CompTest 2004, Bristol

Use of phase-stepping photoeasticity to measure interfacial shear stress in single fibre model composites

F.M. Zhao, S.A. Hayes and F.R. Jones

Ceramics and Composites Laboratory (CCL), University of Sheffield

E.A. Patterson

Department of Mechanical Engineering, University of Sheffield

R.J. Young

Manchester Materials Research Centre, UMIST

Outline

- Background
- Phase-stepping polariscope and experimental system
- Materials and experimental procedure
- Results from photoelastic analysis
    1. Single Al_2O_3 fibre model composite
    2. Single glass fibre model composite
- Conclusions

Ceramics and Composites Laboratory
The University of Sheffield

Background

- Interfacial response within a fibre composite controls the reliability of a structure
- A good correlation between composite strength and interfacial shear strength has proved difficult
- Current analysis relies on fibre stress calculations and/or indirect measurement (LRS)
- Role of the "matrix" not easily included
- Need for full stress analysis at the interface for the micro-mechanics of interfacial failure and model validation

Aims of research

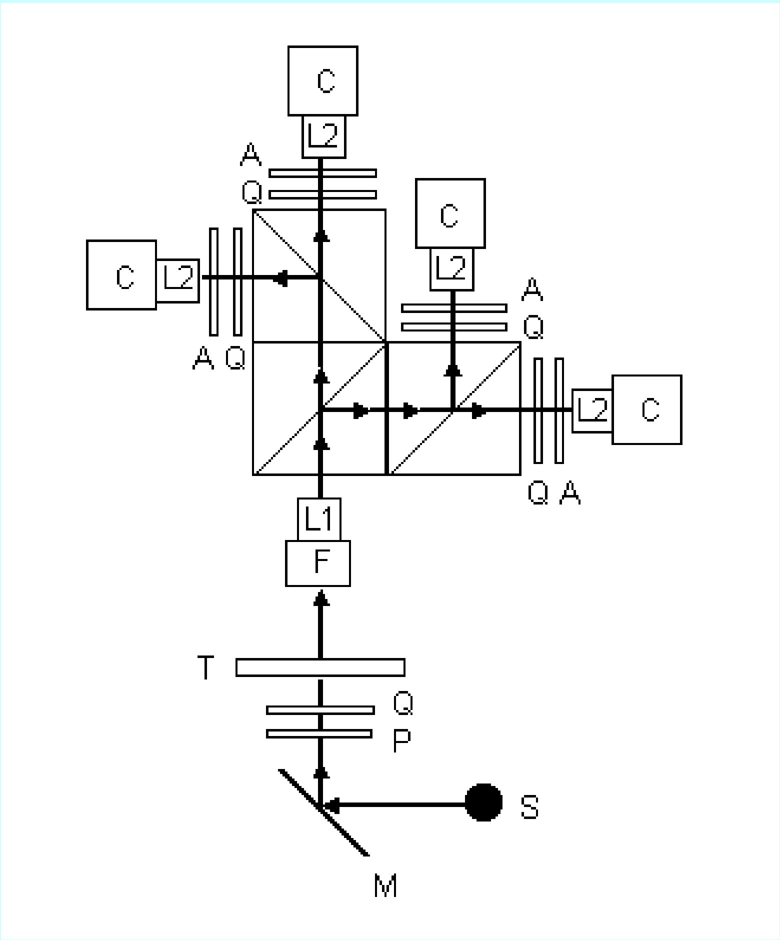
- Develop a polariscope based on phase-stepping photoelastic technique for micro-measurement
  (Prof. Patterson's group, Dept of Mechanical Engineering, University of Sheffield)

- Characterise the mechanical response of composite interface under external load for Sapphire fibre
  1. Matrix stress field and interfacial shear stress *(Prof. Jones' group, CCL, University of Sheffield)*
  2. Tensile stress in the fibre using florescence spectroscopy *(Prof. Young's group, UMIST, Manchester Materials Centre)*

- Examine the effects of coating, interfacial debonding and matrix crack on stress transfer for E-glass and carbon fibres
  (Prof. Jones' group, CCL, University of Sheffield)

CCL
Ceramics and Composites Laboratory
The University of Sheffield

An arrangement of optical device and light path



- **Four CCD cameras are used for collecting photoelastic images simultaneously**
- **Cubic beam-splitters provide four elliptically polarized light beam**
- **The pairs of quarter-wave plates and analysers are orientated so as to generate four phase-steps in photoelastic data**

Image number	Orientation of quarter-wave plate	Orientation of analyser
1	$\pi/4$	$\pi/4$
2	0	0
3	$\pi/2$	$\pi/2$
4	0	$\pi/4$

CCL

Theoretical model for the instrument

<u>E.A. Patterson & Z.F. Wang *J Strain Analysis 33 1998 1-15*</u>

$$E_1 = \frac{a^2}{2}(1 - \cos 2\theta \sin \delta) \qquad E_2 = \frac{a^2}{2}(1 + \sin 2\theta \sin \delta)$$

$$E_3 = \frac{a^2}{2}(1 - \sin 2\theta \sin \delta) \qquad E_4 = \frac{a^2}{2}(1 - \cos \delta)$$

