V_{g,f}]_H \quad (5)$$

where $[V_{C,f}]_H$ and $[V_{g,f}]_H$ are the hybrid ratio (by

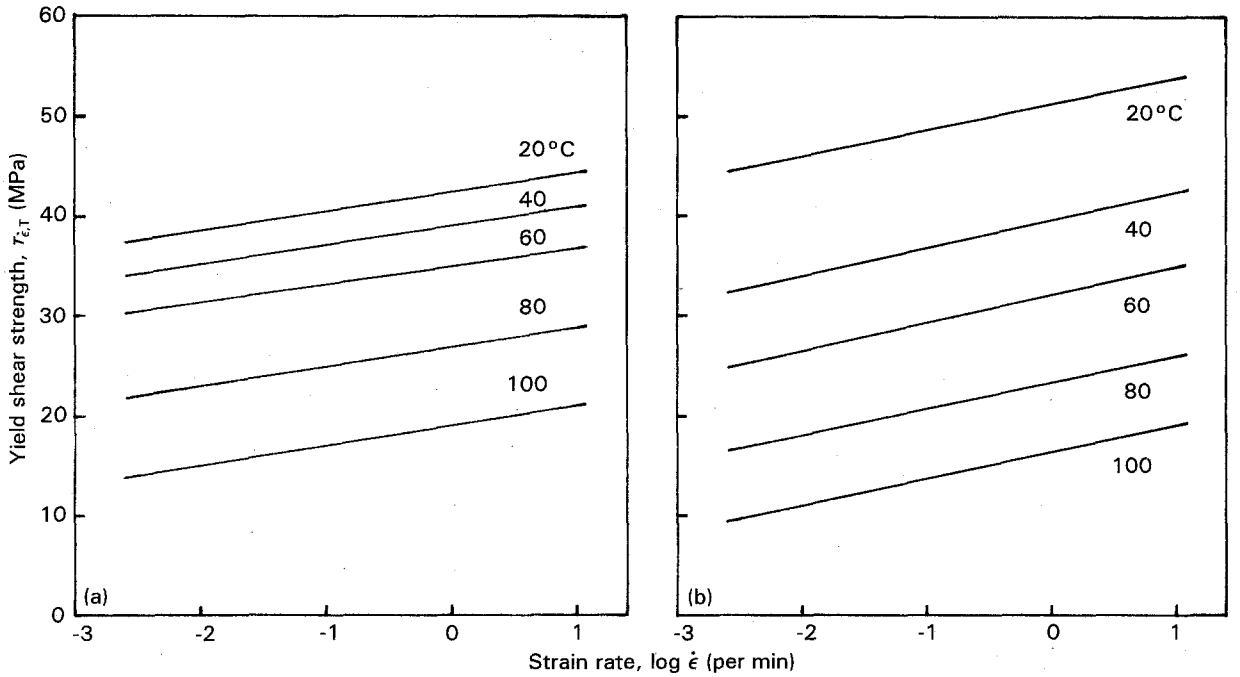

Figure 3 Relation between strain rate and yield shear strength at fibre–matrix interphase calculated from Equation 3. (a) Carbon fibre–epoxy resin system. (b) Glass fibre–epoxy resin system.

