PHOTOELASTIC MEASUREMENT OF MATRIX STRESS FIELD AND INTERFACIAL SHEAR STRESS IN SINGLE GLASS FIBRE MODEL COMPOSITES

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ABSTRACT

Phase-stepping photoelasticity has been used to measure directly the matrix stress field and interfacial shear stress around the free-end of a short glass fibre with and without coating. E-glass fibre was coated by plasma-polymerisation using acrylic acid and octadiene (90:10). The two-dimensional model is composed of a single short E-glass fibre embedded in a cold cured epoxy matrix. The present technology enables full profiles of the stress field in the matrix and at the interface to be obtained from complex situations where initiation and propagation of the interfacial debonds at fibre-ends, fibre-breaks and matrix cracks occurred as well as the interface yielded. The results from photoelastic analysis show that the level of interfacial adhesion has a significant influence on both the interfacial shear stress and the matrix stress in the vicinity of the fibre.

1. PHASE-STEPPING PHOTOELASTICITY

The micromechanics of failure at the interface in fibre-composites is still in need of a full description so that more precise models of stress-transfer through the interface region can be developed. In this way the reliability and durability of a composite can be optimised. Phase-stepping photoelasticity has been used to obtain a series of matrix and interfacial shear stress contour maps for model composites at various levels of applied matrix stress on a micron scale during fragmentation of an embedded fibre [1-2]. This gives a direct measurement of the stress transfer profile in the presence of the range of damage events.

The experimental system is composed of a phase-stepping automated polariscope, four CCD cameras, a microscope and mini-tester. The optical elements of the polariscope are arranged so as to generate four phase-steps in the photoelastic data. Therefore, the four images required for isochromatic and isoclinic parameters over a full field of view can been captured simultaneously during fragmentation testing. Interference fringe patterns from the matrix and the interface are isochromatic and provide contours of the differences in principal stress. The isoclinics are related to principal stress directions. Finally, the shear stress at the interface can be determined experimentally. In phase-stepping photoelasticity, isoclinic angle, θ, and relative retardation, δ, are given by solving the light intensity equations of the four phase-stepped images [3]. The relative retardation, δ, in the specimen is related to the fringe order [4], N, by $\delta = 2\pi N$. For a two dimensional model, the maximum shear stress τ_{max}, can be written as

$$\tau_{\max} = \frac{1}{2}(\sigma_1 - \sigma_2) = \frac{N f_\sigma}{2t} \qquad (1)$$

where t is the thickness of sample and f_σ is the stress-fringe constant. Hence, interfacial shear stress along the fibre direction can be obtained by [5, 6]

$$\tau_i = \tau_{\max} \sin 2\theta \qquad (2)$$

2. EXPERIMENTAL

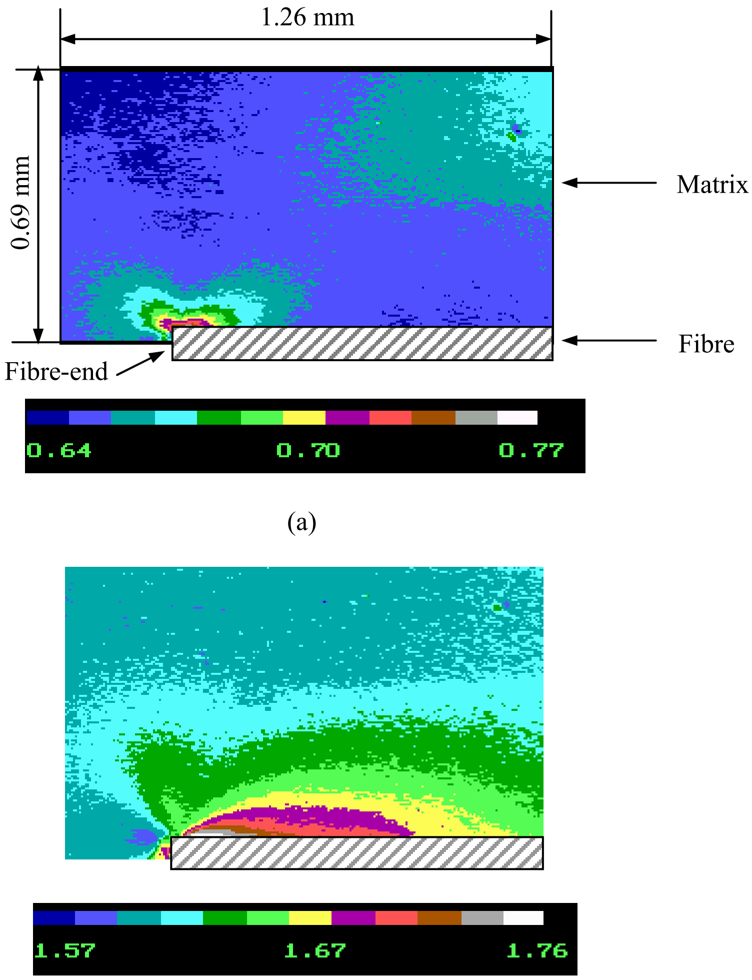
In the present study, model composites with differing interfaces were created from single short E-glass fibre (average diameter 80 μm, supplied by Institute of Polymer Research Dresden, Germany) embedded in a cold-cured epoxy resin, Araldite LY5052 and Aradur HY5052, 100:38. The resin cured at room temperature for at least 7 days. Plasma polymerisation, acrylic acid and Octadiene (90:10) were used to coat the glass fibre conformally. The coating can lead to a good interfacial adhesion between uncoupled unsized E-glass fibre and the thermal-cured epoxy resin [7]. However, a weak interface can be created between E-glass fibre and a cold-cured resin [8]. A good interface was obtained between uncoupled unsized glass fibre and epoxy resin [9]. The Young's modulus and tensile strength of the resin matrix were 3200 and 72 MPa, respectively. All specimens were subjected to uniaxial tension, and photoelastic patterns in the epoxy matrix were obtained at various matrix stresses within a region of 1.317 × 1.317 mm. Contour maps of isochromatic fringe orders and the distribution of clinic angle in the matrix could be quantified through processing the images using the code developed by Patterson *et al* [3], so that interfacial shear stress profile could be calculated.

