A new method to normalize the effect of matrix properties on the value of interfacial shear strength obtained from the fragmentation test

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A new method, based on tensile yield strength and strain, has been developed to normalize the effect of matrix properties on the critical fibre length and the interfacial shear strength obtained from the fragmentation test. It is argued that the conventional data normalization technique which employs elastic properties of the matrix, is fundamentally flawed because the model employed to calculate interfacial shear strength assumes perfect plasticity. Single embedded fibre fragmentation in a range of epoxy resins with differing mechanical properties has been used to validate the new method. Stoichiometric quantities of the current agent were used to keep the same interfacial chemistry. The proposed method provides more consistent interfacial shear strength data than existing theories. Furthermore, this normalization technique can also be used to predict the interfacial shear strength of glass fibres embedded in a range of support resins, such as vinyl ester or epoxy resins. For these cases, a thin layer of the phenolic resin was used on the glass fibre to keep the interface chemistry the same.

1. Introduction

It is well known that composites produced by incorporating brittle high modulus fibres in a polymeric matrix have outstanding mechanical properties. This led to the early use of polymer composites in the high-technology aerospace industry and now in more general engineering applications. The mechanical properties of discontinuous fibre composites depend critically on the efficient transfer of stress between the matrix and fibres.

The single-fibre fragmentation test is now commonly used for measuring the interfacial shear strength of different fibre–matrix systems [1–10]. The single-fibre fragmentation test involves embedding a filament in a matrix coupon and applying a tensile force. As the applied strain increases, the embedded fibre breaks repeatedly at points where the fibre strength is exceeded. This phenomenon is known as multiple fibre fracture. Continued application of strain results in further fragmentation until all the remaining fibre lengths become so short that the shear stress transfer along their length can no longer build up to the necessary value of tensile stress to cause further fracture. The shortest fibre length that can fracture on application of load is defined as the critical fibre length. Earlier work by Ohsawa *et al.* [11] provided the basis of the semi-empirical analysis of the test data. The critical fibre length, l_c, is given in terms of average fibre length, $\bar{l}$, as follows

$$l_c = \frac{4\bar{l}}{3} \quad (1)$$

The interfacial shear strength from the fragmentation test is calculated assuming the interfacial shear stress is constant over the fragment length either due to matrix flow in a completely plastic matrix or due to frictional stress transfer as a result of fibre debonding. Based on the constant shear model proposed by Kelly and Tyson [12], the interfacial shear strength, τ, is given as

$$\tau = \frac{r_f \sigma_{fu}}{l_c} \quad (2)$$

where r_f is the average fibre radius and σ_{fu} is the tensile strength of the fibre with length equal to the critical fibre length.

1.1. The effect of matrix properties

This methodology (Equations 1 and 2) for the calculation of the interfacial shear strength from the fragmentation test data does not consider the effect of the matrix properties other than the fact that the matrix

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transfers stress to the fibre across the interface. The influence of matrix properties on the interfacial shear strength and the critical fibre length obtained from the fragmentation test have been the subject of many studies, and it has been shown that the value of the interfacial shear strength depends on the matrix properties even though the interface chemistry remains the same [5–7]. Thus, it is necessary to use a suitable technique to normalize the value of the interfacial shear strength with respect to matrix properties where the fragmentation test is used to (a) measure the interfacial shear strength of the same fibre using different matrix resins, and when different cure schedules are used (b) study the effect of hygrothermal and other conditioning environments on the interfacial shear strength because the resin properties will also change.

Environmental factors such as elevated temperature, high humidity, corrosive fluids and ultraviolet irradiation lead to physical and/or chemical degradation of the matrix polymer in the form of a reduction in modulus and strength. An environment can also cause a loss of adhesion at the fibre–matrix interface. Because the fibre strength and modulus are generally unaffected in the short term, a study of the effect of a hygrothermal environment on the interfacial shear strength of the polymer composites requires a technique which can segregate the influence of the matrix from interfacial adhesion.

