X-ray Diffraction for Strain Measurement in Composite Fibres

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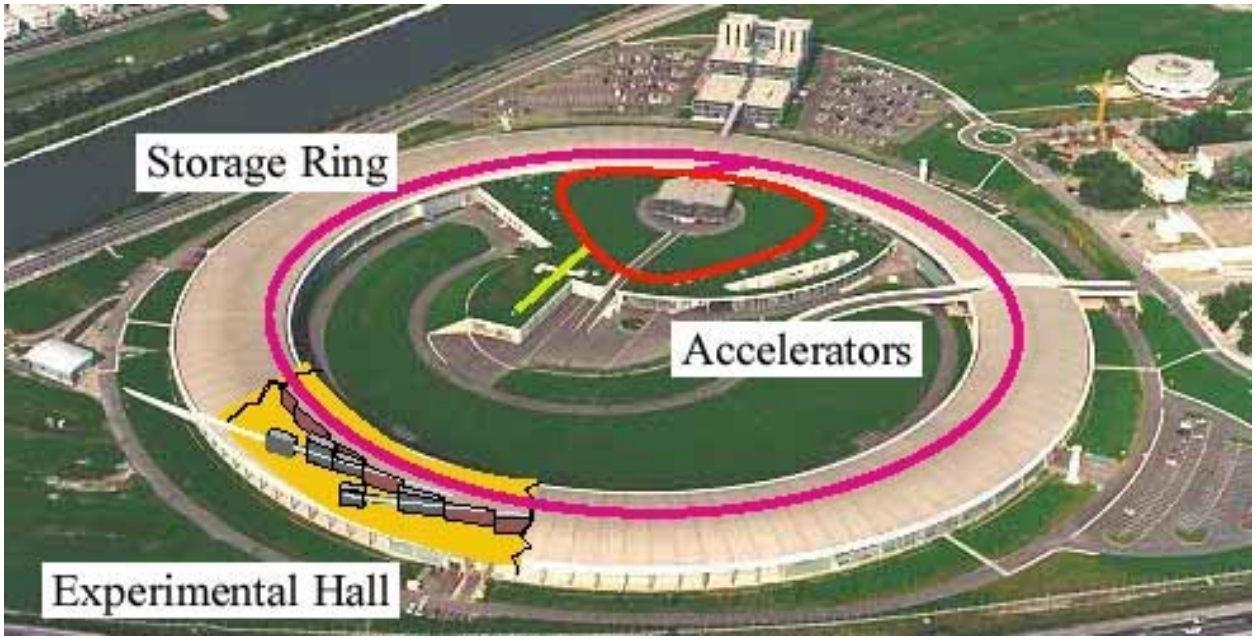
Outline

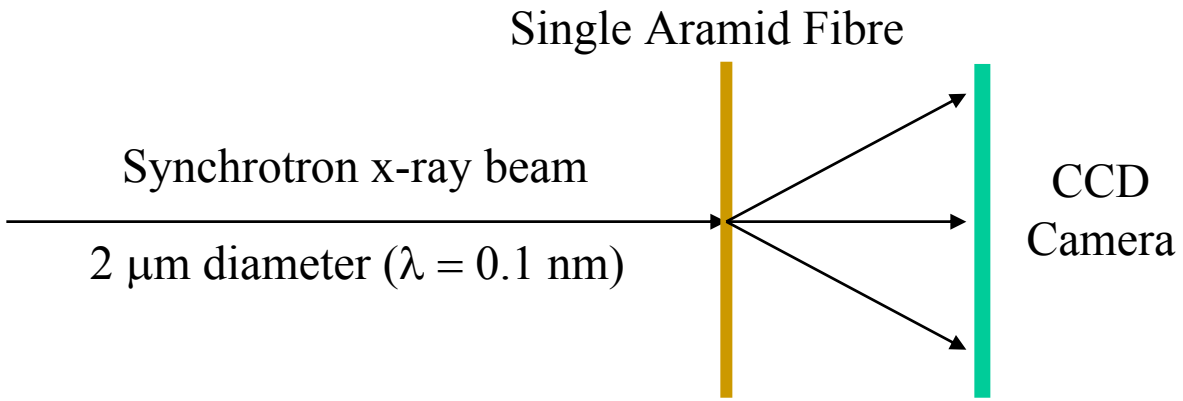
- Synchrotron microfocus X-ray diffraction
- Deformation of single aramid fibres
- Cross-ply laminate
  - microstructure
  - local fibre deformation
- Characterisation of the microstructure of woven composites
  - out-of-plane tilt
  - in-plane orientation
  - local fibre deformation
- Conclusions

ESRF Synchrotron - Beamline ID13

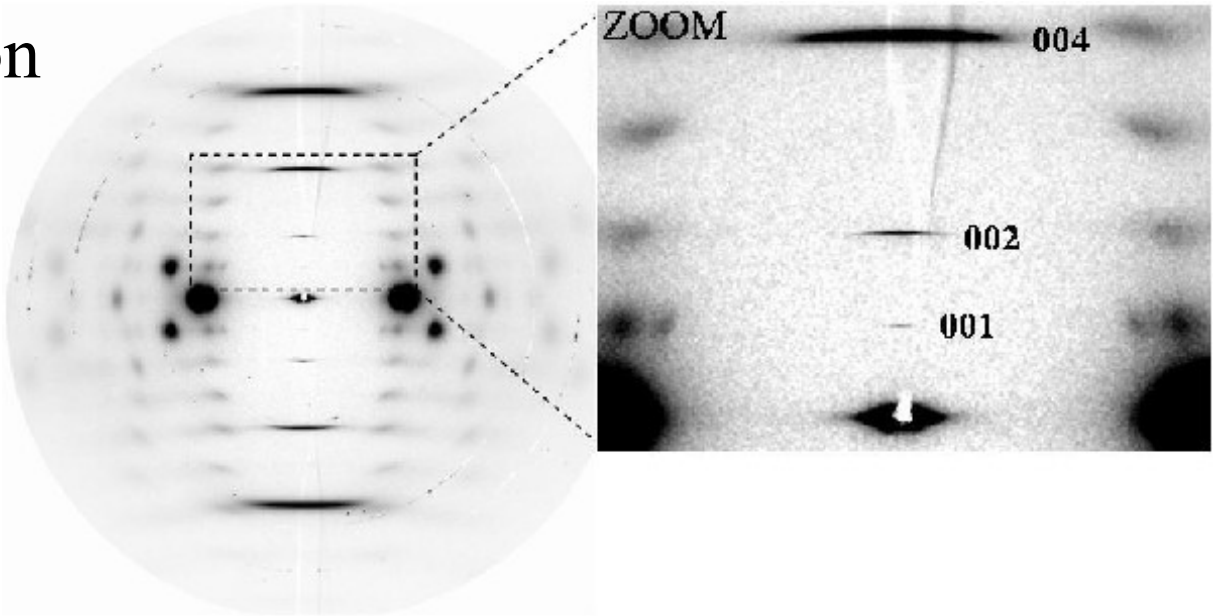


- High-intensity monochromatic beam - $\lambda = 0.1$ nm
- 2 μm beam diameter
- Single fibre diffraction – 12 μm diameter fibre
- Simultaneous deformation/diffraction