Isoclinic angle

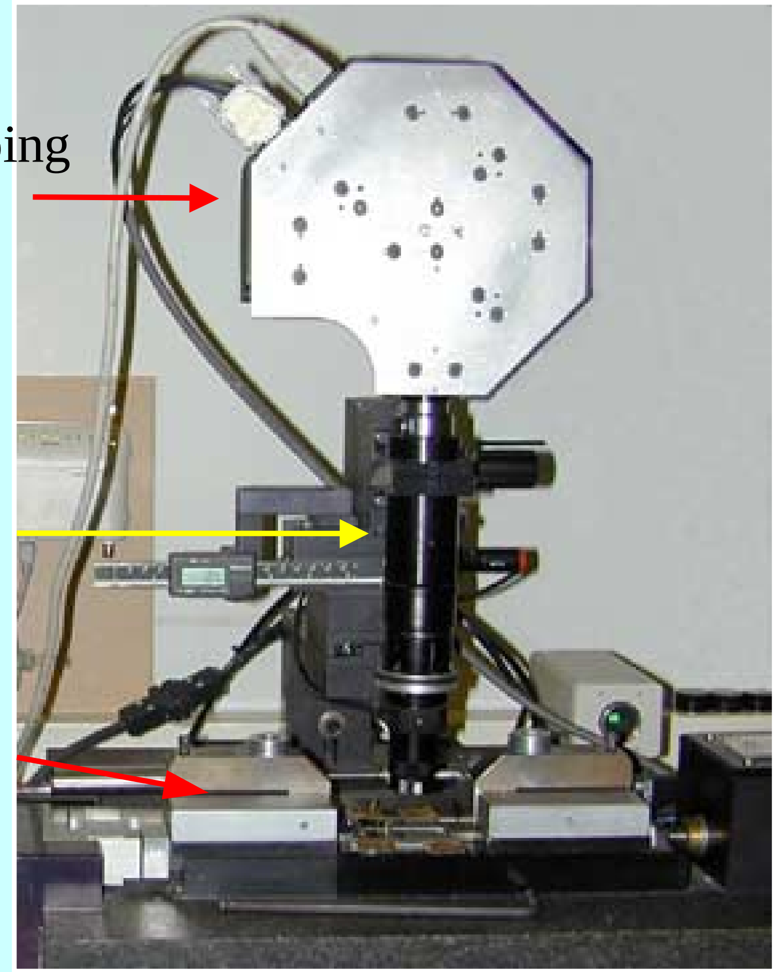
$$\theta = \frac{1}{2}\tan^{-1}\left(\frac{E_2 - E_3}{E_2 + E_3 - 2E_1}\right)$$

Relative retardation

$$\delta = \frac{1}{2}\tan^{-1}\left(\frac{E_2 - E_3}{Sin2\theta(E_2 + E_3 - 2E_4)}\right)$$

Ceramics and Composites Laboratory
The University of Sheffield

Experimental system



- A filter (wavelength of 542±10) produces an essentially mono-chromatic green source
- A multiplex combines four signals into a single composite image
- The composite image is re-divided into four phase-steeping images and processed by a software operation

$$N = \frac{\delta}{2\pi}$$

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

$$\tau_i = \tau_{\max} \sin 2\alpha$$

CCL
Ceramics and Composites Laboratory
The University of Sheffield

Single fibre model composites (SFC)

- *Al_2O_3 and E-glass fibres*

	Al_2O_3	E-glass
Young's modulus	**414 GPa**	**72 GPa**
Diameter	**125 μm**	**80 μm**