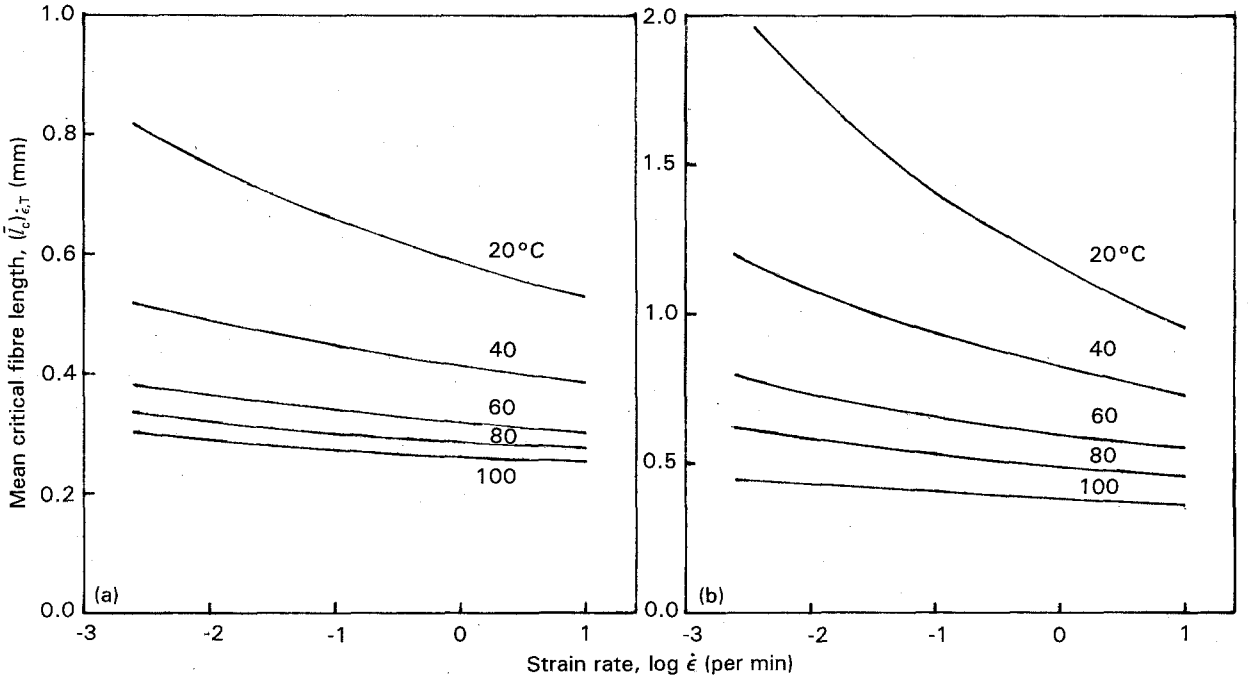

Figure 4 Relation between strain rate and mean critical fibre length calculated from Equation 4. (a) Carbon fibre–epoxy resin system. (b) Glass fibre–epoxy resin system.

TABLE I Thermal stress $[\sigma_r]_T$ (MPa)

Temperature (°C)	Carbon fibre–epoxy resin system	Glass fibre–epoxy resin system
20	10.2	10.6
40	7.42	7.68
60	4.17	4.39
80	0.77	0.79
100	0.38	0.38

volume) 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 5 by substituting the tensile strengths $[\sigma_{C,f}]_c$ of CFRP and $[\sigma_{g,f}]_c$ 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 5) to the tensile strength over

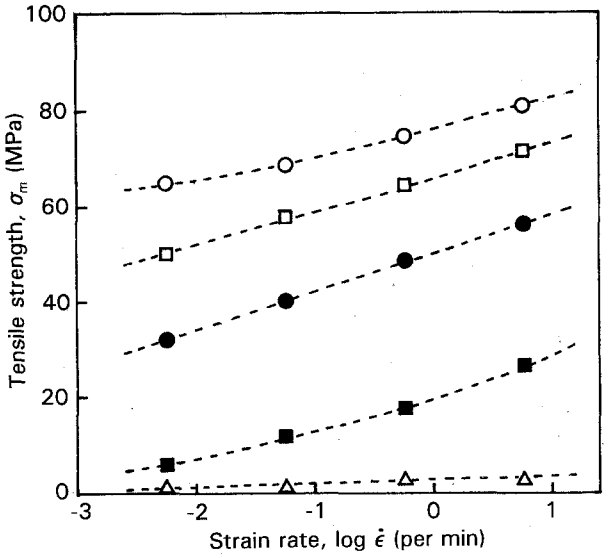

Figure 5 Relation between strain rate and tensile stress of epoxy resin at fibre breaking strain at various temperatures. ○ 20 °C; □ 40 °C; ● 60 °C; ■ 80 °C; △ 100 °C.

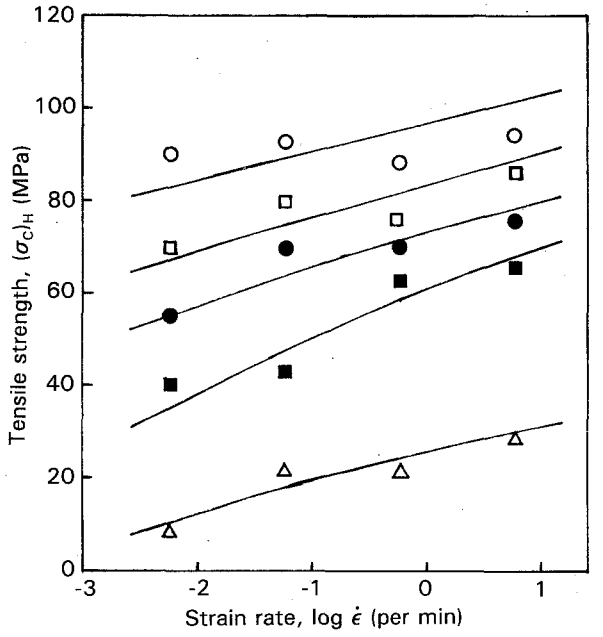

Figure 6 Relation between strain rate and tensile strength of hybrid composite at various temperatures. ○ 20 °C; □ 40 °C; ● 60 °C; ■ 80 °C; △ 100 °C; — value calculated from Equation 5.