Aramid Single-Fibre Microfocus X-ray Diffraction



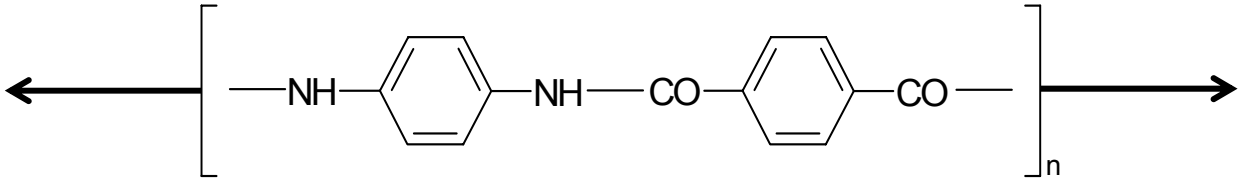
Diffraction Pattern



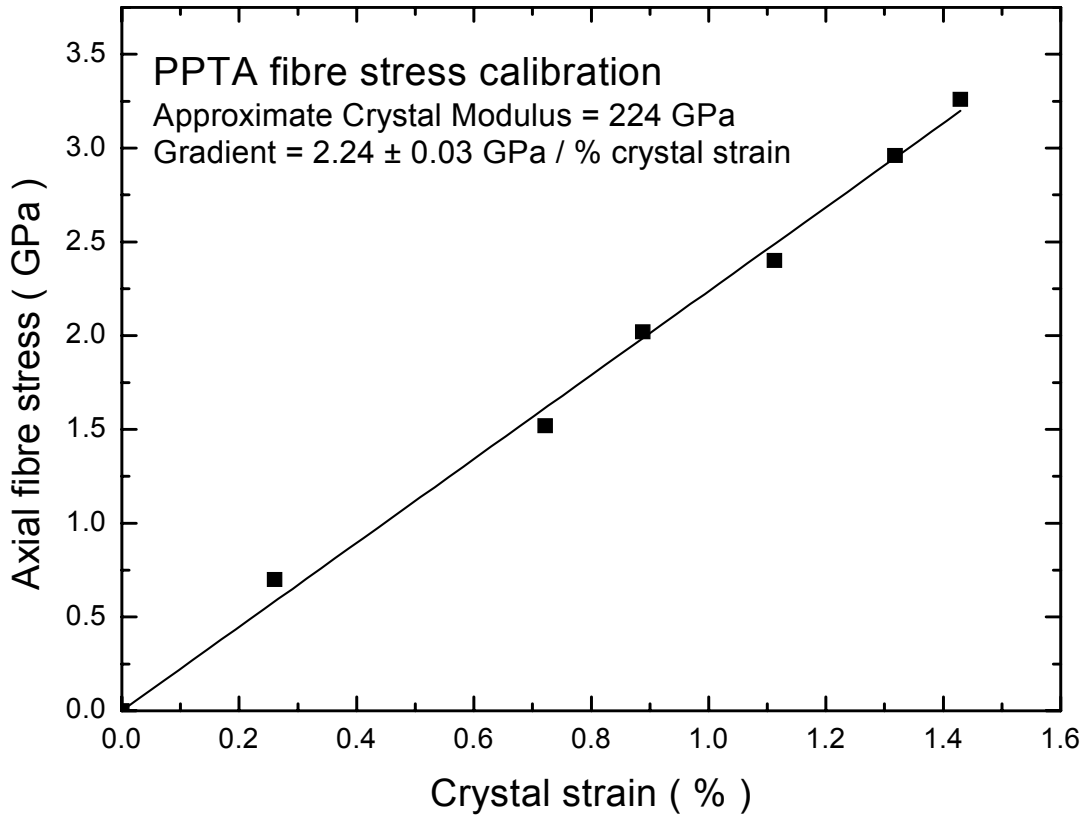
Fibre axis

00*l* streaks moves closer to central spot under stress → crystal strain

Crystal Deformation



Stress
Stress on Fibre



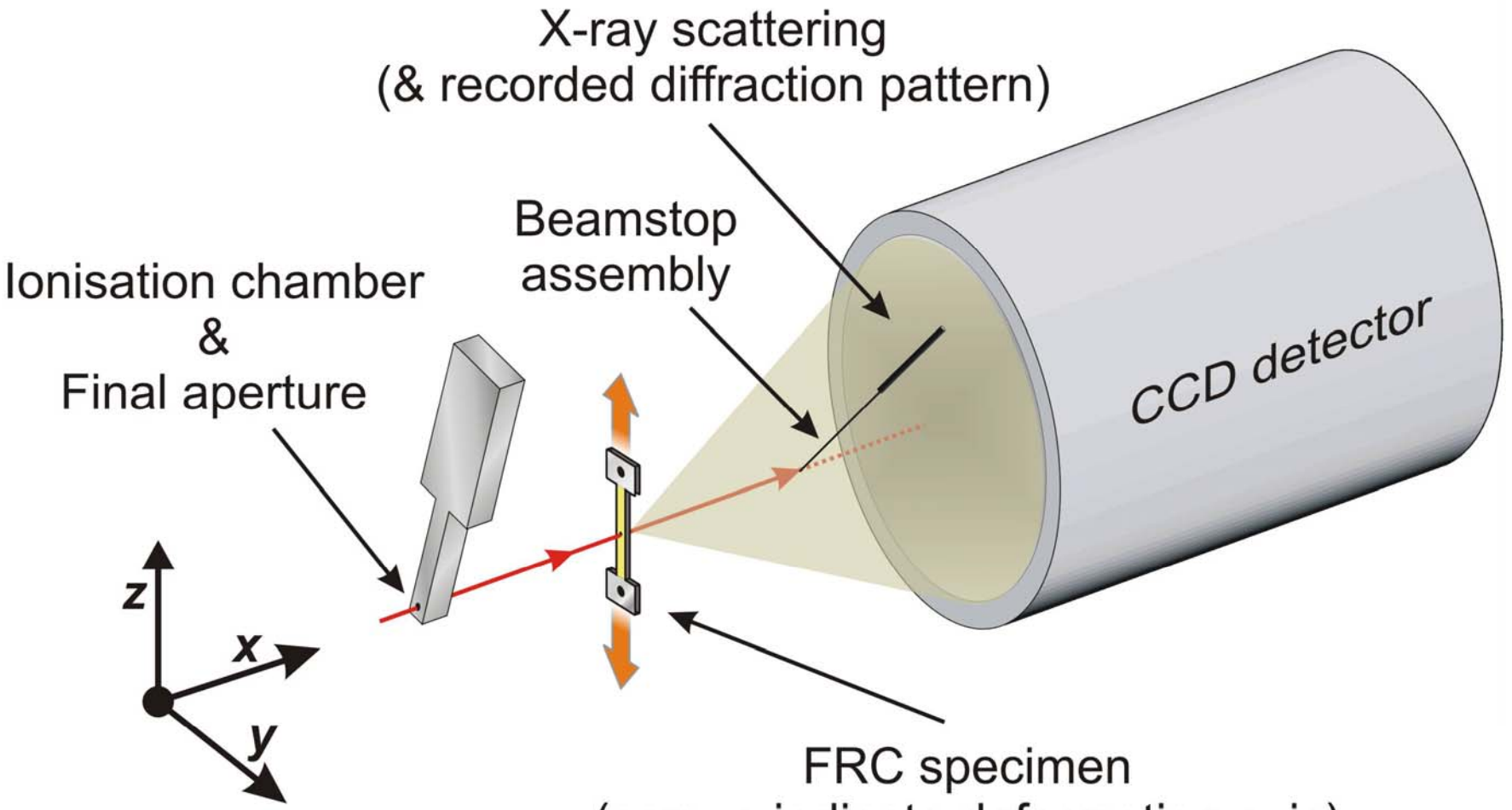
Calibration for Micromechanics analysis

Strain
Crystal Strain

$$\varepsilon_c = \frac{c_0 - c_\sigma}{c_0}$$

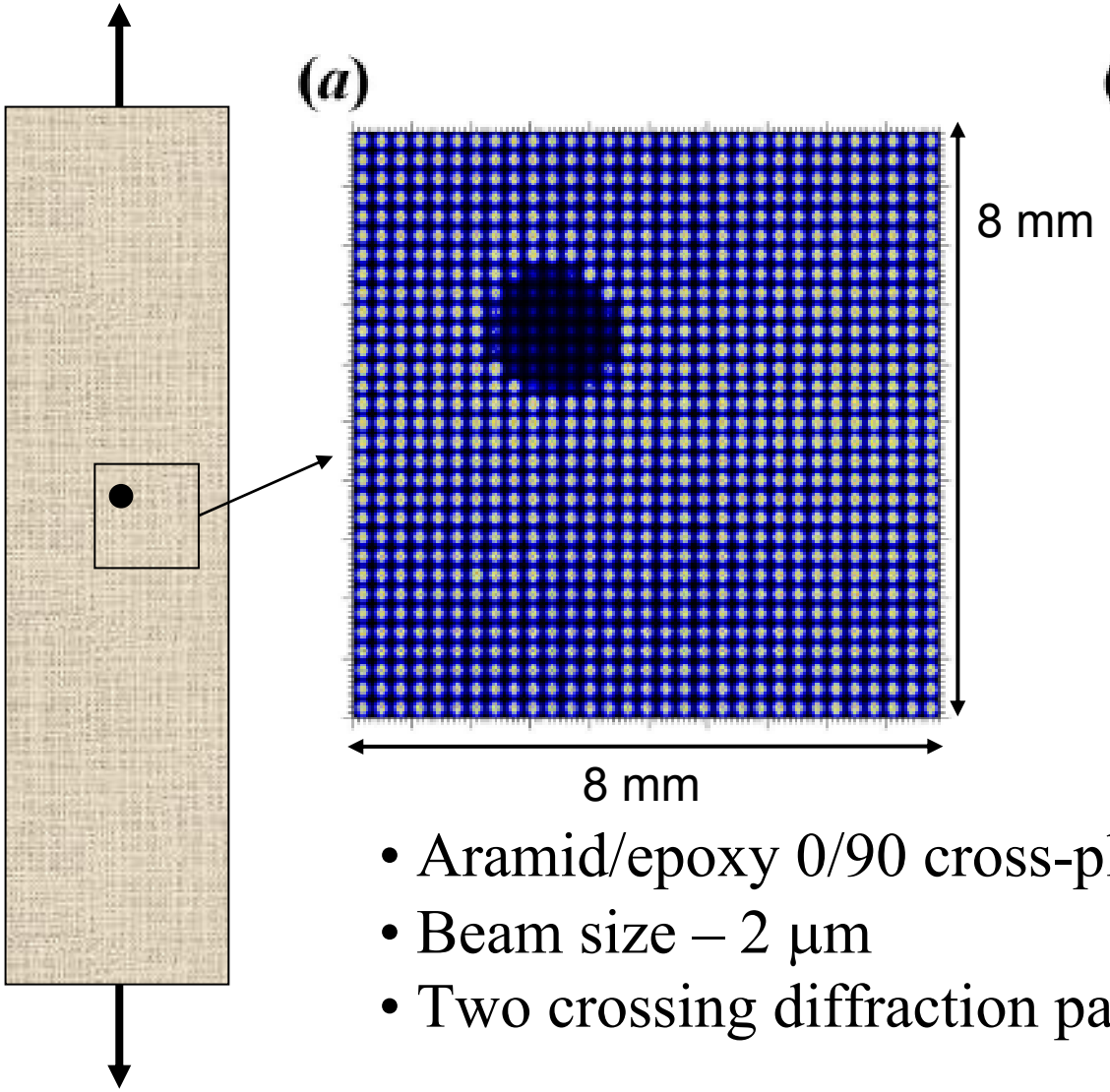
Young RJ, Eichhorn SJ, Shyng Y-T, Riekel C, Davies RJ (2004) *Macromolecules* **37**:9503