3. RESULTS AND DISCUSSION

Interfacial debonding always appeared at the fibre-end as the applied stress increased. Extensive debonding occurred at the poor interface for the coated fibre. Interfacial shear stress at the bonded interface cannot reach a higher value and the fibre length in the region of the bonded interface is reduced factually. Thus the stress, causing the fibre to fracture, cannot be transferred efficiently to the fibre. At the same levels of applied matrix stress, much more fragments can generate for the uncoupled unsized fibre than the coated fibre. The present technology enables full profiles of the stress field in the matrix and at the interface to be obtained from complex situations where initiation and propagation of the interfacial debonds at fibre-ends, fibre-breaks and matrix cracks occurred as well as the interface yielded.

Figs 1a and 1b show the contours maps of fringe orders in the matrix around the free-end of the coated E-glass fibre at two levels of applied matrix stress, 8.56 and 17.66 MPa. The continuous isochromatic pattern is shown using twelve colours from blue to white. The twelve colours also have the relevant numerical scale indicating the value of the fringe order. The dimension of the matrix region is approximately 1.26 by 0.69 mm. Maximum shear stress in the matrix and at the interface is proportional to the fringe order according to Eq (1). It can be seen that there is a region of high fringe order around the face-end and along the fibre edge, which indicates that a high stress concentration zone exists. The stress was transferred to the fibre from the matrix to the fibre by the locally enhanced matrix shear stress and the interfacial shear stress. It is worth noting that the shape and the size of the stress concentration zone are different at two applied stresses, which is related to the initiation and the propagation of interface debonding at the face-end and at the fibre edge along the fibre. The stress concentration zone extends continuously towards the fibre centre under load because of the growth of an interfacial debond [2,8].

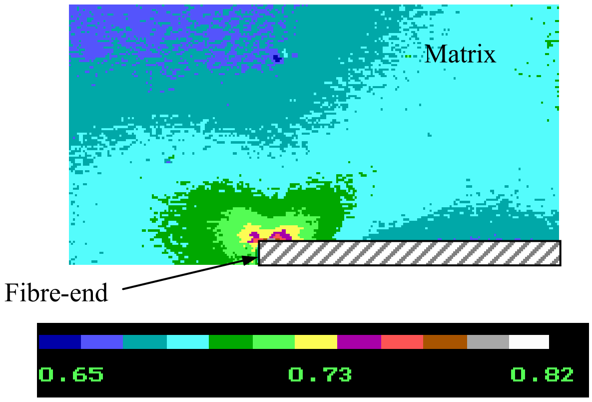
The numerical values in Fig 1 show that the peak value of the interfacial fringe order appears in the bonded region. At 8.56 MPa, however, the fringe order reaches a maximum in the matrix very close to the bonded interface and then reduces slightly at the bonded interface. This suggests that the shear stress at the bonded interface cannot reach a maximum because of the initiation of interfacial yielding for the weak interfacial adhesion. At 17.66 MPa, a similar tendency can be observed, but the fringe order at the bonded interface is obviously lower than the maximum in the matrix nearby. This indicates a further yielding at the bonded interface. The weak interface shows to have a large influence on the rising in the shear stress at it. No fibre break was observed at the applied matrix stress of 17.66 MPa, which suggests that the stress transfer at the weak interface is not efficient.