1.2. Existing normalization techniques

The existing normalization techniques for the fragmentation test data are due to Galiotis *et al.* [13] and Termonia [14, 15]. Galiotis *et al.* [13] simplified the shear lag model of Cox [16] to study the dependence of the critical fibre length on the elastic modulus of the matrix and concluded that

$$\tau \propto \left(\frac{E_m}{E_f}\right)^{1/2} \tag{3a}$$

or

$$l_c \propto \left(\frac{E_f}{E_m}\right)^{1/2} \tag{3b}$$

where E_f and E_m are the fibre and matrix moduli, respectively.

Equations 3a and b can be used to normalize the value of the interfacial shear strength obtained from the fragmentation test. For example, if τ_1 is the interfacial shear strength of a fibre embedded in a resin of elastic modulus E_{m_1} (known as the base resin), then the interfacial shear strength τ_2, of the same fibre embedded in another resin of elastic modulus, E_{m_2}, will be given by

$$\tau_2 = \tau_1 \left(\frac{E_{m_2}}{E_{m_1}}\right)^{1/2} \tag{4}$$

Termonia [14, 15] investigated the effect of the matrix properties on the interfacial shear stress in a single short fibre embedded in an infinite three-dimensional network of matrix using a finite difference approach. He proposed two cases:

(i) when $E_f/E_m < 20$

$$l_c \propto \left(\frac{E_f}{E_m}\right) \tag{5a}$$

(ii) when $E_f/E_m > 20$

$$l_c \propto \left(\frac{E_f}{E_m}\right)^{1/2} \tag{5b}$$

For case (ii), where $E_f/E_m > 20$, both the shear lag and the finite difference approaches predicted the same effect of matrix property on critical fibre length. Hence forth, Equations 3 and 4 will be referred to as the square root relationship.

1.3. Limitations of the existing normalization techniques

Several experimental studies have concluded that the effect of the matrix properties on the interfacial shear strength can be successfully predicted using the square root relationship [5–7]. This agreement between the experimental and theoretical predictions is despite the fact that the assumptions of the data reduction technique for the fragmentation test and normalization techniques for the fragmentation test results do not agree. For example, the constant shear model assumes that the shear stress at the fibre–matrix interface is limited by the shear yielding of the matrix. Finite element analysis of a single glass fibre-reinforced polymer composite has shown that the shear yielding of the matrix occurs at very low applied strains ($\sim 0.6\%$) reaching a plateau of shear stress at the fibre–matrix interface [18]. As the applied strain increases, the matrix near the fibre surface further yields and, consequently, the length of the plateau region increases. On the contrary, both the shear lag and finite difference models assume that the fibre and the matrix behaves elastically and can transfer infinite shear stress before failure. Hence, a normalization technique for the fragmentation test results is required which utilizes the same assumptions as the data reduction technique.

Netravali *et al.* [7] used the fragmentation test to show that the value of the interfacial shear strength did not change significantly but with a tendency to lower values when matrices of higher shear modulus were employed. This effect cannot be explained on the basis of the square root relationship (shear lag model or finite difference analysis) under any circumstance. Both the shear lag and finite difference approaches predict an increase in the value of the interfacial shear strength with increase in tensile modulus of the supporting matrix. However, it is possible to predict a decrease in τ, as observed by Netravali *et al.* [7], on the basis of the plasticity effect technique (Section 4). This occurs because interfacial shear strength increases with matrix yield strength but decreases with matrix yield strain. Consequently, the combined effect of matrix yield strength and strain may be a reduction in the interfacial shear strength even though the elastic modulus of the matrix may be higher (Section 5).

Drzal [5] studied the dependence of τ on the bulk properties of the matrix, produced in a range from brittle elastic to ductile plastic using stoichiometric quantities of the curing agent to retain the fibre–matrix interface chemistry. A nearly linear relationship between the interfacial shear strength and product of matrix strain multiplied by the square root of the shear modulus was observed, i.e. $\tau \propto (G_m \varepsilon_m)$. This is in line with the shear lag model. However, the author could not extend this relationship to values of interfacial shear strength less than 35 MPa.

The purpose of this study was to propose and validate a new technique, based on the elasto-plastic properties of the embedding resin, for normalizing the effect of matrix properties on the value of interfacial shear strength obtained from the fragmentation test.