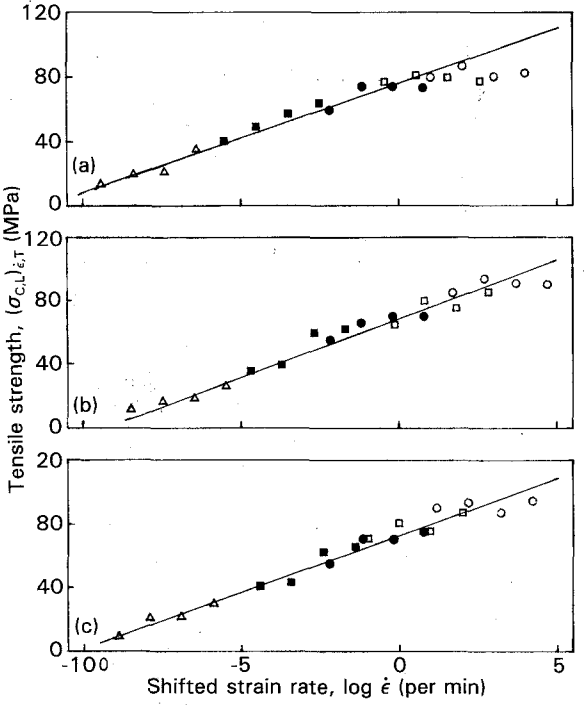

Figure 7 Tensile strength master curve: reference temperature is 60 °C. (a) Carbon fibre–epoxy resin composite. (b) Glass fibre–epoxy resin composite. (c) Hybrid composite. ○ 20 °C; □ 40 °C; ● 60 °C; ■ 80 °C; △ 100 °C; — value calculated from Equations 1 and 5.

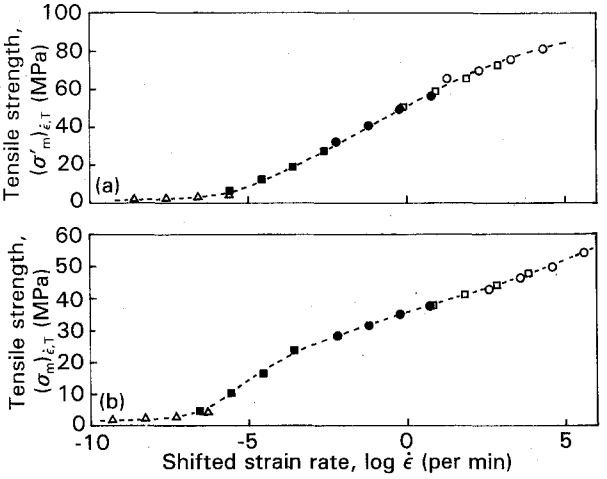

Figure 8 Tensile strength and tensile stress master curve: reference temperature is 60 °C. (a) Tensile strength of epoxy resin. (b) Tensile stress of epoxy resin at fibre breaking strain. ○ 20 °C; □ 40 °C; ● 60 °C; ■ 80 °C; △ 100 °C.

the entire range of the experimental strain rate (5.9×10^{-3}–5.9 mm/mm/min). However, the experimental values at a higher strain rate and lower temperature are lower than the calculated values. It is inferred that this is a result of the same mechanism as mentioned earlier.

Data in Figs 1 and 6 are shifted along the strain rate axis to obtain master curves of the tensile strength, as shown in Fig. 7. In Fig. 7, the reference temperature is 60 °C, and is the same as that used for strain rate–temperature superposition in the interfacial shear strength experiments [15, 16]. For the above mentioned reason, it is considered important to superpose the experimental values at a lower strain rate at a lower temperature range. Although there exists a slight deviation, data can be superposed into a single master curve. It implies that the strain rate–temperature superposition holds for the tensile strength of both composites and the hybrid composite.