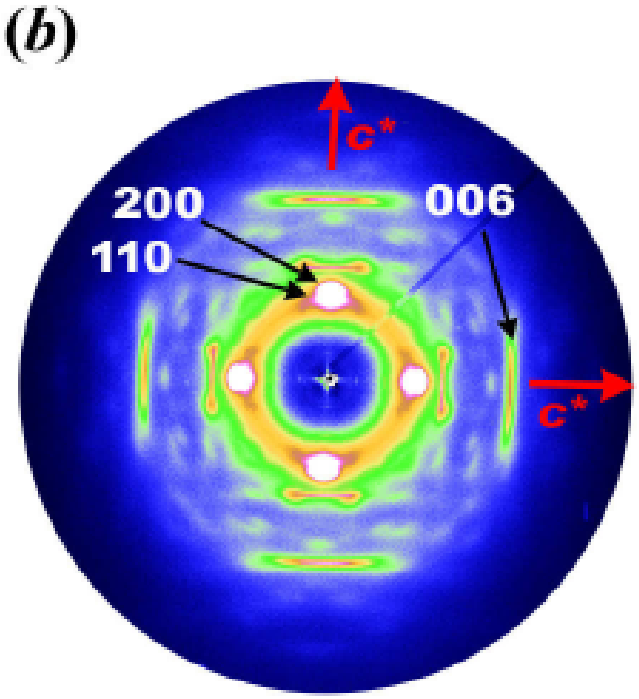
Microfocus Diffraction of Aramid Composites



Kevlar/epoxy

Diffraction Pattern from a 0/90 Cross-ply Laminate





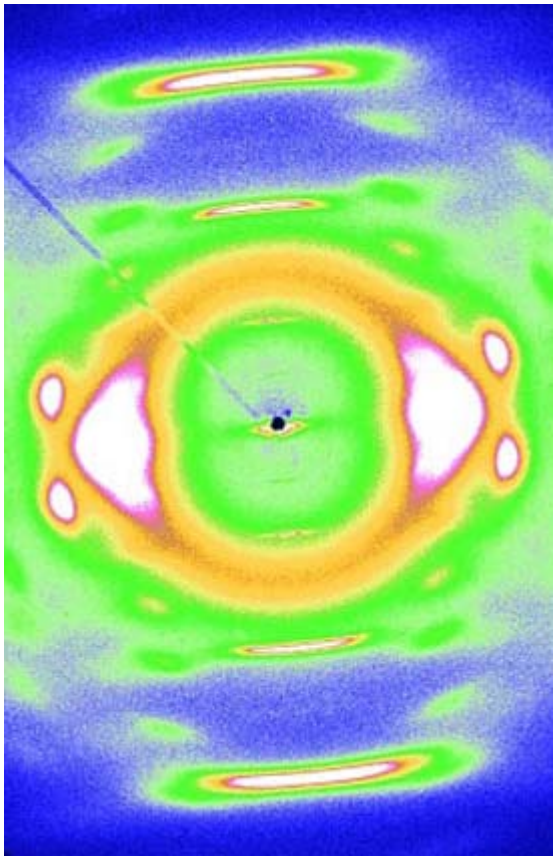
- Aramid/epoxy 0/90 cross-ply laminate
- Beam size – 2 μm
- Two crossing diffraction patterns

Imaging Microstructure and Stress Fields Within a Cross-Ply Composite Laminate', R.J. Davies, S.J. Eichhorn, J.A. Bennett, C. Riekel and R.J. Young, *Composites Science and Technology*, **69**, (2009) 567.

