EVALUATION OF THE INTERFACE STRENGTH IN METAL/POLYMER COMPOSITE SYSTEMS

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Abstract

Among the several test methods to characterize the fibre-matrix interface in fibrous composite materials, the single fibre fragmentation test is one of the most simple in terms of experimental setup, and at the same time the amount of data that can be extracted from one single test is significant. In this work, the single fibre fragmentation test method was implemented to assess the interface shear strength obtained for a single steel filament embedded in an unsaturated polyester resin. Furthermore the single fibre fragmentation test result was modelled and the results substantiated using finite element analysis (FEA) considering the material behaviour as being linear elastic. The stress distributions obtained from the FEA and the one-dimensional Cox model were analyzed and compared. A comparison of obtained average interface shear stresses at filament failure shows, that the different models have certain and different ranges of applicability, which in some cases can lead to misinterpretations and erroneous conclusions regarding the filament/resin interface properties.

1 Introduction

The performance of polymer composites materials is to a large extent determined by the fibre resin interface properties. There are several methods, which can be used to characterize the interface properties including the single fibre pull out, micro-tension, micro-indentation, and single fibre fragmentation tests [1-5]. Single fibre fragmentation tests are frequently used to characterize the interface mechanical properties between glass or carbon fibres and the polymer resin in composite materials due to its relative simplicity in the testing setup. Furthermore it offers the advantage over other competing methods that the number of fragments that can be obtained from one single test specimen is typically large, thus enabling a complete statistical analysis [1-3]. There are several studies completed with the purpose to describe the stress transfer between resin and the fibres, especially for the fragmentation test [5]. The fragmentation of the fibres initially was observed and reported by Kelly and Tyson (1965) in tungsten fibres embedded in a copper matrix. Based on these observations and using a simple in-plane force balance they proposed a simple equation to estimate the average shear stress, which in turn is interpreted as the interface shear strength $\tau = \sigma_{f_{lc}} d/2l_c$ [4, 5], where $\sigma_{f_{lc}}$ is the tensile strength of the fibre at the fragment length, d is the fibre diameter and l_c is the critical fragment length. In the Kelly and Tyson relation only the tensile strength of the fibre and the fragment length are used as model parameters. However, as the single fibre fragmentation test in reality involves complex 3D phenomena that are not addressed in the model, the Kelly and Tyson relation equation may underestimate or overestimate the interface shear strength. An alternative one dimensional elastic stress transfer model (shear lag model) was proposed by Cox in order to study the matrix-fibres interaction [6]. Cox developed the model based on the following assumptions: linear elastic material properties, the matrix material transfers shear and tensile stresses, the fibres and the matrix share only loading/stresses along the fibre direction, which implies that the matrix strain is uniform, and that the stress transfer between matrix and fibre depends of the displacement difference of one point in the fibre and the same point expressed in the matrix in absence of the fibre [1, 6]. For the single fibre composite the Cox equation can be expressed by:

$$n = \left[\frac{E_m}{E_f(1+\nu_m)\ln(R/r)}\right]^{1/2} \qquad (1)$$

$$\sigma = E_f \varepsilon_1 \left[1 - \frac{cosh\,(nz/r)}{cosh\,(nL/r)}\right] \qquad (2)$$

$$\tau = \frac{1}{2} n E_f \varepsilon_1 \frac{sinh\,(nz/r)}{cosh\,(nL/r)} \qquad (3)$$

where: E_f and E_m is the fibre and matrix modulus, ν_m is the matrix Poison's ratio, R and r is the fibre and matrix diameter, ε_1 is the far field strain applied to the single fibre composites.

Several types of fibres are being used as reinforcement in polymer composite materials [1, 3]. The most widely used fibres are carbon and glass fibres, but metal fibres are also being introduced as a potential replacement for carbon and glass fibres for some specific applications [7]. The low cost and high mechanical properties (including ductility) of steel filaments (or cords composed of tows of steel filaments) compared to the traditional reinforcement systems is the main motivation to explore the potential and reliable application of polymers reinforced by steel filaments/cords for civil engineering, automotive, and others applications. A significant "challenge" when using polymers reinforced by steel filaments/cords is the polymer matrix-steel interface properties. In this work the matrix steel-filament interface properties are investigated using the single fibre/filament fragmentation test method in which a single steel filament is embedded in a polymer matrix. Furthermore, the observed damage and failure mechanisms in the fragmentation process will be discussed. In order to validate the fragmentation test results, linear elastic finite element modelling has conducted including the resin curing shrinkage induced during the manufacturing of the test specimen. Moreover the interface shear strengths obtained using the Kelly and Tyson, Cox and FEA models will be compared