2. Experimental procedure

2.1. Fragmentation test

Water-sized (unsized) A1100 (γ-aminopropyltriethoxysilane)-coupled and water-sized uncoupled E-glass fibres (Owens-Corning Fibreglas Ltd) were used. The epoxy resin was a blend of Epikote 828 (Shell) and Araldite GY298 (Ciba Geigy). Epikote 828 is a diglycidyl ether of bisphenol-A and GY298 is a long-chain aliphatic epoxy resin. The curing agents, nadic methylene anhydride (Stag Polymers and Sealants) and Capcure 3-800 (Henkel Performance Chemicals), were used in various proportions. The epoxy equivalent weights for Epikote 828, GY298, nadic methylene anhydride and Capcure 3-800 are 181–194, 400–450, 178 and 330 g, respectively. The formulation of the epoxy resins are given in Table I. Blends with higher than 65 p.h.r. Epikote 828 had failure strains less than 10% whereas those with less than 50 p.h.r. Epikote 828, the glass fibre buckled during cure, making them unsuitable for the fragmentation test.

The single-fibre fragmentation test coupons were prepared by adhering the glass filament to two ends of a U-shaped steel wire with general purpose glue. A PTFE mould of dimensions 80 mm × 10 mm × 2 mm was cleaned and placed in an oven before filling with resin to aid the removal of the surface voids in the final moulding. The resin was mixed and placed in an oven to reduce its viscosity for mixing, degassing and pouring. Once the mould was filled with the resin, the fibre was carefully placed in the centre of the mould. The samples were then cured for 4 h at 80 °C, 3 h at 130 °C and then allowed to cool in the oven overnight.

The samples were ground to a correct thickness of 1.6–1.7 mm in the central portion and 1.8–1.9 mm at each end. The samples were then polished so that the fibre could be seen through an optical microscope.

The samples were subjected to 10% strain on the Mayes tensile testing machine as recorded by an extensometer fitted to the central region of the specimen. The average cross-sectional area of each sample was measured. The force against extension was recorded during each test. The fibre fragment lengths were measured by optical microscopy using a graticule.

The strength of the fibre was measured at a particular gauge length (6.25 or 6.35 mm) with an Instron 1026 tensile testing machine. The fibre diameter was measured with a scanning electron microscope (SEM). Fibre strength, σ_{fu}, at the critical fibre length, l_c, can be calculated from the Weibull distribution as follows [17]

$$\frac{\sigma_l}{\sigma_{fu}} = \left(\frac{l_c}{l_1}\right)^{1/m} \quad (6)$$

where σ_l is the fibre strength at a particular gauge length l_1, and m the Weibull modulus. The relationship between the average fibre length and the critical fibre length given by Ohsawa *et al.* [11] and the constant shear model of Kelly and Tyson [12] was used to calculate the interfacial shear strength from the fragmentation test results (Section 1).

TABLE I Formulations of epoxy resins (p.h.r.) employed for the fragmentation test

Material	ER65/35	ER60/40	ER55/45	ER50/50
Epikote 828	65	60	55	50
Araldite GY298	35	40	45	50
NMA	68.89	66.65	64.51	62.23
Capcure 3-800	25.78	24.96	24.12	23.28

2.2. Bimatrix fragmentation test

To check the validity of the different normalization techniques described above, across a wide range of the supporting matrices for the fragmentation test, two epoxy resins and a vinyl ester resin were also employed. To keep the interface chemistry the same, a thin layer of the phenolic resin was formed by pulling the fibre through an orifice as discussed below. This test method is known as the bimatrix fragmentation test and is used to measure the interfacial shear strength of the fibres in brittle resins [19, 20]. Phenolic resin IR2245 was supplied by Hepworth Minerals and Chemicals Ltd, containing the curing agent, hexamine, for curing thermally. The unsized and uncoupled glass fibre was supplied by Owens-Corning Fiberglas (OCF). Unsized and uncoupled glass fibre was used to promote the interface failure at the glass fibre–phenolic resin interface.