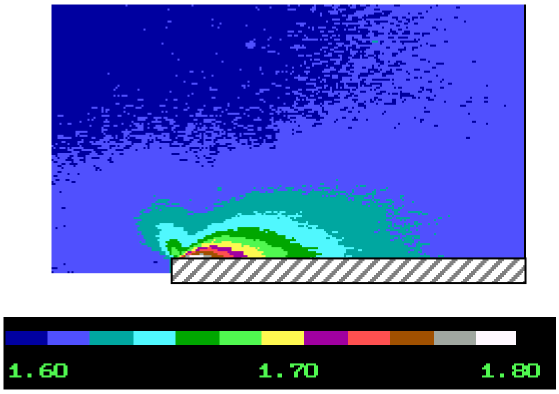
(b)

Fig. 1 Contour map of fringe order in an epoxy matrix around the free-end of a coated glass fibre at (a) 8.56 and (b) 17.66 MPa for fibre length $L_f = 27.55$ mm

Figs 2a and 2b show the contours maps of fringe orders in the matrix around the free-end of an uncoupled unsized E-glass fibre at almost same loadings, 8.63 and 17.45 MPa. It can be seen that the stress concentration zones around the free end of the uncoupled unsized fibre are similar to that in Fig 1 for the coated fibre. However, the size of the stress concentration zone is much smaller at 17.45 MPa, compared with the coated fibre in Fig 1b. This is due to the following two reasons. The uncoupled unsized fibre has a smaller debonded region at the interface at the fibre-end. Therefore, the maximum shear stress at the bonded interface moves towards the fibre centre over a short distance and a small stress concentration zone formed along the fibre [2]. At the end of the coated fibre, there are several small matrix cracks perpendicular to the fibre direction as shown in Fig 3. The contour maps of fringe order in Fig 1 were obtained from the matrix around the fibre-end in Fig 3. These cracks were initiated, where the matrix was adhered to the fibre adjacent to a debonded region. This caused an additional stress concentration.
From the numerical value in Fig 2, the fringe order is found to reach a maximum at the bonded interface at 8.63 MPa, which indicates that the interfacial shear stress can rise with external loading because the bonded interface for the uncoupled unsized fibre has a high yielding strength compared with the coated fibre. At 17.45 MPa, the maximum fringe order at the bonded interface is almost equal to that in the nearby matrix, showing that the bonded resin at the interface was yielding. Three fibre-breaks were observed at the applied matrix stress of 17.45 MPa, which suggests a relative efficiently stress transfer at the good interface.



(a)



(b)

Fig. 2 Contour map of fringe order in an epoxy matrix around the free-end of an uncoupled unsized glass fibre at (a) 8.63 MPa for fibre length, L_f = 18.56 mm and (b) 17.45 MPa for fibre length, L_f = 8.37 mm

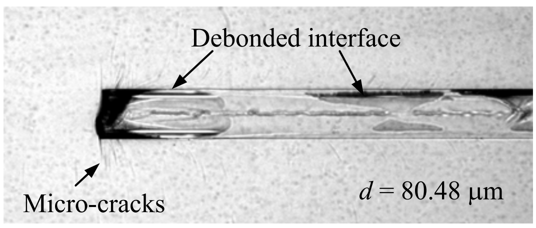


Fig. 3 A micro-photo of the coated fibre embedded in the epoxy matrix after test

Figs 4 and 5 give the profiles of the interfacial shear stress calculated using Eq. (1) and the values of the fringe order in Figs 1 and 2 and the relevant isoclinic angle measured by phase-stepping photoelasticity. At a low applied matrix stress (around 8.56 MPa), the profile of the interfacial shear stress for the coated fibre is similar to non-coated fibre but its maximum is lower. For both fibres, the maximum did not appear at the fibre-ends because the interface was partially debonded [2]. When the applied matrix stress was further increased to about 17.45 MPa, different profiles of interfacial shear stress for both fibres can be observed in Figs 4 and 5. For uncoupled unsized fibre, the peak in the interfacial shear stress distribution moved towards the centre the fragmented fibre over a distance of 0.067 mm from the fibre-end. The distance is slightly longer than that (about 0.041 mm) at 8.63 MPa, indicating that the interfacial debond was growing slowly and gradually. In the region of the bonded interface, the maximum in the interfacial shear stress distribution reduces approximate exponentially.