2 Materials and experimental setup

In this study Zinc coated high strength single steel filaments embedded in an unsaturated polyester resin have been considered. The mechanical properties of the constituent materials are shown in Table 1. Traditionally, the single fibre fragmentation test has been used successfully to characterize the interface shear strength for composite systems utilizing carbon, glass and other fibres which diameters that are lower than 20µm. In this study steel filaments with a diameter of 100µm is considered, and consequently the fragmentation test sample dimensions should be redesigned. Assuming linear elastic behaviour for the steel filament and the polyester resin, and using the rule of mixtures, the minimum cross sectional area to obtain fragmentation is ~2.33mm^2. However, to avoid premature failure due to manufacturing defects, a cross sectional area of 90mm^2 was used. Dogbone samples with a steel filament inserted were manufactured by casting resin into a silicone rubber mould. To avoid filament misalignment, the filaments were pre-strained using 200g of weight. The effective length of the dogbone samples was 220mm.

All the fragmentation tests were performed using an electro-mechanical Zwick/Z100 tensile testing machine operated in deformation control. Based on preliminary tests a loading rate of 0.05mm/min was demonstrated to be appropriate to achieve filament fragmentation. During the testing the filament damage and failure process was monitored using a 50× magnification optical stereomicroscope. Moreover, as the unsaturated polyester resin is transparent a planar photoelasticity technique was employed to observe the birefringence phenomena caused by the developing local stress concentrations around the filament fragment ends, and to localize the areas/points where the filament fragmentations occurred. Fig 1 shows the experimental setup used.

3 Finite element modelling

To validate the experimental results, a single steel filament embedded in polyester resin was modelled using the commercial FEA code ANSYS. Material linear elasticity was assumed, and the problem was simplified by assuming axi-symmetry (32000 axi-symmetric 2D plane183 elements were used). Fig. 2 shows the model geometry (OEFA is the steel filament). OD is a symmetry axis, OB is the axis of axi-symmetry, the load is applied to the CB edge as a prescribed axial strain of 3.54%, and the AFF'B is an empty volume representing the cavity created by the fracture of the filament. Perfect interface bonding is assumed (line EF). The polyester resin displays a high volumetric shrinkage (ΔV_{shr} = 8%), and a thermal analogy was used to simulate the manufacturing shrinkage pressure acting on the steel filament. For the thermal analogy, an equivalent thermal expansion coefficient was estimated using the average elasticity modulus over the time (assuming a linear relation between shrinkage strain and Young´s modulus over time), which is approximately 50% of the volumetric shrinkage. Assuming gradient temperature (ΔT) -1°C, the equivalent coefficient expansion obtained is α_{shri}= 0.01299/°C.

4 Results and Finite Element validation

Six samples were tested and the summary of the results are shown in Table 2. Small fragments were obtained with an average fragment length to diameter aspect ratio of $L_{Aver}/D = 17$, which indicate a high efficiency in the stress transfer from the resin to the filament. Furthermore, shorter fragments may represent high interfacial shear strength. The tensile strength of the single steel filament was obtained for different filament gauge lengths (5, 10, 15 and 20mm) showing that the tensile strength is almost constant for different gauge lengths and the average value is showing in Table 1. This is contrary to observations for glass and carbon fibres where the strength is higher when measured for shorter fibre gauge lengths [8]. With the Kelly and Tyson relation, the shear strength obtained corresponding to the average fragment length was ~ 89MPa, which is very high compared to the values obtained for glass and carbon fibres [3, 6].

The FEA results show that the resin shrinkage is not reflected in the axial stress along the fragment and in the interfacial shear stresses along the interface. However, as shown in Fig. 3, the radial stress induced by the resin in the fibre-resin interface increases to ~17MPa due to the shrinkage. Large radial stresses are observed near to the fragment end, and this is due to the lower deformation of the fragment in the axial direction and due to the transverse contraction of the resin (Poisson's ratio effect).

The embedded steel filament is subjected to tensile stress during the loading, and consequently the tensile strength can be set as a failure criterion for the filament. Fig. 4 shows the maximum axial stresses obtained from the FEA model normalized with respect to the filament tensile strength, as a function of filament length to diameter aspect ratio (L/D). The filament fragmentation occurs (filament tensile failure) when the axial stress in the embedded filament reaches the tensile strength of the single filament (3016MPa). From Fig. 4 it is seen that the critical filament length corresponds to L/D=16.5, (i.e. a fragment length of 1.65mm) which is very similar to the average value experimentally (1.7 mm, see Table 2). Thus, the experimentally observed and the FEA predictions of the fragment lengths are almost identical with a 2.9% difference. However the very small fragment lengths to diameter ratio obtained (16.5-17 here) is not comparable to the values obtained in glass and carbon fibre systems [3 and 9], where much larger values are typically obtained.