- *Araldite LY5052/HY5052 cold cured epoxy resin*

Curing at room temperature for at least 7 days

Young's modulus: 3.20 GPa

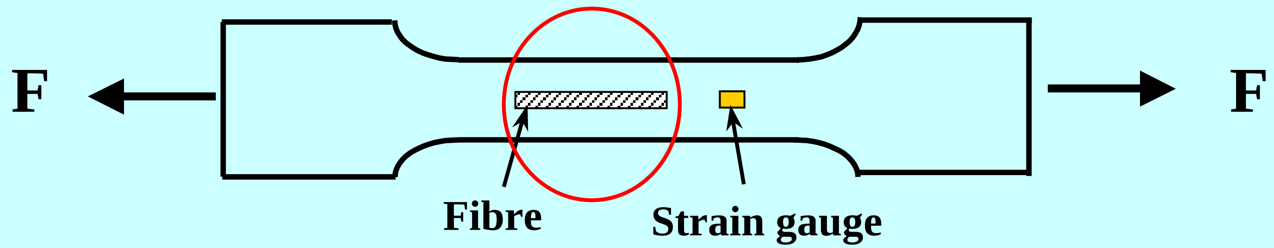
Shear modulus: 1.18 GPa

Tensile strength: 70 MPa,

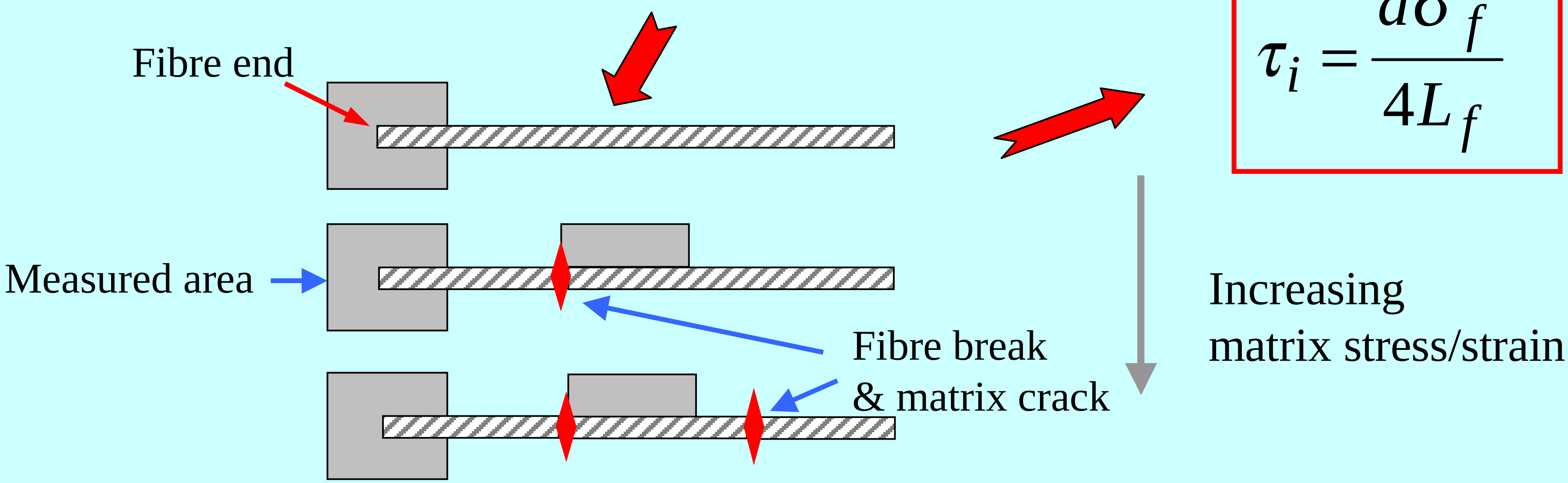
Stress constant f_σ: 26.24 MPa/mm

CCL
Ceramics and Composites Laboratory
The University of Sheffield

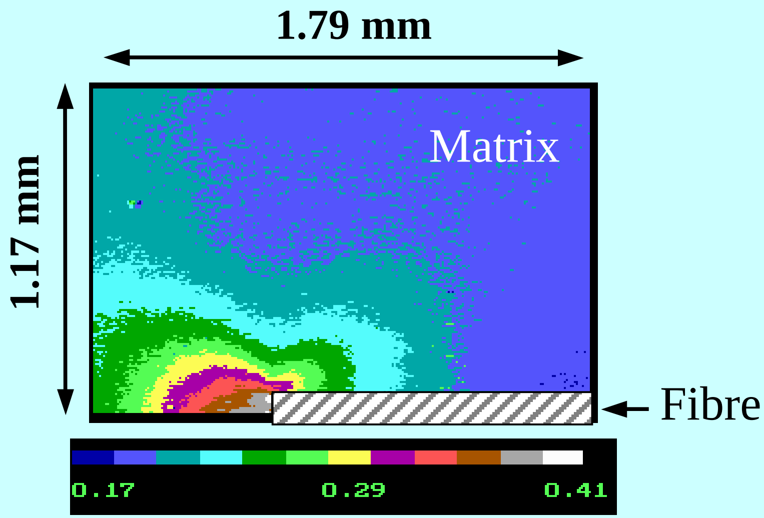
Fragmentation test of SFC and photoelastic measurement



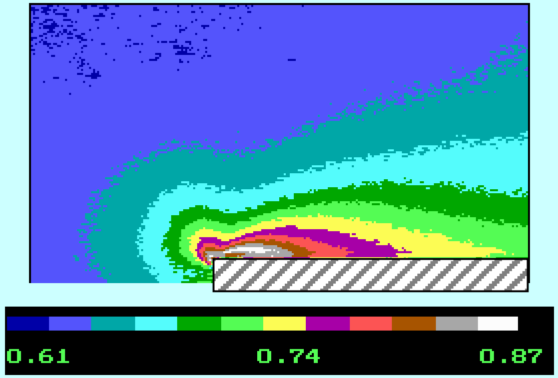
$$\tau_i = \frac{d\sigma_f}{4L_f}$$



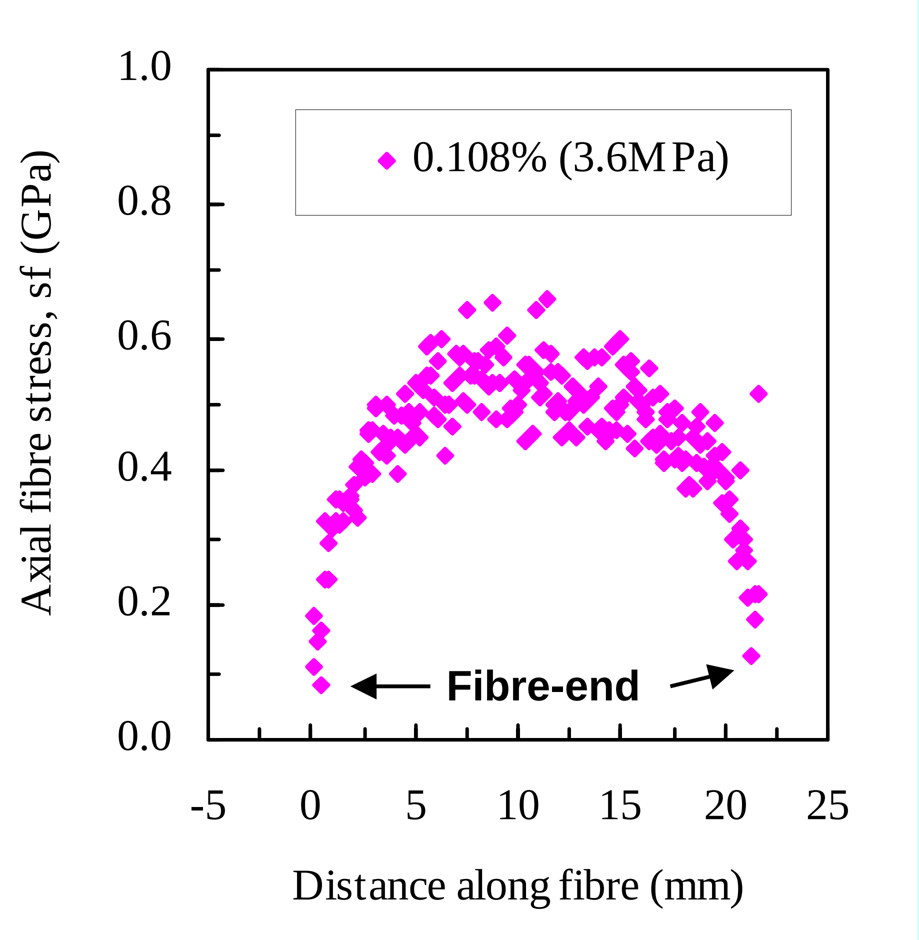
Contour maps of fringe order in the matrix and axial fibre stress profile (Al_2O_3 fibre)