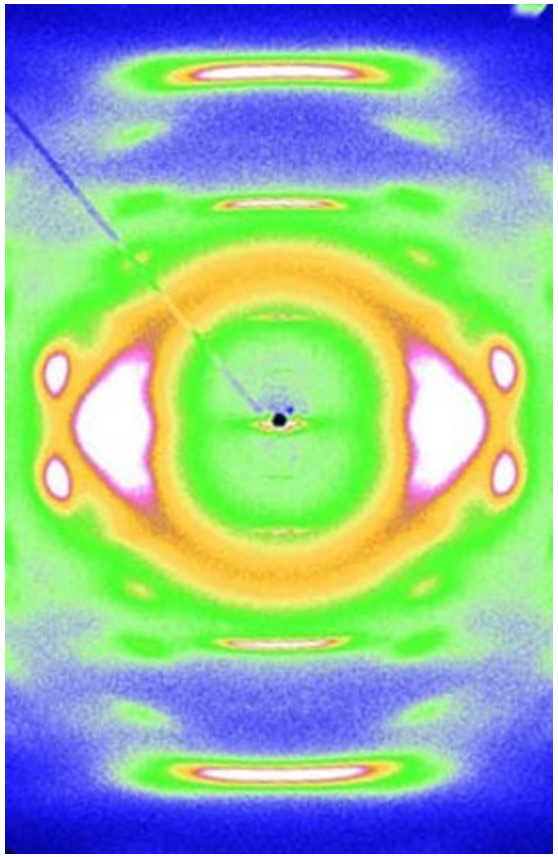
Determination of Fibre Misalignment

Diffraction patterns from an aramid fibre tow at different angles of rotation

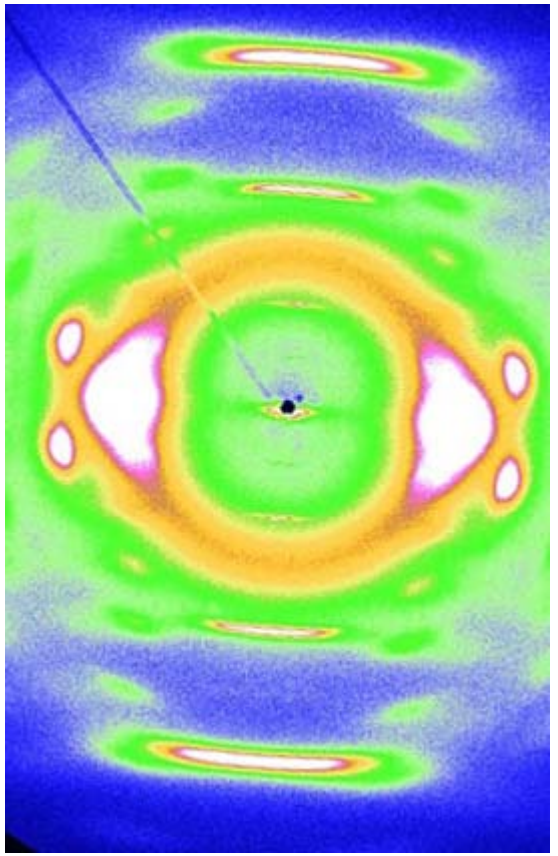
-5º



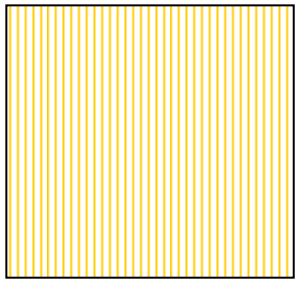
0º



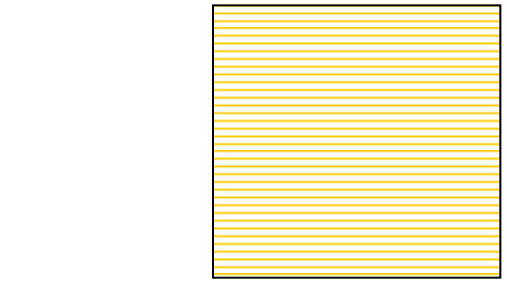
+5º



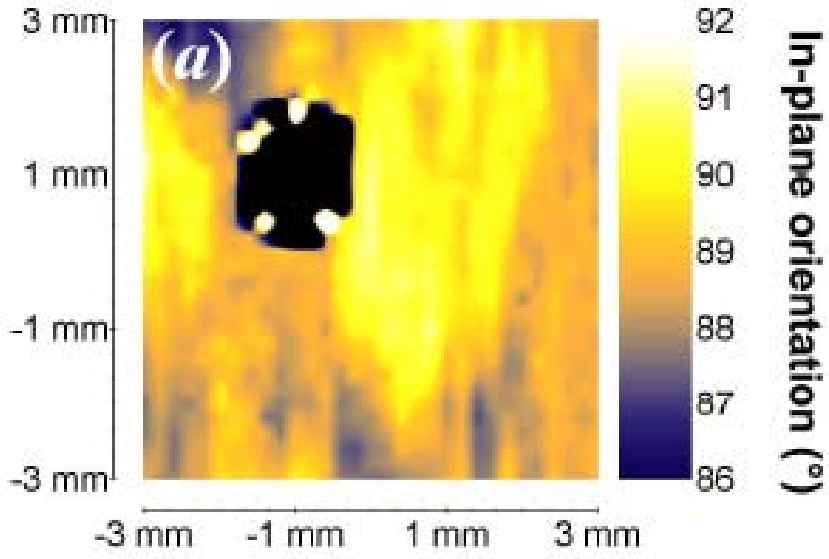
In-Plane Fibre Orientation: Cross-ply

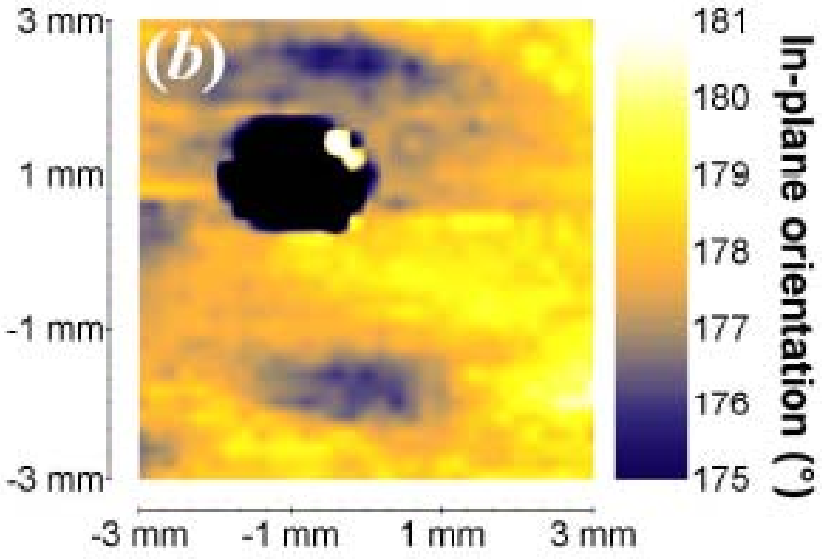


Longitudinal Fibres



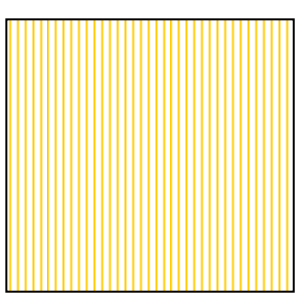
Transverse Fibres



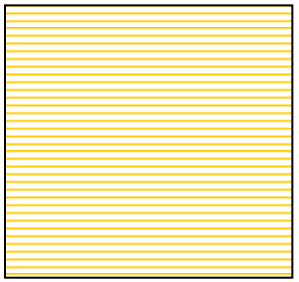


Misalignment determined from relative rotation of the two diffraction patterns

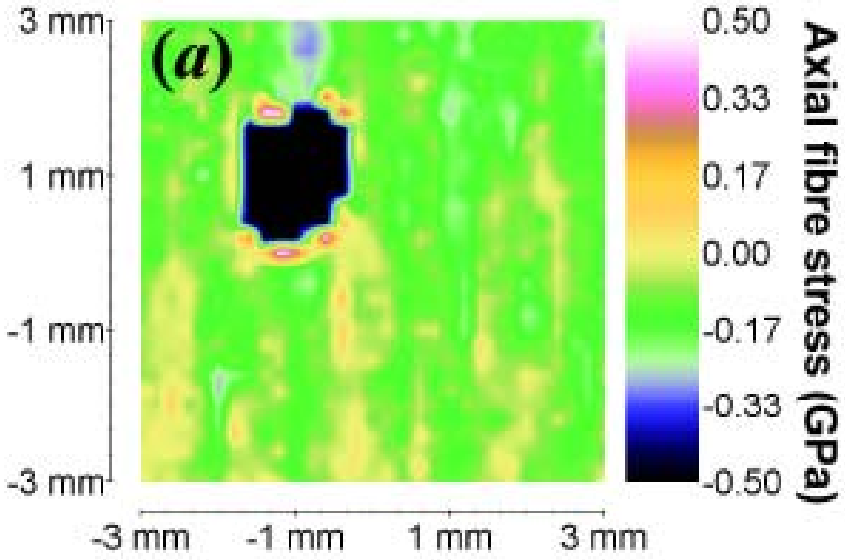
Initial Axial Fibre Stress: Cross-ply



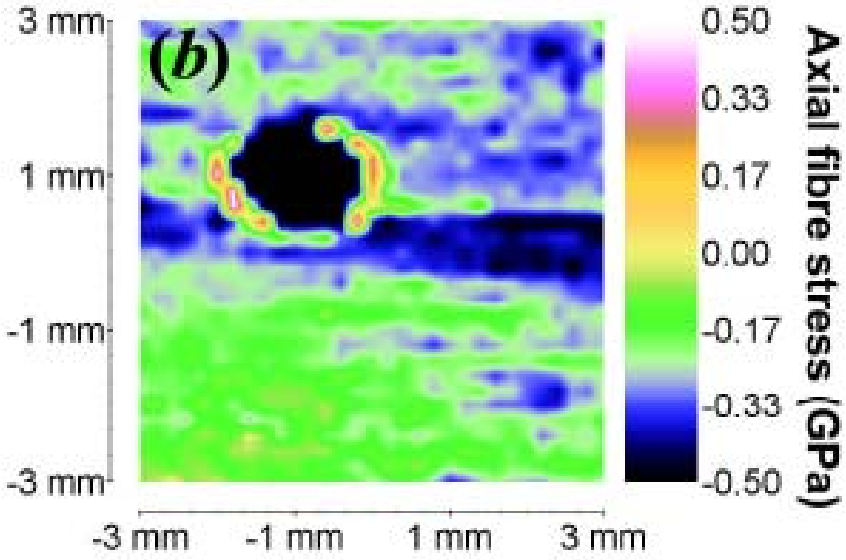