Three support resins were used, two epoxy resins and one vinyl ester resin. The vinyl ester resin used was Derakane 411-45, supplied by Dow Chemicals Company, cured with cobalt accelerator E (1.0% vol/wt), DMA accelerator D (0.5% vol/wt) and MEKP catalyst M (2.0% vol/wt), all supplied by Scott Bader Company Ltd. The vinyl ester resin was cured at room temperature for 24 h before testing. Epoxy support resin 1 was epoxy resin Epikote 828 (Shell Chemicals) mixed with Araldite GY298 (Ciba-Geigy), and cured with nadic methylene anhydride (NMA) curing agent (Astor-Stag Ltd.) and Capcure 3-800 (Henkel Corporation). For epoxy support resin 2, Araldite CY208 (Ciba-Geigy) was used in place of Araldite GY298. The formulation of two epoxy resins are shown in Table II. Epoxy resin 1 was cured at 55 °C for 18 h,

TABLE II The formulation of the epoxy support resins employed for the bimatrix fragmentation test

Materials	Epoxy resin 1 (p.h.r.)	Epoxy resin 2 (p.h.r.)
Epikote 828	52	70
Araldite GY298	48	–
Araldite CY208	–	30
NMA	80	70
Capcure 3-800	40	30

130 °C for 3 h and then cooled slowly in the oven to room temperature. The epoxy resin 2 was cured at 80 °C for 4 h, 130 °C for 3 h and cooled slowly in the oven to room temperature [19, 20].

A single filament separated from the glass fibre roving was coated with a thin layer of phenolic resin by pulling the fibre filament through a small orifice covered with a 50% phenolic resin solution in industrial methylated spirit (IMS). The thickness of the coating was measured by scanning electron microscopy and was found to be ≈ 2 μm. The two ends of the coated filament were stuck to the two ends of a U-shaped steel wire with a general purpose glue, and then placed in an oven at 165 °C for 5 min to cure the phenolic resin [19, 20]. The specimen preparation, testing and data reduction technique for the bimatrix fragmentation test was the same as that for the simple fragmentation test.

3. Results

The mechanical properties of the glass fibres used in the fragmentation test are given in Table III.

3.1. Fragmentation test

The mechanical properties of the epoxy resins and the fragmentation test results are given in Tables IV and V, respectively. It can be seen from the table that the elastic modulus and the yield strength of the epoxy resin decreases as the amount of the flexibilizer resin (Araldite GY298) increases. The yield strain of the matrix shows a very complex pattern of change with the amount of the flexibilizer. However, the change in the value of matrix yield strain with increased amount of flexibilizer is not drastic (Table IV). Typical stress–strain curves of the epoxy resins for the fragmentation test are shown in Fig. 1. It can be seen that all the epoxy resins show a similar tensile stress/strain profile in the form of distinctive initial elastic modulus, yield strength and yield strain of the matrix. Table V shows that the average fragment length in the fragmentation test specimens increases with the amount of the flexibilizing resin. This is reflected in a reduction in the interfacial shear strength, calculated from the Kelly–Tyson equation.

Examination of the fragmentation test specimens (unsized A1100 coupled fibres) by optical microscopy did not show any interfacial debonding. Only transverse matrix cracks initiated at the fibre fracture were observed at the end of the fragmentation test in the specimens irrespective of the epoxy resin used. The use of the constant shear model to calculate the value of interfacial shear strength from the fragmentation test data will cause inaccuracies when the damage pattern in the test specimens changes from interfacial

TABLE III Fibre strength test data for unsized glass fibre with different coupling agents

Property	A1100 coupled fibre	Uncoupled fibre
Gauge length for fibre strength measurement (mm)	6.25	6.35
Average fibre strength at the gauge length (GPa)	2.529	1.892
Standard deviation in average fibre strength (GPa)	0.389	0.501
Average fibre diameter (μm)	17.14	14.71
Standard deviation in the fibre diameter (μm)	0.99	1.23
Weibull parameter	7.37	4.418

TABLE IV Mechanical properties of the epoxy resin for the fragmentation test

Epoxy resin	Tensile modulus (GPa)	Tensile yield strength (MPa)	Tensile yield strain (%)
ER 65/35	2.92	51.01	3.09
ER 60/40	2.52	44.91	2.82
ER 55/45	2.13	37.89	2.51
ER 50/50	1.56	30.87	3.26