σ_{app} = 3.60MPa, (ε_{app} = 0.108%)



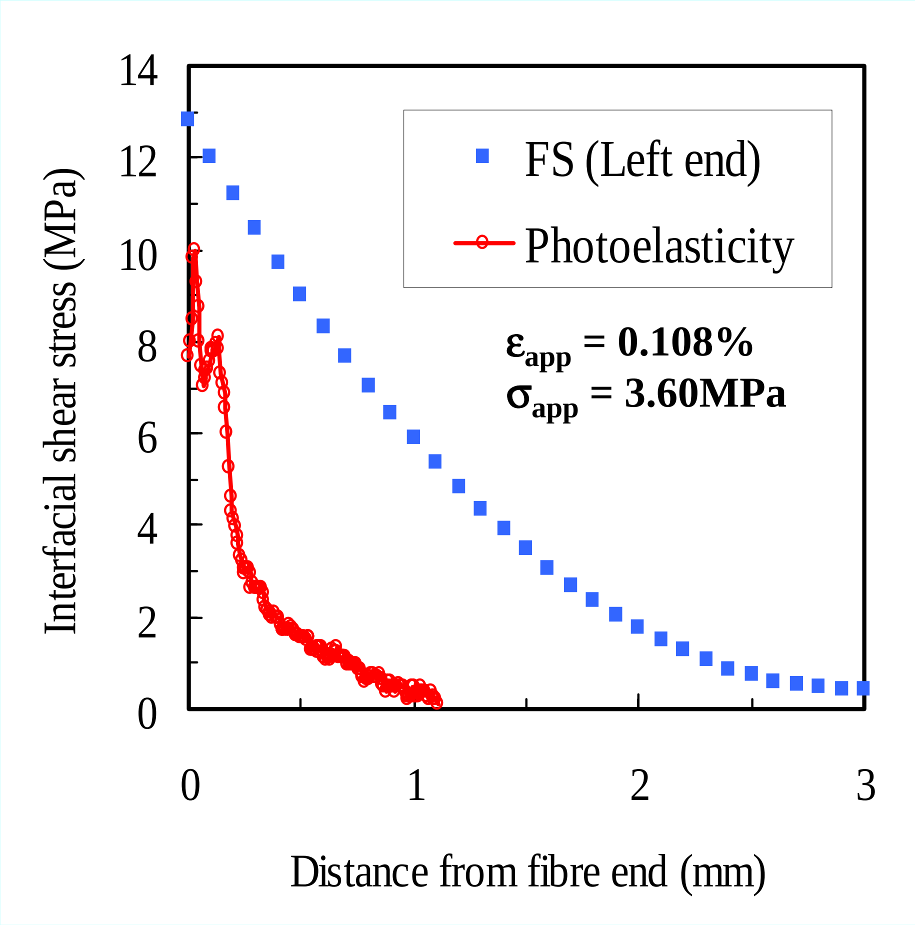
σ_{app} = 6.54MPa, (ε_{app} = 0.204%)



Florescence spectroscopy

CCL
Ceramics and Composites Laboratory
The University of Sheffield

Comparison of IFSS (at free-end) photoelasticity and fluorescence spectroscopy



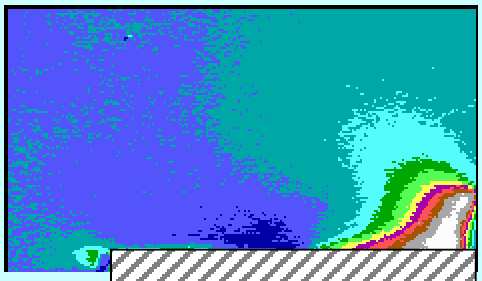
Inferring τ_i from axial fibre stress

$$\tau_i = \frac{d\sigma_f}{4dx}$$

σ_f: axial stress in the fibre
d: fibre diameter

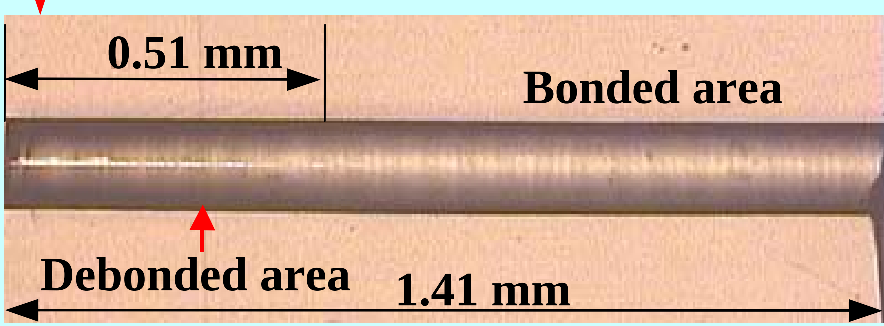
- Axial fibre stress, σ_f, including the contribution from the face-end
- The stress transferred across the face-end of the short fibre leads to the difference
- Over-estimating τ_i