The solid lines in Fig. 7 represent calculated values of $\sigma_{C,L}$ and $[\sigma_c]_H$ obtained from Equations 1 and 5, respectively, by substituting the yield shear strength $\tau_{\dot{\epsilon},T}$ and the mean critical fibre length $(\bar{l}_c)_{\dot{\epsilon},T}$ calculated from Equations 3 and 4, respectively, into Equation 1 for τ and l_c. In these calculations, experimental values of σ_m and σ'_m at the shifted strain rate are

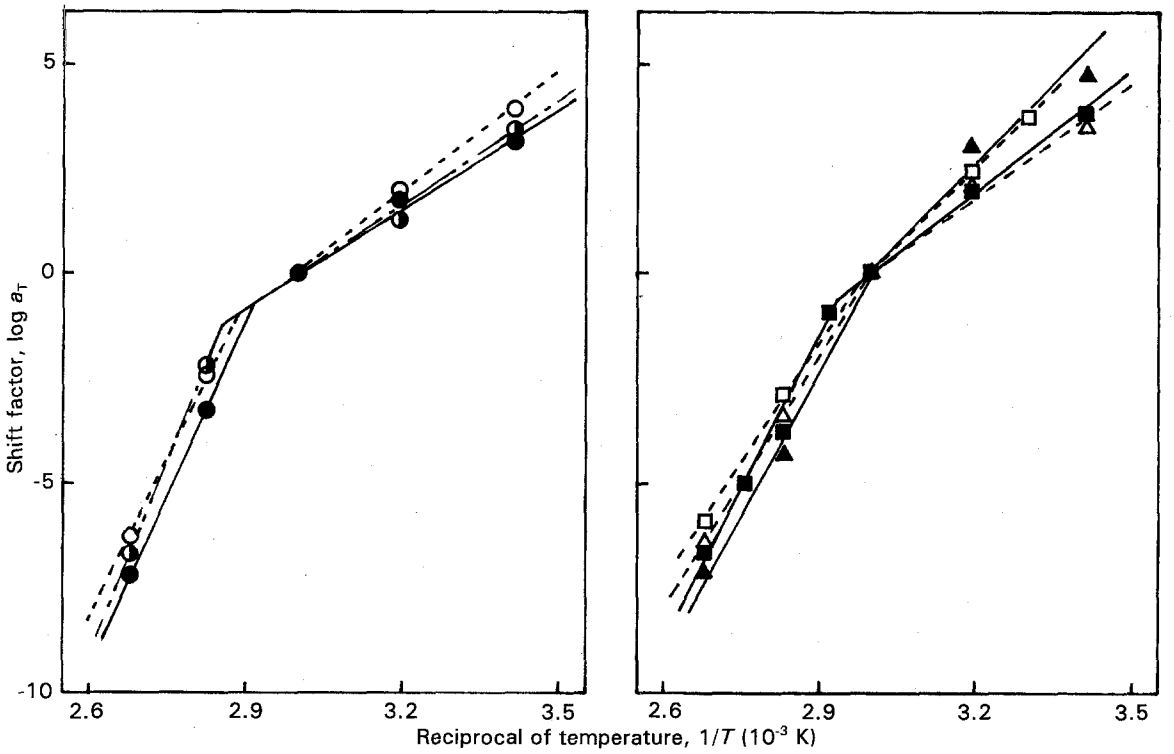

Figure 9 Shift factors as a function of the reciprocal of temperature. ● Tensile strength of carbon fibre–epoxy resin composite; ○ tensile strength of glass fibre–epoxy resin composite; ◐ hybrid composite; ■ yield shear strength at carbon fibre–epoxy resin interphase; □ yield shear strength at glass fibre–epoxy resin interphase; △ tensile strength of epoxy resin; ▲ tensile stress of epoxy resin at fibre breaking strain.

TABLE II Apparent activation energy ΔH (kJ/mol)

Properties	Lower temperature range (20–60 °C)	Higher temperature range (70–100 °C)
Tensile strength of carbon composite	163.5	490.6
Tensile strength of glass composite	187.6	478.0
Tensile strength of hybrid composite	156.3	572.4
Tensile strength of epoxy resin	178.9	378.4
Yield shear strength at carbon fibre–epoxy resin interphase	179.5	420.7
Yield shear strength at glass fibre–epoxy resin interphase	233.3	391.4

shown in Fig. 8. These master curves are also obtained by shifting data in Figs 2 and 5 along the strain rate axis (the reference temperature is 60 °C).

With these composites, the experimental values agree approximately with the calculated values. However, the experimental values at a higher strain rate are lower than the calculated values. It is conceivable that this may be caused by the ineffective fibres at the side of the specimen, which were shorter than the critical fibre length and behaved as a stress concentrator, and were formed during preparation.