The distribution axial stresses along the filament and the shear stress along the filament-resin interface were analyzed and compared for a fragment length of 1.65 mm using the Cox model (eq. 2 and 3) and FEA models, and the results are shown in Fig. 5. The axial and shear stresses obtained using the Cox model are considerable lower than predicted by the FEA results. However, a much better agreement is obtained for longer fragment lengths, and for the stresses away from the fragment edge [5, 10, and 11]. For shorter fragment lengths the area of high stress concentrations towards the filament end is considerably longer [10].

The Kelly and Tyson equation provides a quantity which is interpreted as the average interface shear stress at filament failure. From the Cox and FEA models, the average shear stress at filament failure can be determined by integrating the interface shear stresses obtained along the interface length ($\tilde{\tau} = 1/l_c \int_0^{lc} \tau_x \, dx$).

Fig. 6 shows the average shear stresses at filament failure obtained from the Kelly and Tyson equation (using the average and critical fragment length criteria), FEA and the Cox model. The Cox model predictions agree well with the FEA results for the longer fragment lengths, where the Kelly and Tyson model underestimate the average shear stress. The average fragment lengths reported in literature for glass and carbon fibre/resin systems are in the range of ~300-1200 μm, corresponding to fragment length/diameter ratios in the range of L/D ~20-170 [3, 12]. Some references report a generally good agreement between the average shear stress obtained using the Kelly and Tyson equation and FEA predictions. However, from Fig. 6 it is seen that a good agreement between the two models is only obtained in the approximate fragment length/diameter ratio of L/D=15-35. A similar misunderstanding can be observed by comparing the Kelly and Tyson equation with the Cox model results where a good agreement is only obtained for the approximate range of L/D=30-45.

Conclusions

The single fibre fragmentation test was successfully adopted for the assessment of the interface strength properties of 0.1 mm high strength steel filaments embedded in unsaturated polyester resin. The tensile strength is not sensitive to the gauge length of the tested steel filaments, as observed in the literature for the conventional fibres used for reinforcement in composite materials as e.g. glass and carbon fibres [8]. Short fragment lengths were obtained, and using the Kelly and Tyson equation, apparent high interface shear strength was estimated.

During the loading of the fragmentation test sample, high radial compression stress development was observed at the fragment edge. The resin shrinkage stresses do not have significant influence on the filament edge compression stress, however at the central part of the filament high compression stresses were observed.

The short fragment lengths obtained in the experiments were substantiated using detailed FEA modelling. Furthermore the average interface shear stresses at filament failure (i.e. interface shear strength estimates) predicted using the Kelly and Tyson and Cox models has been shown only to have reasonable accuracy within a limited range of filament fragment lengths. Thus, it is concluded that the Cox and the Kelly and Tyson models should be used with care, since erroneous conclusions may otherwise be drawn with respect to the interface mechanical properties of a specific filament and resin system.

Table 1: Mechanical properties of zinc coated ultra high strength steel filaments and unsaturated polyester.

	Steel Filament	Unsaturated Polyester
Diameter [mm]	0.1	-
Longitudinal tensile modulus [GPa]	209	1.289§
Tensile strength [MPa]	3016	45.75§
Strain to failure	~0.021	~0.06*§
Poisson's ratio	0.30	0.375§

§ Tested at 0.05mm/min * Non-linear ultimate strain

Table 2: Summary of Fragmentation test results

Sample	Number of Fragments	Average. Frag. Length (mm)
1	84	1.758
2	51	1.965
3	88	1.724
4	55	1.509
5	10	1.791
6	17	1.471
		1.703