Effect of debonding and crack

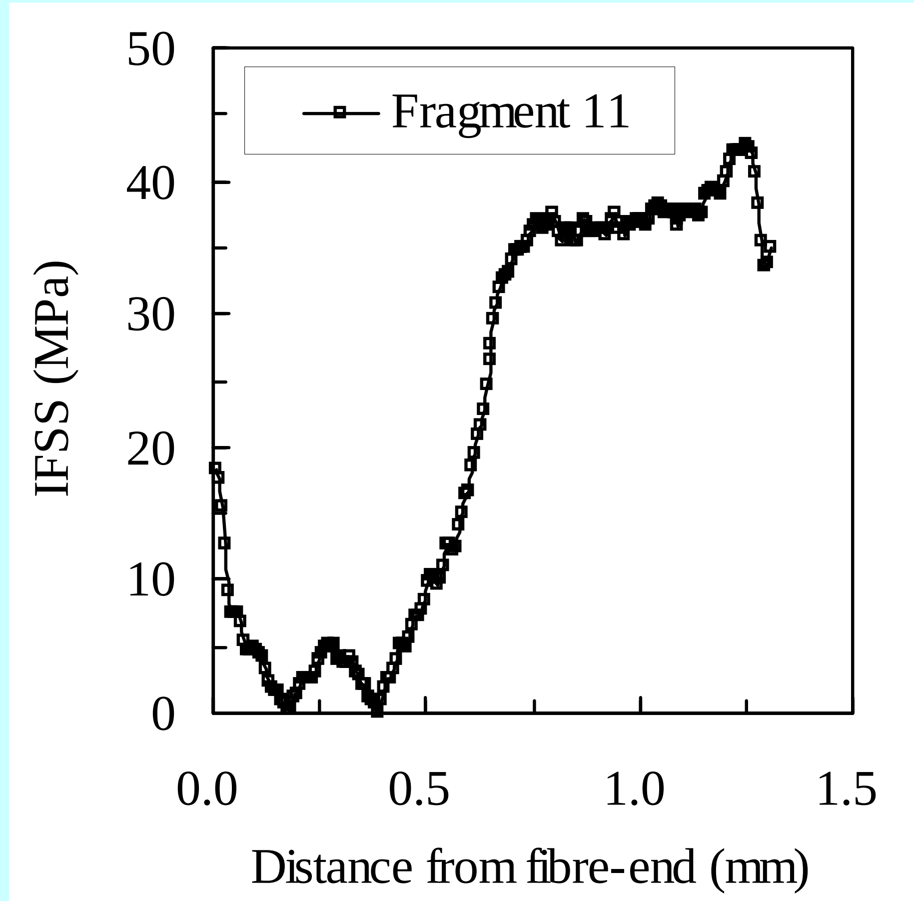


Crack tip

Fibre-end

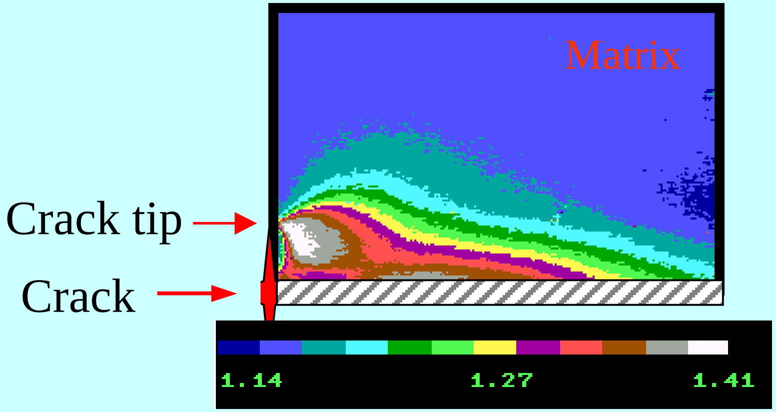


Crack

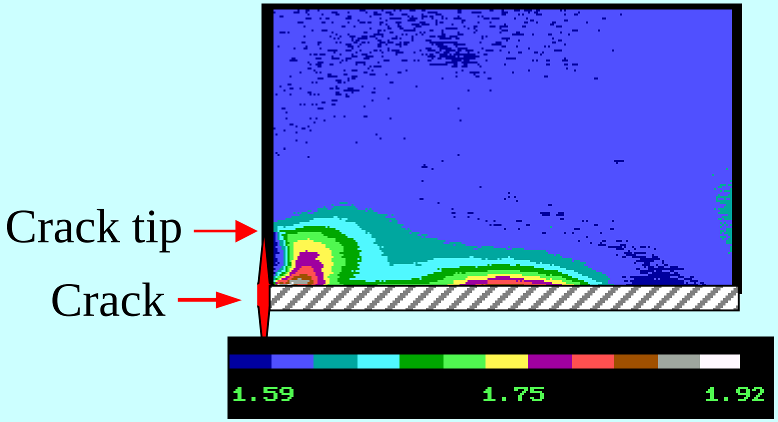


σ_{app} **= 16.08 MPa,** ε_{app} **= 0.48%**

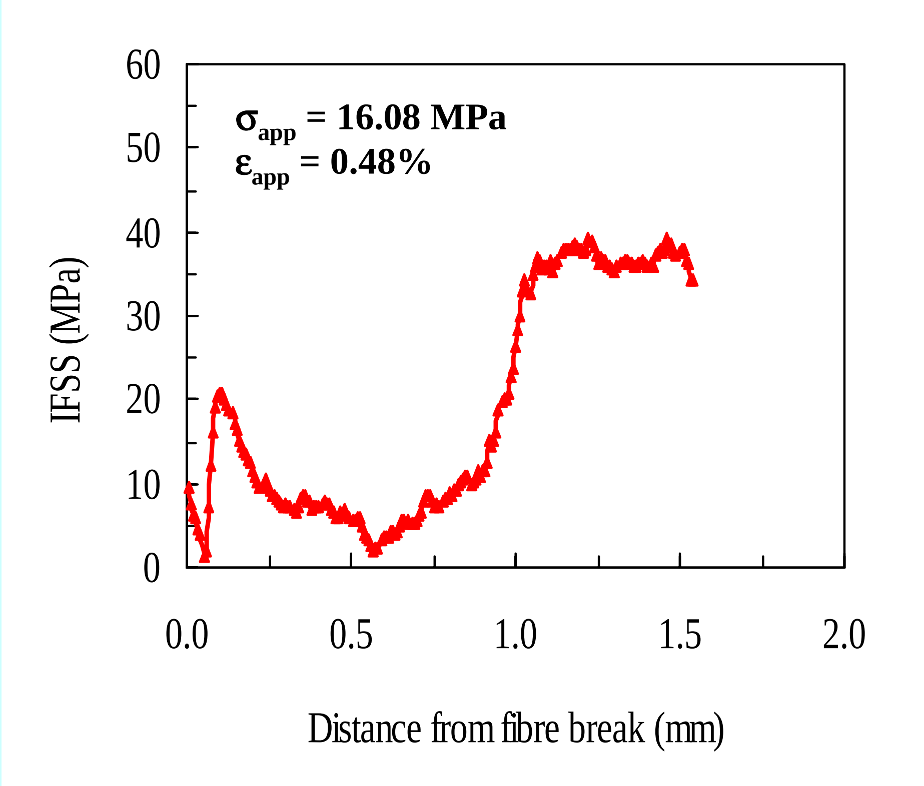
Contour maps of fringe order and IFSS profile at a fibre-break

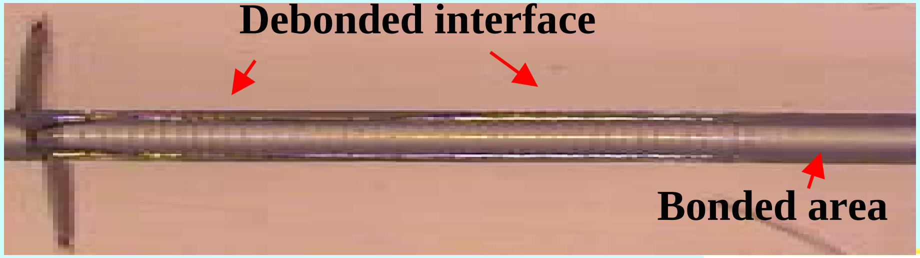


σ_{app} = 13.10 MPa, ε_{app} = 0.388%