Residual Compressive stresses



Longitudinal Fibres



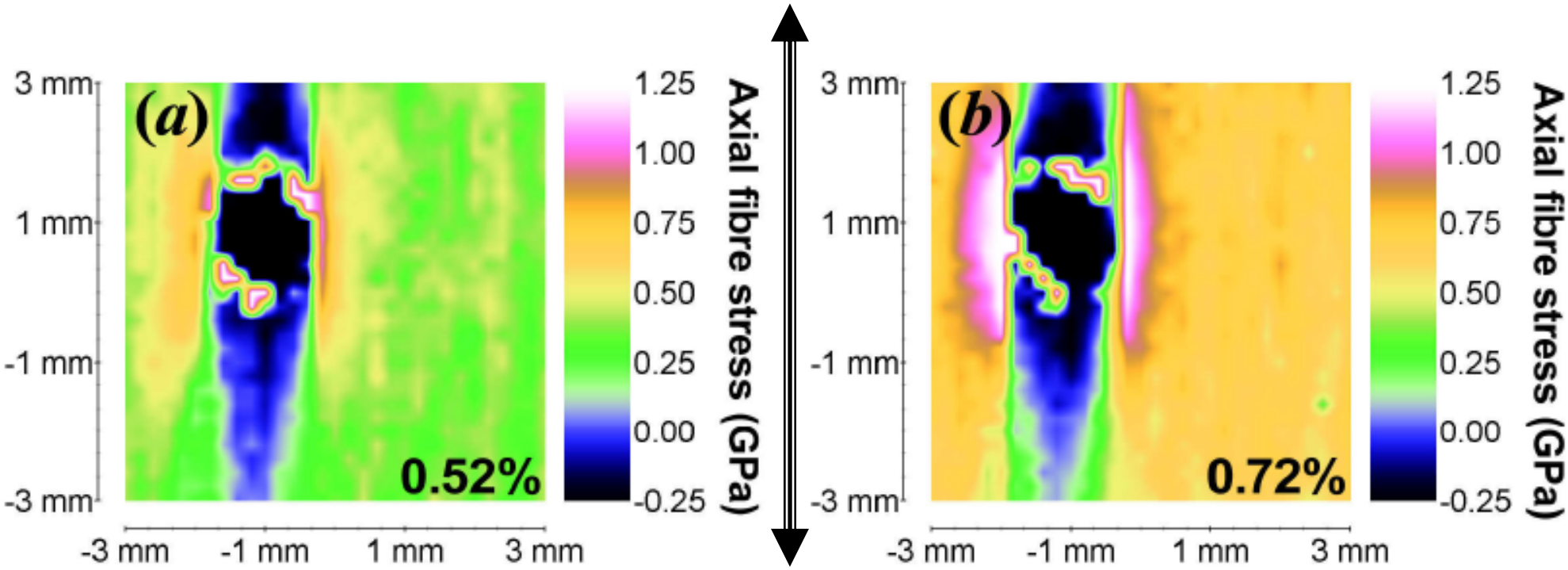
Transverse Fibres



Fibre stress determined from position of 006 peak in diffraction pattern

Development of Fibre Stress during Deformation

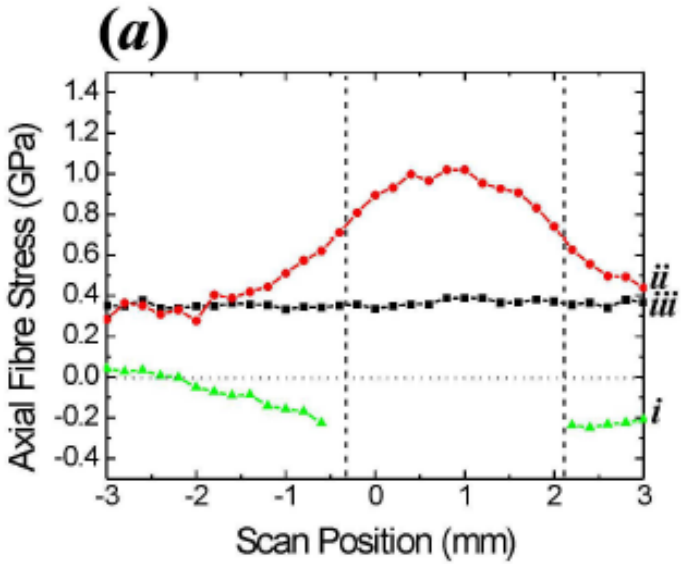
Longitudinal fibres

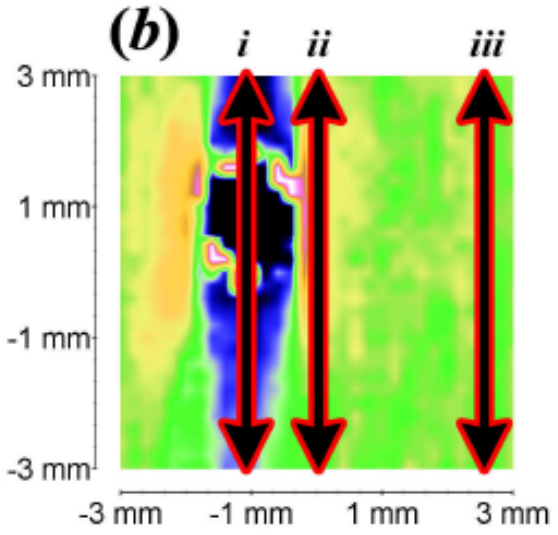


- Non-uniform stress distribution
- Stress concentration around the hole

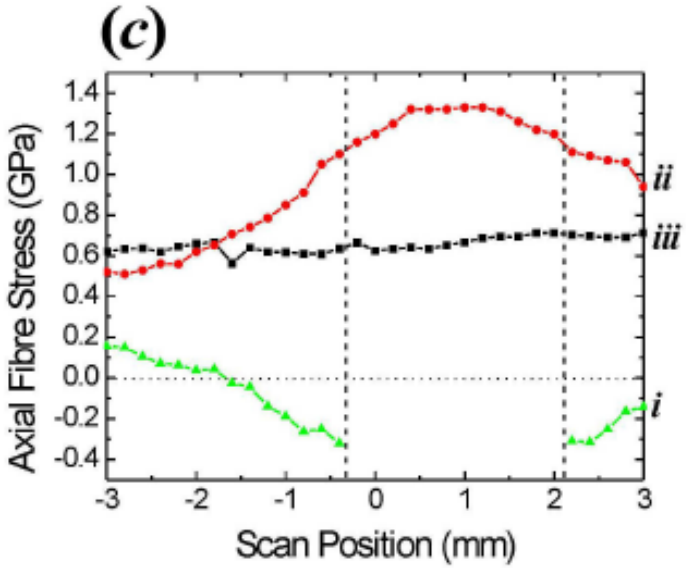
Variation of Local Fibre Stress

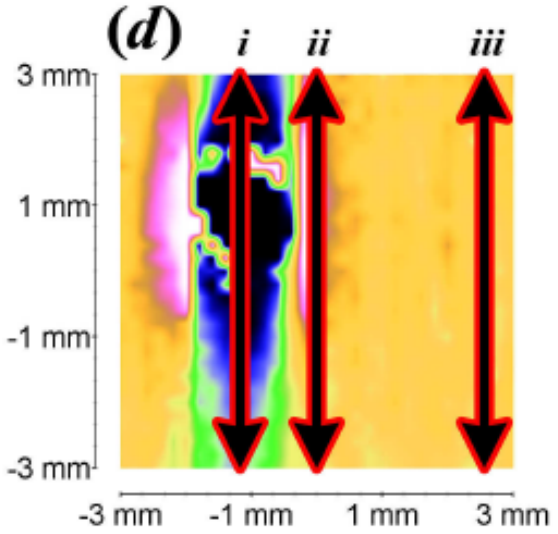
0.52% Strain



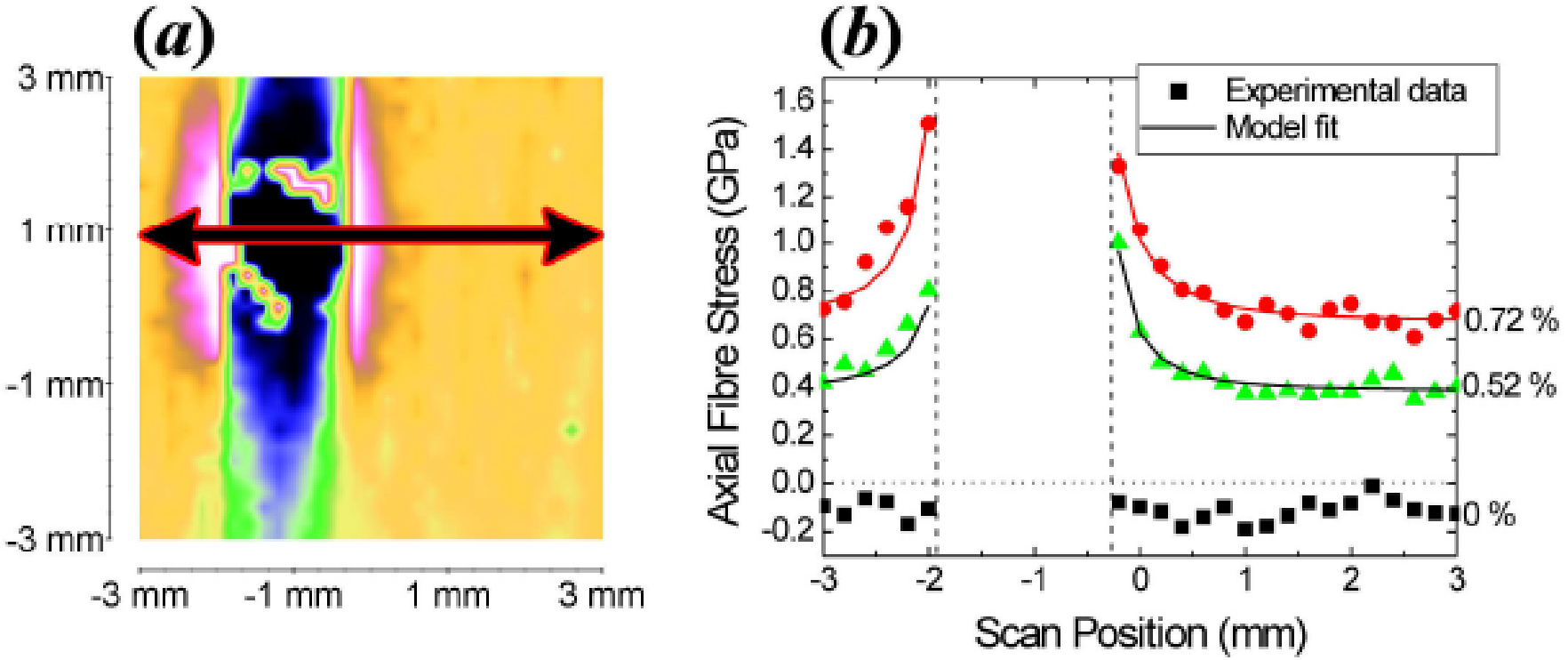


0.72% Strain





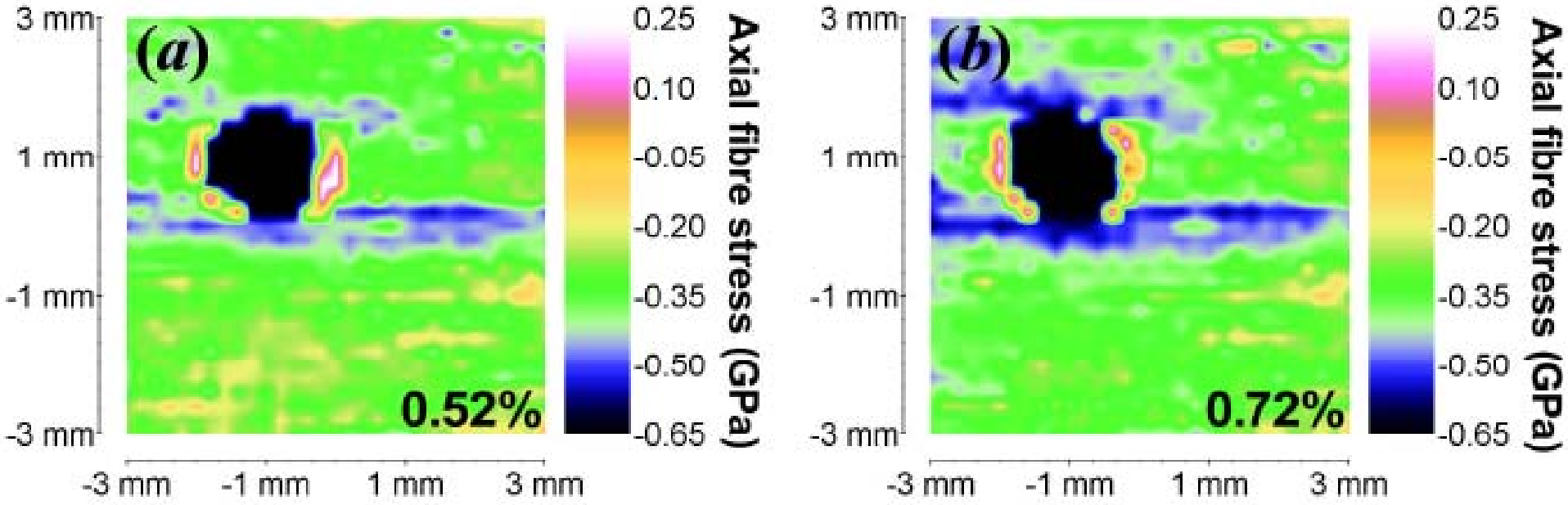
Stress Concentration at the Hole



- Longitudinal fibres
- Scan across the hole
- Fits the model for an isotropic material