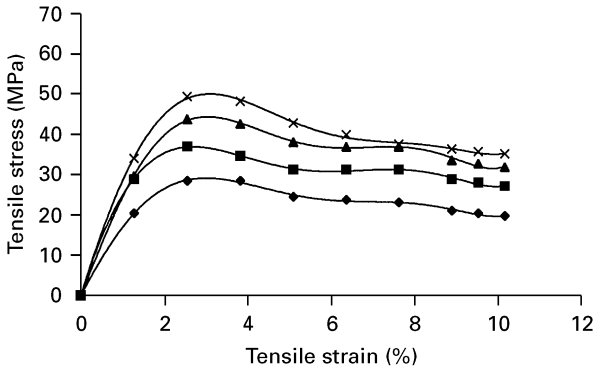

Figure 1 Typical stress–strain curves of epoxy resins for the fragmentation test: (◆) ER 50/50 , (■) ER 55/45, (▲) ER 60/40, (×) ER 65/35.

TABLE V Fragmentation test results for unsized A1100-coupled glass fibre embedded in different epoxy resins

	ER 65/35	ER 60/40	ER 55/45	ER 50/50
Average fragment length (mm)	0.472	0.520	0.558	0.603
Number of fragments	289	294	638	321
Critical fibre length (mm)	0.628	0.694	0.744	0.804
Interfacial shear strength (MPa)	47.1	42.1	38.9	35.6

TABLE VI The mechanical properties of the epoxy and vinyl ester support resins

Resin	Young's modulus (GPa)	Tensile yield strength (MPa)	Tensile yield strain (%)
Epoxy resin 1	2.56	40.8	2.88
Epoxy resin 2	3.22	59.9	3.62
Vinyl ester resin	1.33	18.5	2.39

TABLE VII Bimatrix fragmentation test results for unsized uncoupled fibre embedded in different support resins

	Epoxy resin 1	Epoxy resin 2	Vinyl ester resin
Average fragment length (mm)	0.475	0.327	0.718
Number of fragments	599	440	365
Critical fibre length (mm)	0.633	0.436	0.958
Interfacial shear strength (MPa)	37.8	58.5	22.3

debonding to transverse matrix cracking. Because all the samples showed transverse matrix cracking at the end of the fragmentation test, errors in the calculation of interfacial shear strength from the fragmentation test data are minimized.

3.2. Bimatrix fragmentation test

The mechanical properties of the epoxy resins and fragmentation test results for the bimatrix fragmentation test are given in Tables VI and VII, respectively.

4. The proposed technique for the normalization of the fragmentation test results

Earlier, an axisymmetric finite element model was used to study the effect of matrix plasticity on the shear stress at the fibre–matrix interface and the tensile stress at the centre of an isolated single filament composite [18]. This model was also used to examine the effect of individual matrix properties (initial elastic modulus, yield and cold draw strengths and tensile yield strain) on the stress transfer to the fibre. The following conclusions were drawn.

1. The maximum interfacial shear stress in an isolated embedded short fibre is a function of the tensile yield strength of the matrix, σ_y, which is equal to $\sigma_y/3^{1/2}$ when the effect of hydrostatic pressure on the yield strength of the matrix is considered to be insignificant.

2. The elastic modulus of the matrix determines the rate of the development of fibre tensile stress from the end of the fibre.

3. The maximum tensile stress in the fibre depends on the matrix tensile yield strain, ε_y. For a matrix of high tensile yield strain, a higher tensile stress develops in the fibre in comparison to that which develops in a matrix of low tensile yield strain but identical tensile modulus. The transfer of a higher value of tensile stress to the fragment leads to more fibre fragments and, thus, a lower critical fibre length (Equation 1). Thus, a higher interfacial shear strength is inferred from the fragmentation test data which employ the constant shear model (Equation 2) for analysis. It must be noted that the effect of matrix yield strain on the calculated value of interfacial shear strength is due to the fact that the Kelly–Tyson equation is used to calculate the interfacial shear strength from the fragmentation test. Matrix yield strain does not affect the interfacial shear stress in a single short-fibre composite. The effect of ε_y on the stress transferred to the fibre can be established quantitatively but its extension to the prediction of matrix effect on τ is very difficult because it depends on the fibre–matrix system used and the Weibull distribution of the fibre strengths.