The relationship between the logarithm of the shift factor log a_T to obtain these master curves and the reciprocal of absolute temperature is shown in Fig. 9. For comparison, the shift factors for the tensile strength of the matrix and the yield shear strength at the fibre–matrix interphase are also plotted. With these systems, although there is an inflexion point at temperatures in the region of 70 °C, the logarithm of the shift factor increases almost linearly with increase in the reciprocal of absolute temperature. Namely, it is recognized that a temperature dependence of Arrhenius type holds on the shift factor. The values of shift factor for the tensile strength of composites are closer to those for the yield shear strength at the fibre–matrix interphase rather than those for the tensile strength of the matrix. The inflexion point may be caused by the glass transition of the matrix resin.

Apparent activation energies ΔH obtained from the slope of a straight line are shown in Table 2. ΔH for each composite is close to ΔH for the yield shear strength at the fibre–matrix interphase.

4. Conclusion

Epoxy resin reinforced with a random planar orientation of short carbon and glass fibres was prepared and the strain rate and temperature dependence of the tensile strength of the hybrid composites was examined.

The tensile strength of composites increased as the strain rate increased and the increase in tensile strength became slightly remarkable with increasing temperature.

With each composite the strain rate–temperature superposition held. The strain rate and temperature dependence of tensile strength could be estimated based on the dependence of the mechanical properties of the matrix resin, the interfacial yield shear strength and the critical fibre length. The experimental values at a higher rate were lower than the calculated values. It was hypothesized that this may have been caused by ineffective fibres formed during preparation of the specimen.

The shift factor for superposition was given by a temperature dependence of Arrehenius type.

The strain rate and temperature dependence of the tensile strength of the composites resembled that of the interfacial yield shear strength rather than that of the tensile strength of the matrix resin. The strain rate and temperature dependence of the tensile strength of the hybrid composite could be estimated by the additive rule of hybrid mixtures, using the strain rate and temperature dependence of the tensile strength of both composites.

References

1. Y. MIYANO, M. KANEMITSU and T. KUNIO, *Fibre Sci. Technol.* **18** (1983) 65.
2. J. M. SCHULTZ and K. FRIEDRICH, *J. Mater. Sci.* **19** (1984) 2246.
3. H. VANGERKO and A. J. BARKER, *Composites* **16** (1985) 19.
4. A. GOLOVOY, *Polym. Comp.* **7** (1986) 405.
5. A. J. SMILEY and R. B. PIPES, *Comp. Sci. Technol.* **29** (1987) 1.
6. C. LHYMN and J. M. SCHULTZ, *Composites* **18** (1987) 287.
7. C. LHYMN, Y. LHYMN, R. PECKENS and J. YOUNG, *Composites* **19** (1988) 295.
8. K. FRIEDRICH, R. WALTER, L. A. CARLSSON, A. J. SMILEY and E. J. W. GILLESPIE Jr, *J. Mater. Sci.* **24** (1989) 3387.
9. M. KIMOTO, *Konbunshi Ronbunshu* **47** (1990) 741.
10. B. L. PETERSON, R. N. PANGBORN and C. G. PANTANO, *J. Comp. Mater.* **25** (1991) 887.
11. I.-M. LOW, Y.-M. MAI and S. BANDYOPADHAYAY, *Comp. Sci. Technol.* **43** (1992) 3.
12. M. KANEMITSU, S. AMAGI and Y. MIYANO, *Reinforced Plastics Jpn* **34** (1988) 464.
13. M. NAKATA, Y. MIYANO, M. SUZUKI and Y. HATTORI, *J. Jpn. Soc. Comp. Mater.* **16** (1990) 22.
14. J. ARONHIME, H. HAREL, A. GILBERT and G. MAROM, *Comp. Sci. Technol.* **43** (1992) 105.
15. M. MIWA, T. OHSAWA, K. HATTORI and Y. SHUKUYA, *Sen-i Gakkaishi* **35** (1979) T-190.
16. M. MIWA, T. OHSAWA and Y. ADACHI, *ibid.* **41** (1985) T-223.
17. M. MIWA, T. OHSAWA and K. MIURA, *ibid.* **42** (1986) T-193.
18. M. MIWA and N. HORIBA, *J. Mater. Sci.* submitted.
19. M. MIWA, A. NAKAYAMA, T. OHSAWA and A. HASEGAWA, *J. Appl. Polym. Sci.* **23** (1979) 2957.
20. M. MIWA, T. OHSAWA and K. TAHARA, *ibid.* **25** (1980) 795.

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