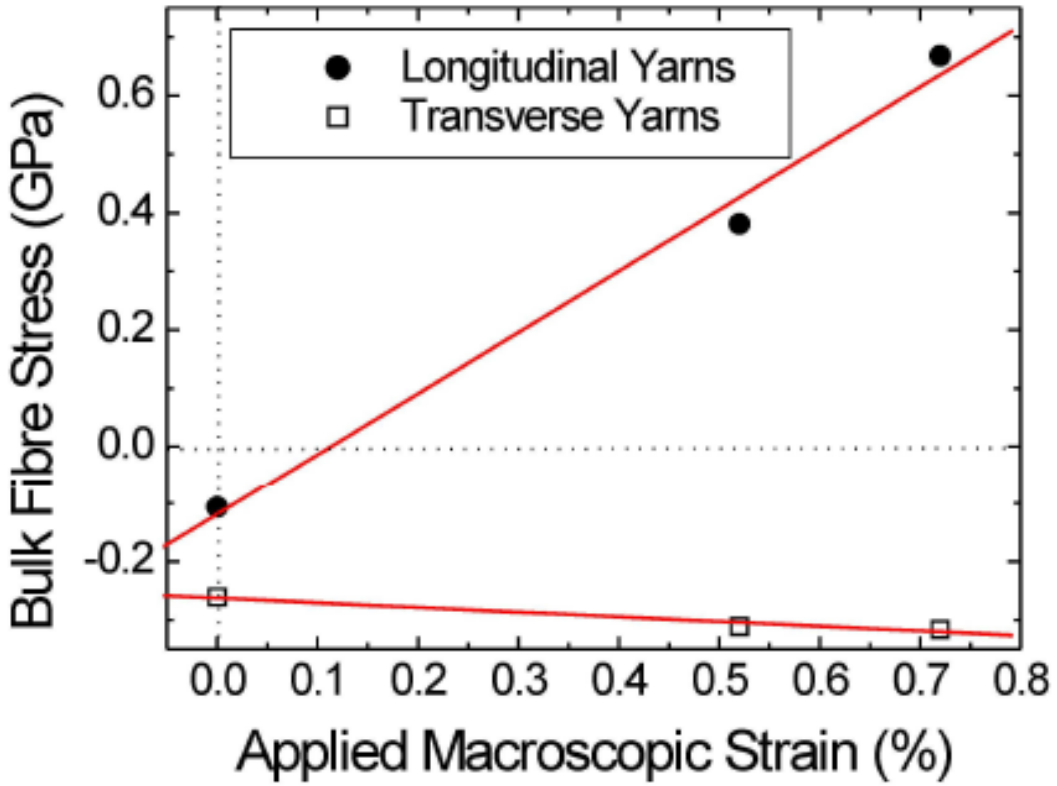
Development of Fibre Stress during Deformation

Transverse fibres



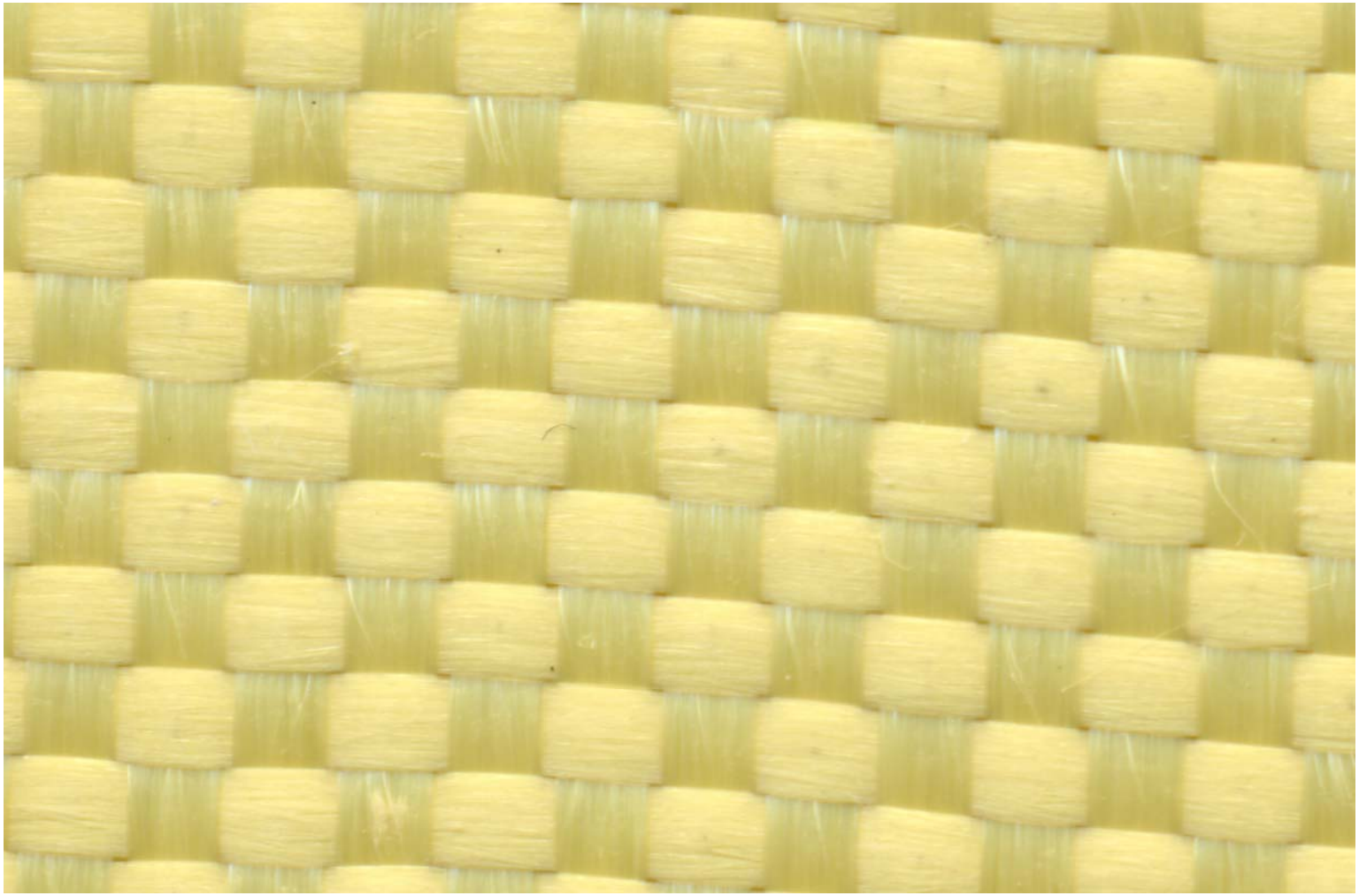
- Non-uniform stress distribution
- Complex stress distribution around the hole

Development of Axial Fibre Stress



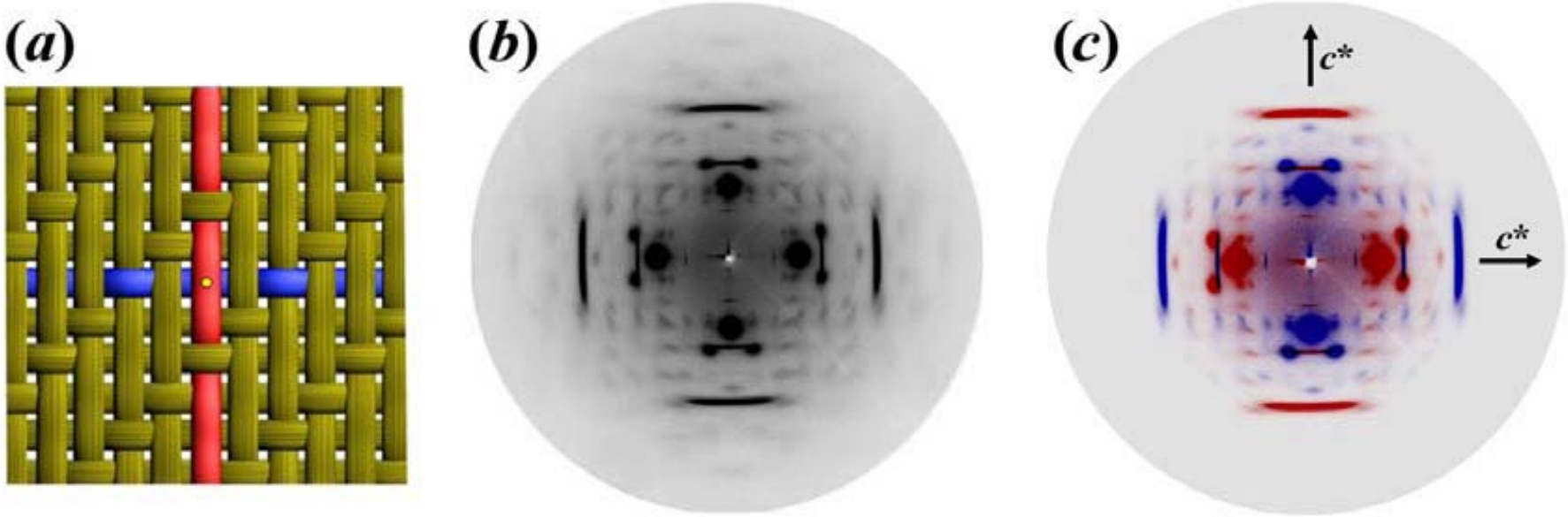
- Only stresses remote from the hole
- Initial residual compression in both plies
- Transverse fibres go further into compression