σ_{app} = 16.08 MPa, ε_{app} = 0.48%





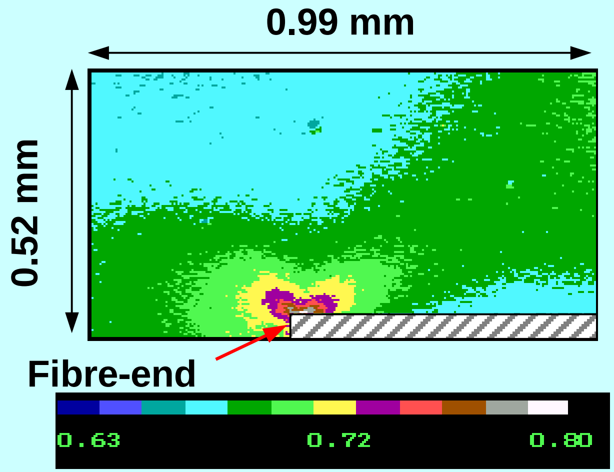
Evaluation of composite interface for glass fibre

1. Uncoated E-glass fibre

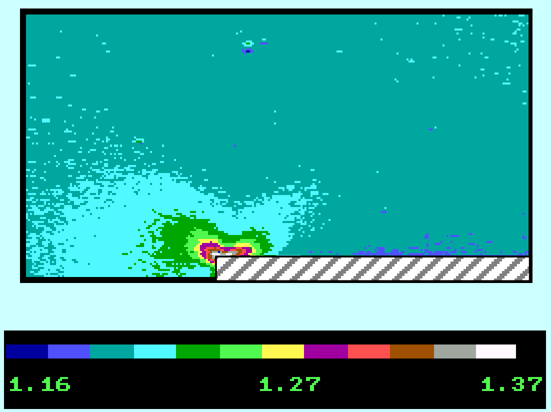
2. E-glass fibre coated by plasma-polymerisation

   Plasma copolymerisation has been used to coat E-glass fibre with acrylic acid /1-7 Octadiene (90:10) for the cold-cured epoxy resin