Thus, the effect of the matrix properties on interfacial shear strength can be related to matrix yield strength and tensile yield strain as follows

$$\Delta\tau = \tau_2 - \tau_1 = \Delta\tau_{\sigma_y} + \Delta\tau_{\varepsilon_y} \quad (7)$$

where $\Delta\tau$ is the difference between the values of the interfacial strength of a filament embedded in Resin 1 (τ_1) and Resin 2 (τ_2). $\Delta\tau_{\sigma_y}$ and $\Delta\tau_{\varepsilon_y}$ are the effects of matrix yield strength and matrix yield strain on the interfacial shear strength respectively. Subscripts 1 and 2 represent the base resin and the resin whose interfacial shear strength is being predicted.

The effect of the matrix tensile yield strength on the interfacial shear strength obtained from the fragmentation test can be given as follows

$$\Delta\tau_{\sigma_y} = \frac{\Delta\sigma_y}{3^{1/2}} = \frac{\sigma_{y_2} - \sigma_{y_1}}{3^{1/2}} \quad (8)$$

The interfacial shear strength obtained from the fragmentation test is an unknown function of the matrix yield strain and can be represented as

$$\Delta\tau_{\varepsilon_y} = f(\Delta\varepsilon_y) = f(\varepsilon_{y_2} - \varepsilon_{y_1}) \quad (9)$$

Hence, from Equations 7–9

$$\tau_2 = \tau_1 + \left(\frac{\sigma_{y_2} - \sigma_{y_1}}{3^{1/2}}\right) + f(\Delta\varepsilon_y) \quad (10)$$

It is very difficult to determine the value of $f(\Delta\varepsilon_y)$ because of the reasons explained earlier. However, Tripathi *et al.* [18] have shown that the effect of matrix yield strain on the value of interfacial shear strength is very small for the conventional matrix resins. If very ductile or elastomeric matrices are employed, the values of $f(\Delta\varepsilon_y)$ is significant and cannot be ignored in the normalization of the fragmentation test data.

Hence, assuming $f(\Delta\varepsilon_y)$ is very small, τ_2 can be given as follows

$$\tau_2 \approx \tau_1 + \left(\frac{\sigma_{y_2} - \sigma_{y_1}}{3^{1/2}}\right) \quad (11)$$

The effect of the matrix properties on the critical fibre length can be calculated by substituting the value of τ from Equation 11 into Equation 2 which still

remains valid because it is basically a balance of force argument.

5. Discussion

5.1. Fragmentation test

The values of τ calculated using the Kelly–Tyson analysis (Equation 2) from the experimental fragmentation test data have been normalized according to the square root relationship (Equation 4) and plasticity effect technique (Equation 11). These values are given in Table VIII. It can be seen that the value of the interfacial shear strength is not an exclusive function of the interface chemistry. In fact, the value of the interfacial shear strength depends on the matrix properties also. The value of τ in epoxy resin ER65/35 has been used as the base resin to predict the interfacial shear strength values for the fibre embedded in epoxy resins ER60/40, ER55/45 and ER50/50. It can be seen that the predictions of the plasticity effect technique are in good agreement with the value of the interfacial shear strength calculated using the Kelly–Tyson model from the experimental fragmentation test data. Although the normalized values of the interfacial shear strength predicted using the square root relationship are also in reasonable agreement with the experimental estimates obtained using the Kelly–Tyson equation, this correlation is coincidental and can be explained on the basis that the elastic modulus of the matrix increases with the yield strength of the matrix in this case.

5.2. Bimatrix fragmentation test

The interfacial shear strength of the bimatrix fragmentation test specimens normalized using the square root relationship and plasticity effect technique along with the Kelly–Tyson estimates obtained from the experimental fragmentation test data are given in Table IX. It can be seen that the predictions of the interfacial shear strength using the plasticity effect technique are closer to the experimental Kelly–Tyson estimates of the interfacial shear strength from the bimatrix fragmentation test in comparison to those obtained from the square root relationship.

The adhesion of the phenolic resin to an uncoupled glass fibre has been shown microscopically to be poor [19]. However, overall, the level of "interfacial friction" is high because of high residual stresses which occur during the preparation of bimatrix fragmentation test specimens. The residual stresses are not accounted for in Table IX which can explain the discrepancy between the predicted values and the experimental estimates of interfacial shear strength [20].