Woven Aramid Composites



Woven aramid fabric impregnated with epoxy resin

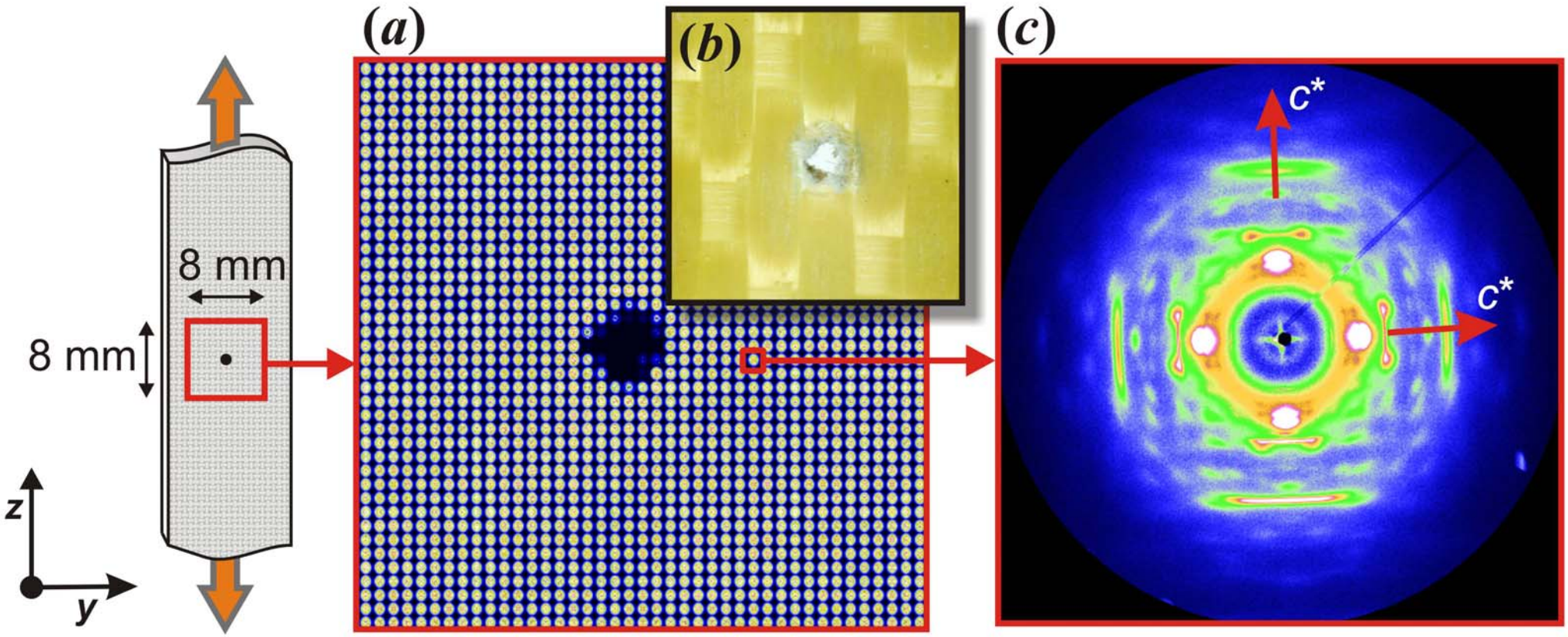
Diffraction Pattern from a Woven Aramid



(Simulated)

- Satin weave
- Beam size – 2 μm
- Two crossing diffraction patterns

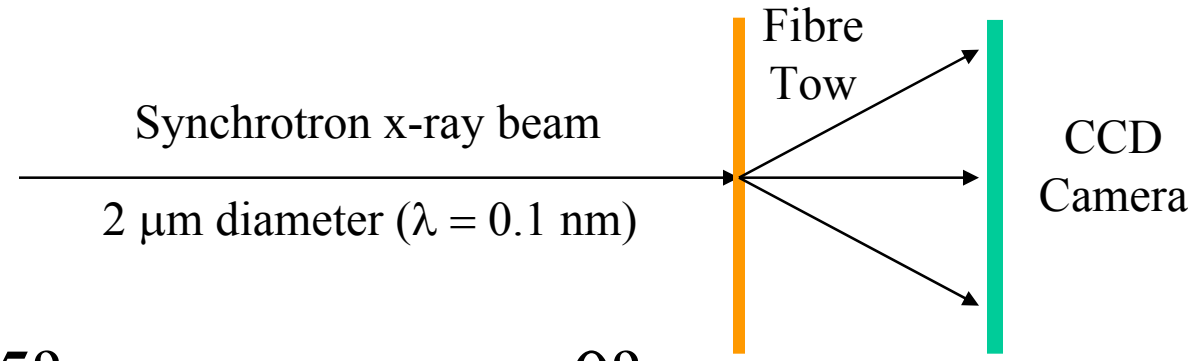
Characterisation of a Woven Aramid Composite



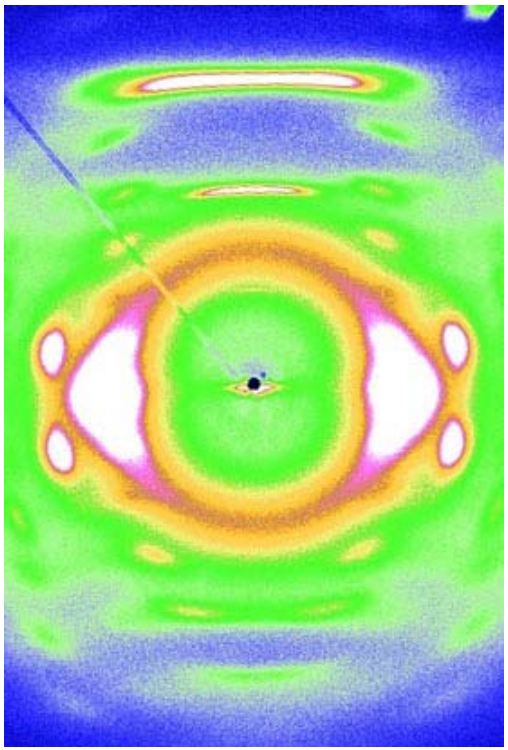
Probing the internal geometry of a woven composite during deformation using an x-ray micro-diffraction imaging technique

Richard J. Davies, Christian Riekel, James A. Bennett, Stephen J. Eichhorn, and Robert J. Young
Applied Physics Letters, (2007) 91:044102.

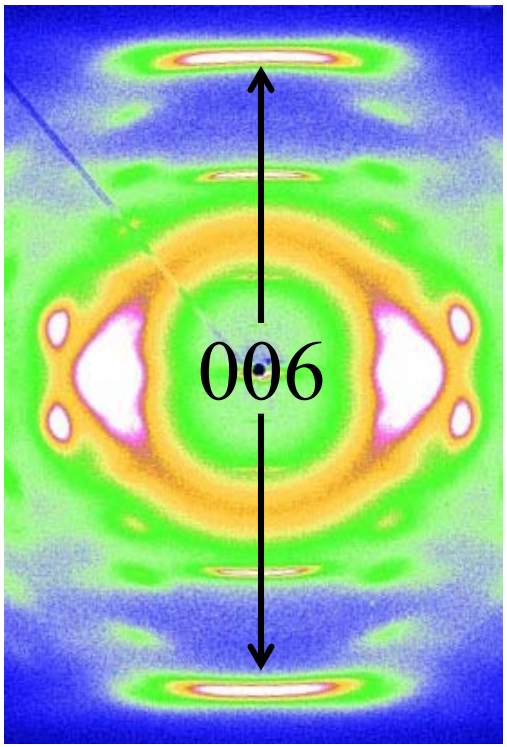
Determination of Out-of-plane Fibre Tilt