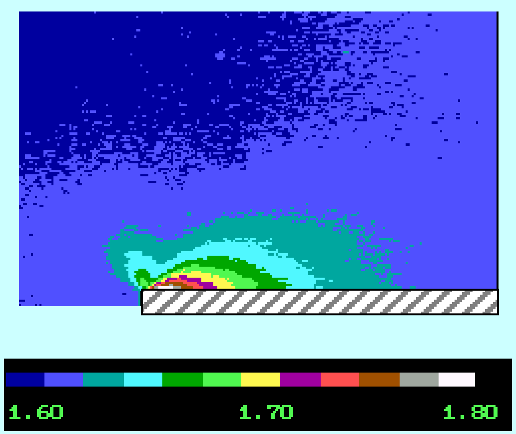
Contour maps of isochromatic fringe order at fibre-end for uncoated E-glass fibre



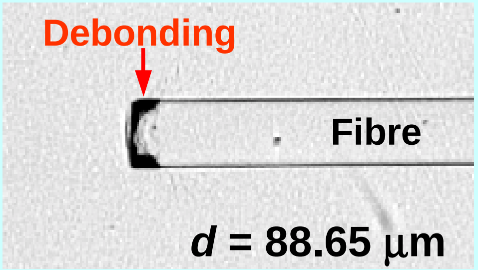
(a) σ_{app} = 8.63 MPa L_f = 18.56 mm



(b) σ_{app} = 14.37 MPa L_f = 8.37 mm

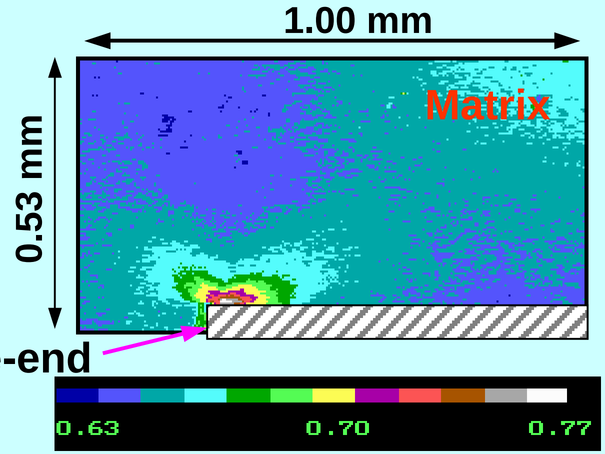


(c) σ_{app} = 17.45 MPa L_f = 8.37 mm

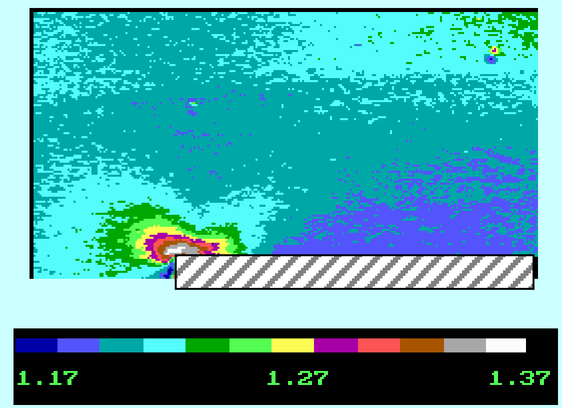


Debonding length: 42.63 µm
Fragment length: 2.09 ± 0.98 mm

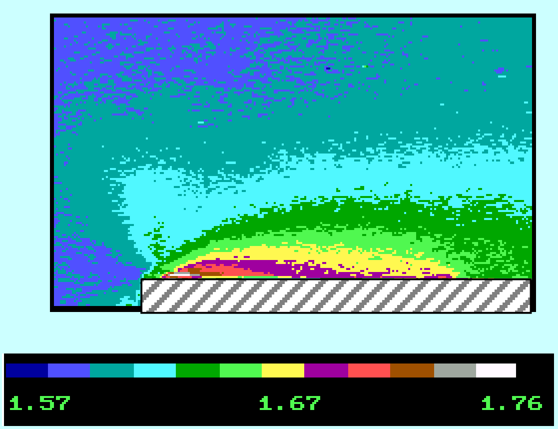
Contour maps of isochromatic fringe order at fibre-end for plasma-coated fibre