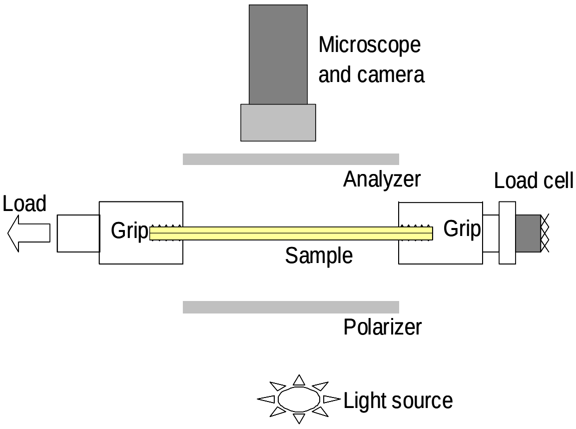

Figure 1: Schematic representation of fragmentation experimental setup

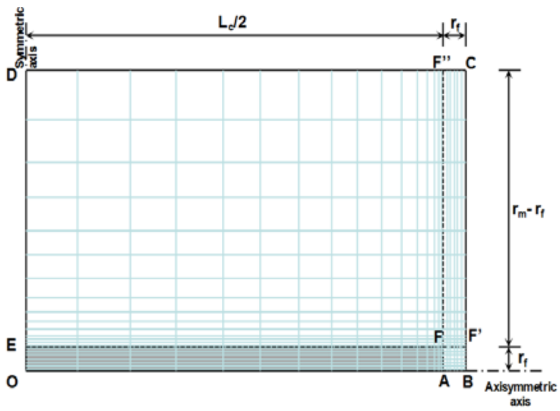

Figure 2: **FEA model - s**chematic showing geometry and meshing for the fragmentation model

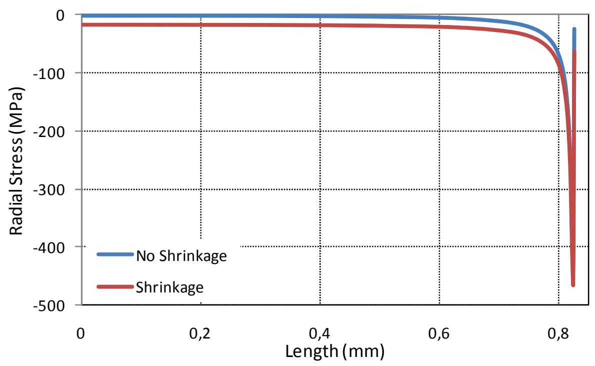

Figure 3: Radial stresses along the filament-resin interface obtained considering shrinkage and no shrinkage effect

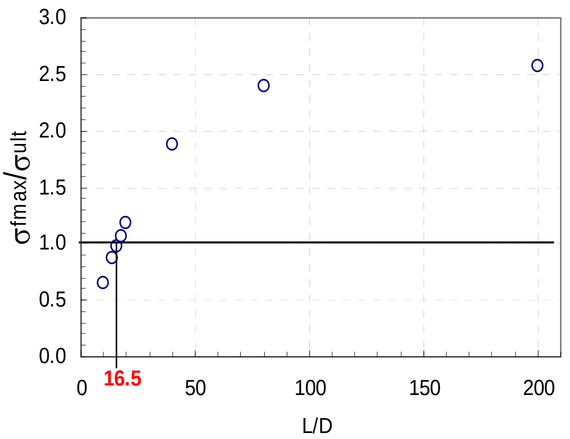

Figure 4: Normalized maximum axial filament stress as a function of fragment length/diameter ratio obtained from the FEA model.

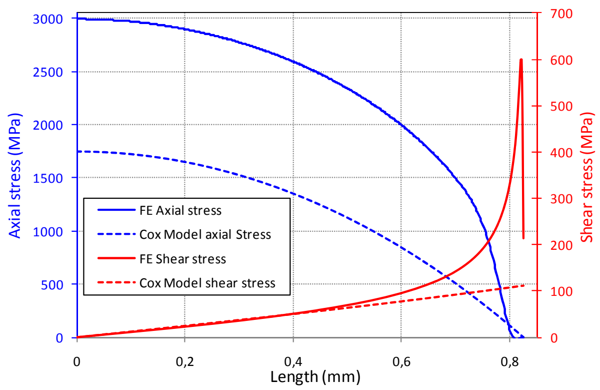

Figure 5: Stresses obtained from the Cox and FEA model along half the filament and interface lengths.

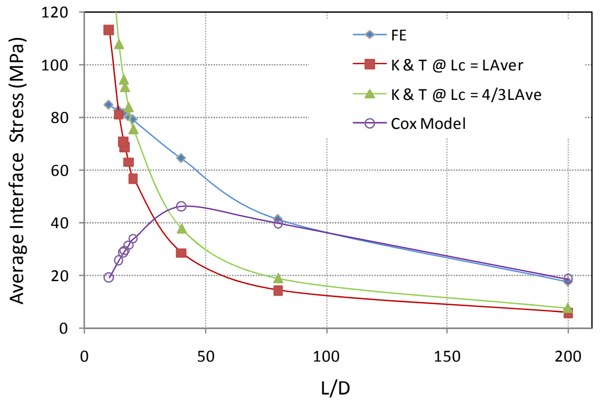

Figure 6: Average interface shear stresses corresponding to filament failure obtained using the FEA, Kelly and Tyson and Cox models as a function of fragment length/diameter ratio.

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