We have been able to normalize the effect of matrix properties on the value of the interfacial shear strength using the yield properties of the matrix. It can be concluded that the matrix yielding occurs at the interface, irrespective of its quality. With a "good" interface when the fibre is coated with A1100 (Table VIII), matrix yielding occurs. With a "poor" interface when uncoupled fibre is coated with the phenolic resin (Table IX), yielding of the support matrix controls the stress transfer. Based on this observation, a stress transfer model for single-fibre composites [21] has been proposed. In this model, yielding of the matrix is more widely observed in the fragmentation test specimens than previously assumed and it (matrix yielding) can even exist in the presence of interfacial debonding. Further evidence for this important role of matrix yielding is presented elsewhere [21].

5.3. The effect of matrix yield strain

So far, we have assumed that the effect of matrix yield strain on the interfacial shear strength predicted by the fragmentation test is very small (Equation 11). Now, we will qualitatively consider the effect of the matrix yield strain on τ predicted on the basis of plasticity effect technique (Equation 10). Because the tensile yield strain of epoxy resin ER60/40 is less than that of epoxy resin ER65/35, the correction factor for τ will be equivalent to the difference of -0.27% in yield strain. Hence, it is expected that the value of τ corrected for the effect of matrix yield strain will be less than 43.6 MPa (Table VIII). This agrees very well with the experimental Kelly–Tyson estimates of

TABLE VIII Comparison of the values of interfacial shear strength obtained experimentally from the fragmentation test (unsized A1100-coupled glass fibre) with those obtained from the normalization according to existing theories

Epoxy resin	The value of τ obtained from the fragmentation test using the Kelly–Tyson equation (MPa)	Normalized value of τ predicted by the plasticity effect technique (MPa)	Normalized value of τ predicted by the square root relationship (MPa)
ER 65/35	47.1	–	–
ER 60/40	42.1	43.6	43.8
ER 55/45	38.9	39.1	40.3
ER 50/50	35.6	35.5	34.4

TABLE IX Comparison of the values of interfacial shear strength obtained experimentally from the bimatrix fragmentation test (unsized and uncoupled glass fibre) with those obtained from the normalization according to existing theories

Support resin	The value of τ obtained from the fragmentation test using the Kelly–Tyson equation (MPa)	Normalized value of τ predicted by the plasticity effect technique (MPa)	Normalized value of τ predicted by the square root relationship (MPa)
Epoxy resin 1	37.8	–	–
Epoxy resin 2	58.5	48.8	42.4
Vinyl ester resin	22.3	24.9	27.2

τ from the fragmentation test. However, it is not possible to predict the exact value of τ for the reasons explained in Section 4. The yield strain of the matrix has a significance influence on the value of the interfacial shear strength. It has been shown that the matrix yield strain controls the fibre fragmentation process during the test and a matrix of higher yield strain leads to the shorter fragment lengths than a matrix of lower yield strain and consequently, a higher value of the interfacial shear strength is estimated from the Kelly–Tyson model [18].

6. Conclusion

The square root relationship (derived from the shear lag model or finite difference method) for the normalization of interfacial shear strength values obtained from the fragmentation test of a single embedded filament in different supporting matrices, is commonly used. However, this relationship only considers the elastic properties of different matrices while the conventional data reduction technique for the fragmentation test based on the Kelly–Tyson model assumes constant shear at the fibre–matrix interface (either through a perfectly plastic matrix or friction caused by interfacial debonding). Hence the main assumption for the calculation of interfacial shear strength from the experimental fragmentation data and that for normalization of this value with respect to matrix properties are in contradiction. A new technique for the normalization of fragmentation test results which is based on the effect of matrix plasticity (tensile yield strength and tensile yield strain) on the stress fields associated with a short embedded fibre, is proposed. Experimental support for the plasticity effect technique is presented. The plasticity effect technique can be used to explain qualitatively the experimental results where the apparent interfacial shear strength is lower in a second matrix of higher elastic modulus [7]. This is, however, not possible to explain on the basis of the modulus square root relationship. Furthermore, the plasticity effect technique can be used to normalize the fragmentation test results irrespective of the chemical nature of the matrix, provided the chemistry at the fibre–matrix interface remains the same. However, care should be taken with the normalization of the fragmentation test results obtained with very ductile or elastomeric matrices, because the value of the interfacial shear strength may be erroneously high as a result of the limitations of the constant shear model [18].

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