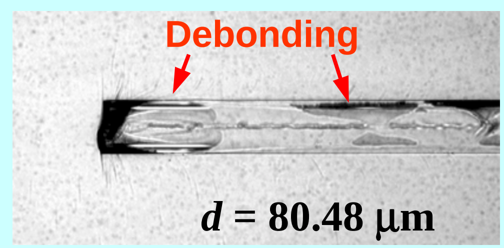
(a) σ_{app} = 8.55 MPa, L_f = 27.55 mm



(b) σ_{app} = 15.92 MPa, L_f = 27.55 mm



(c) σ_{app} = 17.66 MPa, L_f = 27.55 mm



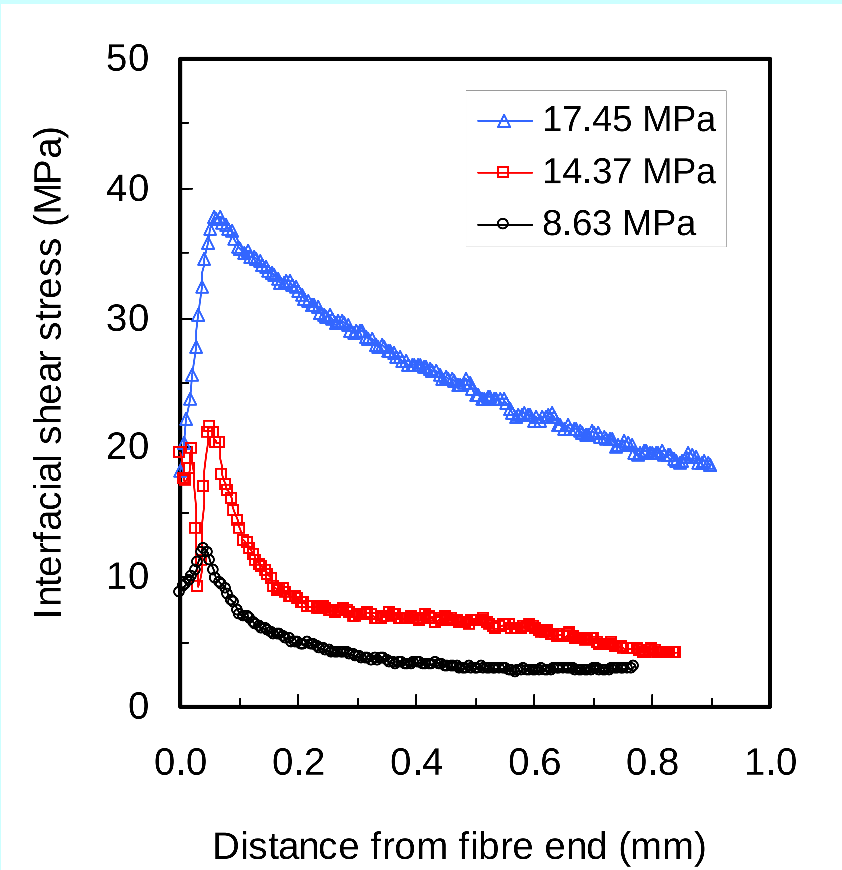
Few fibre-break

Extensive debonding

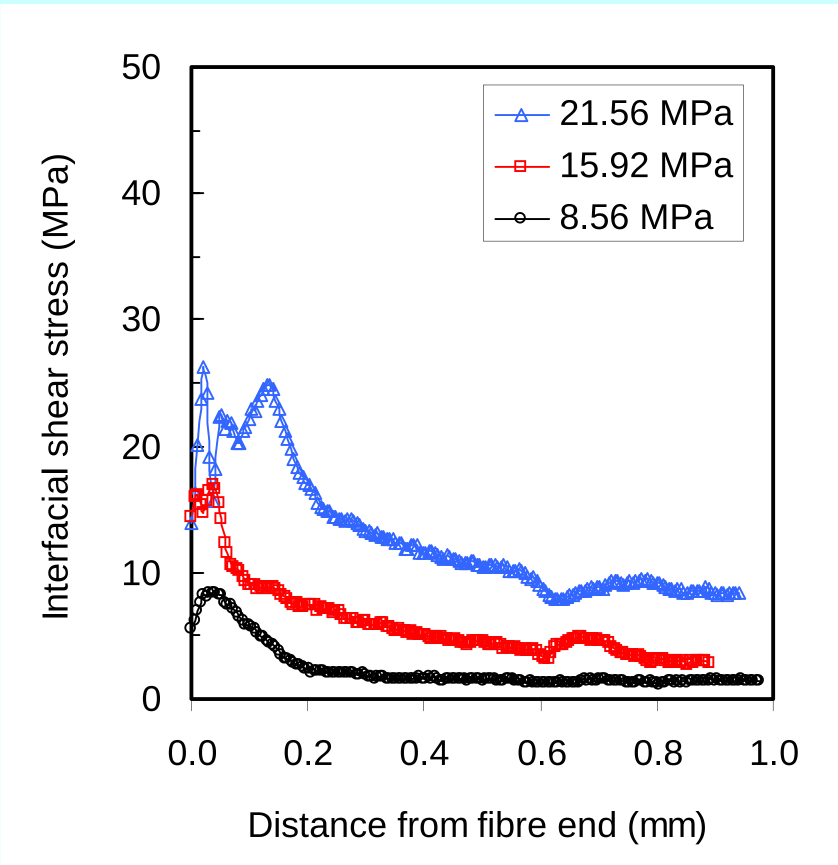
CCL

Ceramics and Composites Laboratory
The University of Sheffield

Interfacial shear stress profile



Uncoated fibre



Plasma-coated fibre

CCL
Ceramics and Composites Laboratory
The University of Sheffield

Conclusions

- Automated phase-stepping polariscope has been used to measure the micro stress field in the matrix near fibre-end or fibre-break and the interfacial shear stress for Al_2O_3 and E-glass fibre epoxy model composites at various levels of applied stress.
- The high fringe order in the matrix near the fibre-end and fibre-break demonstrates that a high stress concentration zone exists. Stress is transferred to the fibre from the matrix by the locally enhanced matrix shear stress.
- The face-end of a short fibre and the transverse matrix crack at a fibre break have been found to have a large influence on stress transfer.
- Phase-stepping photoelastic technique has been found to be effective in identifying the occurrence of the interfacial debonding and quantifying the interfacial shear stress at the debonded and bonded interface.

CCL
Ceramics and Composites Laboratory
The University of Sheffield

Acknowledgements

- EPSRC for funding the research
- Photran Inc. (USA) for the supply of sapphire fibre
- Institute of Polymer Research Dresden (Germany) for supplying E-glass fibre
- The Advanced Composites Group (UK) for supplying epoxy resins

CCL

Ceramics and Composites Laboratory
The University of Sheffield