For the coated glass fibre, the peak in the interfacial shear stress distribution moved towards the centre the short fibre over a distance of approximate 0.20 mm from the fibre-end. The distance is much longer than that (approximate 0.041 mm) at 8.56 MPa, indicating that the interfacial debond was growing more rapidly than the uncoupled unsized glass fibre. The maximum interfacial shear stress is 32.7 MPa, which is less than 37.8 MPa for the uncoupled unsized fibre and reduces slowly because of the additional influence of the small cracks.

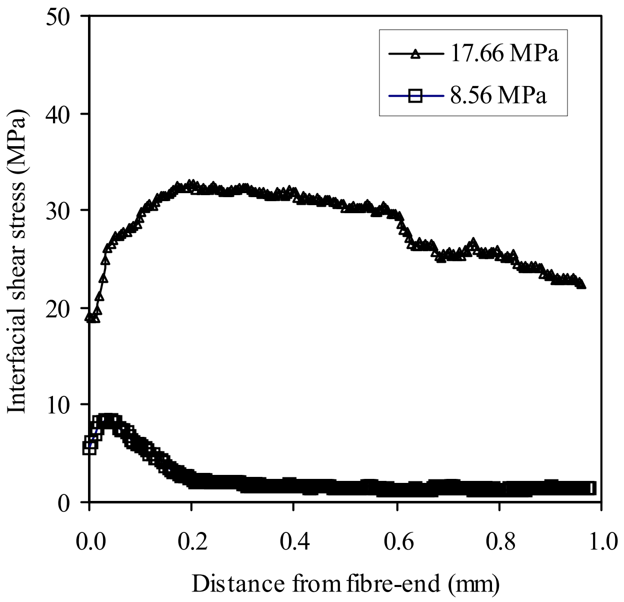


Fig. 4 Profile of interfacial shear stress determined by photoelastic analysis for coated glass fibre at (a) 8.56 and (b) 17.66 MPa for fibre length $L_f = 27.55$ mm

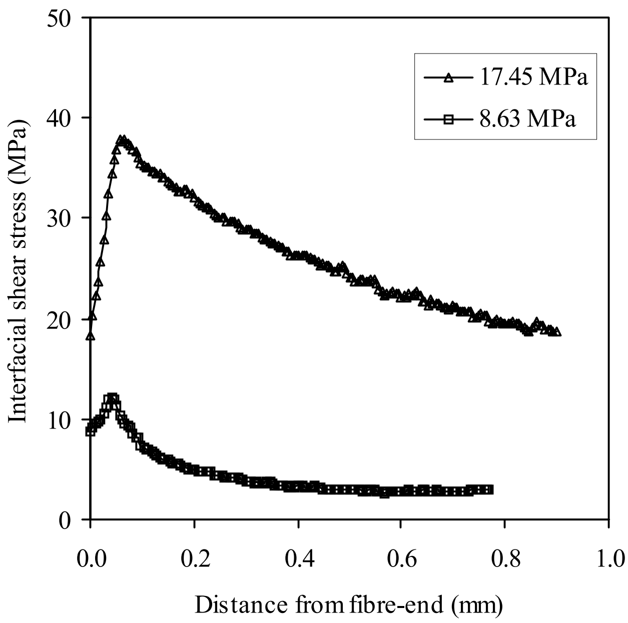


Fig. 5 Profile of interfacial shear stress determined by photoelastic analysis for uncoupled unsized fibre at (a) 8.63 MPa for fibre length, $L_f = 18.56$ mm and (b) 17.45 MPa for fibre length, $L_f = 8.37$ mm

Similarly, the contour maps of fringe order in the matrix around a matrix crack initiated by a fibre-break and the relevant interfacial shear stress have been obtained [8]. The present technique can be used for investigating the situation where matrix cracking and interface debonding coexist at a weak interface.

4. CONCLUSIONS

Photoelastic analysis has been used to measure the micro-stress field in the matrix and at the interface around the end of a short fibre with or without a Plasma-polymerised coating at different applied stresses. A full profile of the matrix stress field has been described in detail using contour maps, and the distributions of the relevant interfacial shear stress have been calculated, which include the effects of interfacial debonding and matrix crack perpendicular to the fibre direction. The results from photoelastic analysis show that the level of interfacial adhesion has a significant influence on both the interfacial shear stress and the matrix stress in the vicinity of the fibre.

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