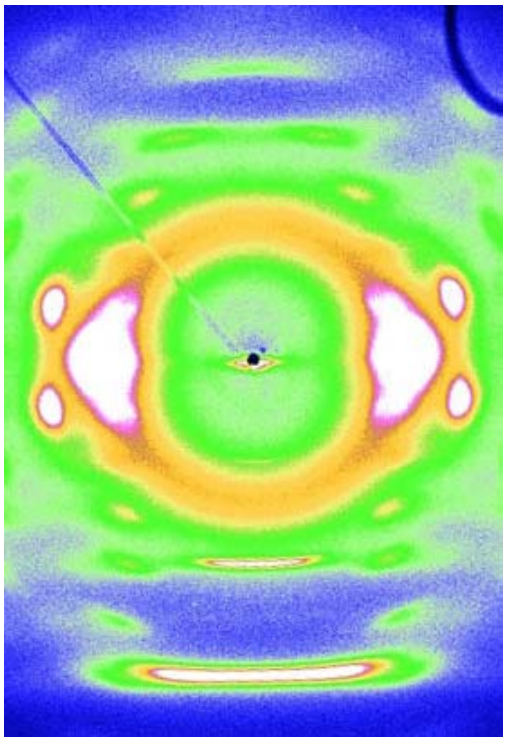
-15°



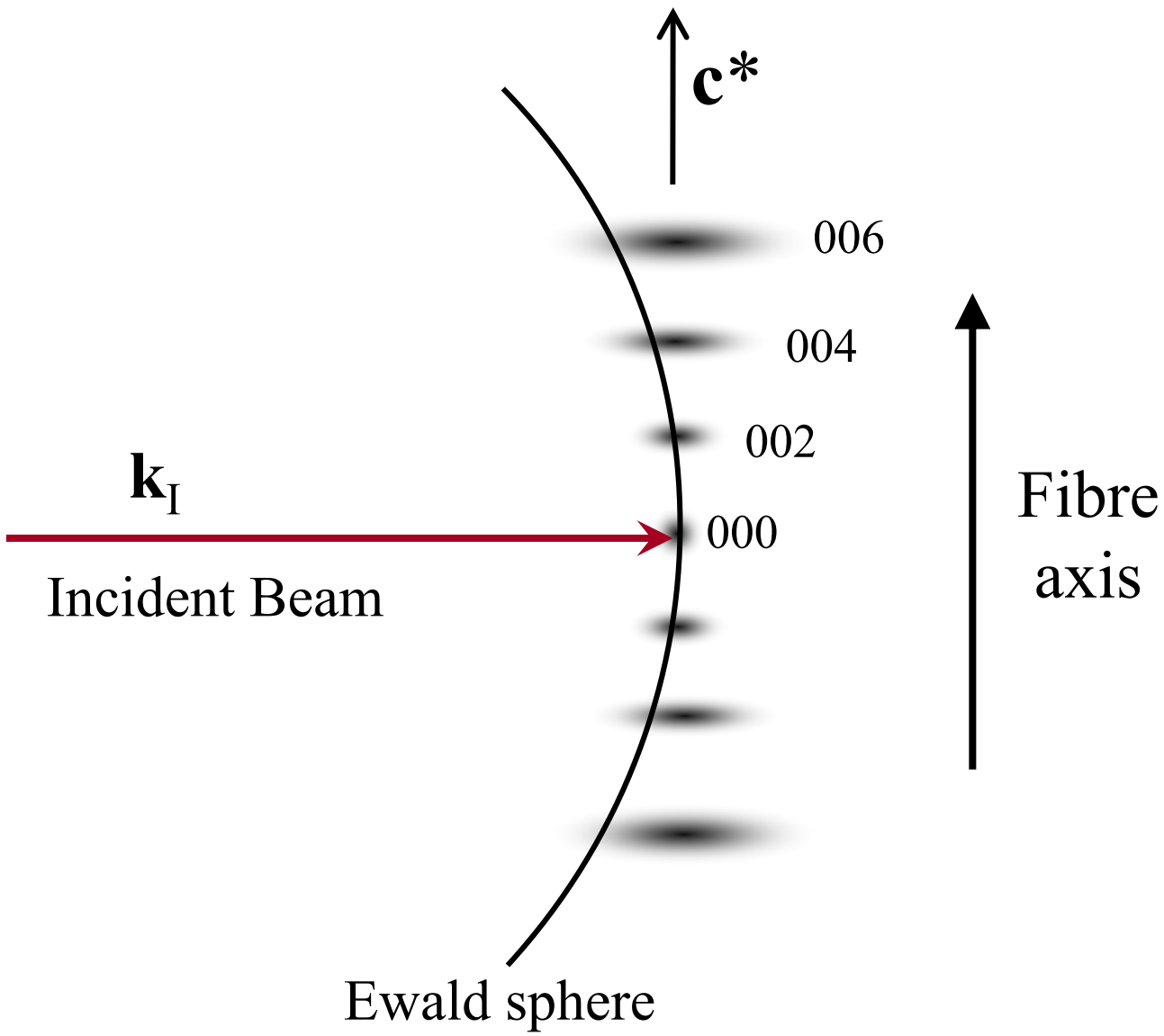
0°



+15°

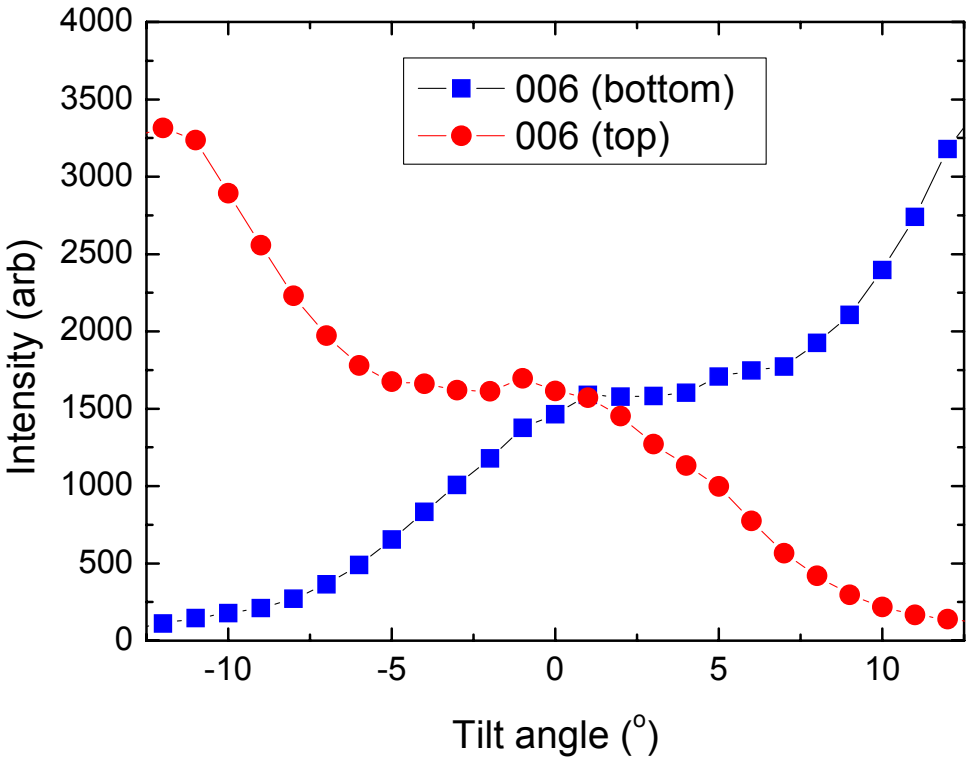


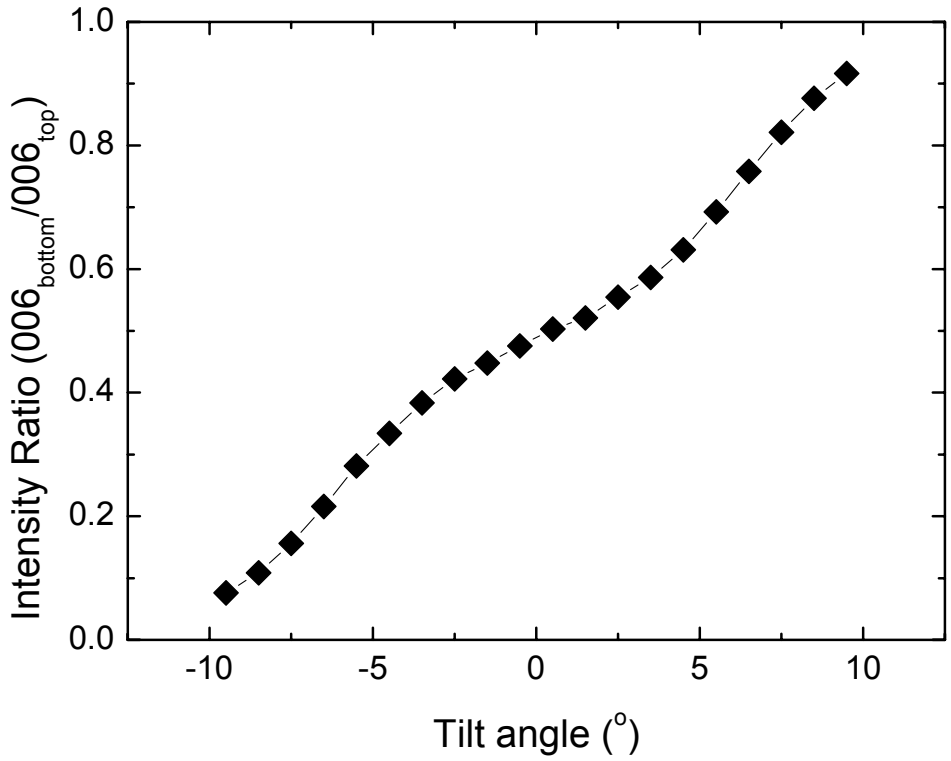
X-ray Diffraction - Reciprocal space



Calibration of Out-of-plane Tilt Angle

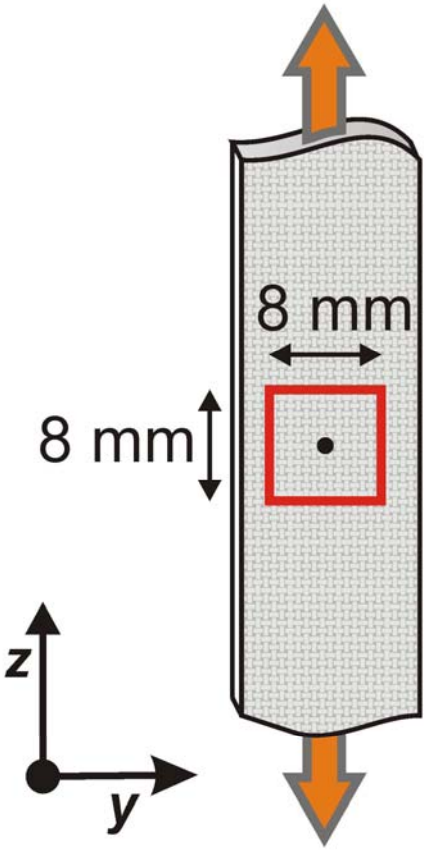
Measure the relative intensity of the top and bottom 006 Bragg reflections as a function of out-of plane tilt angle

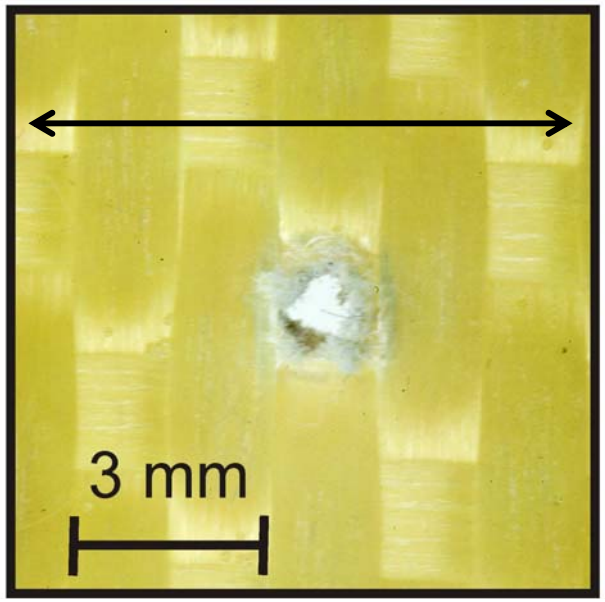




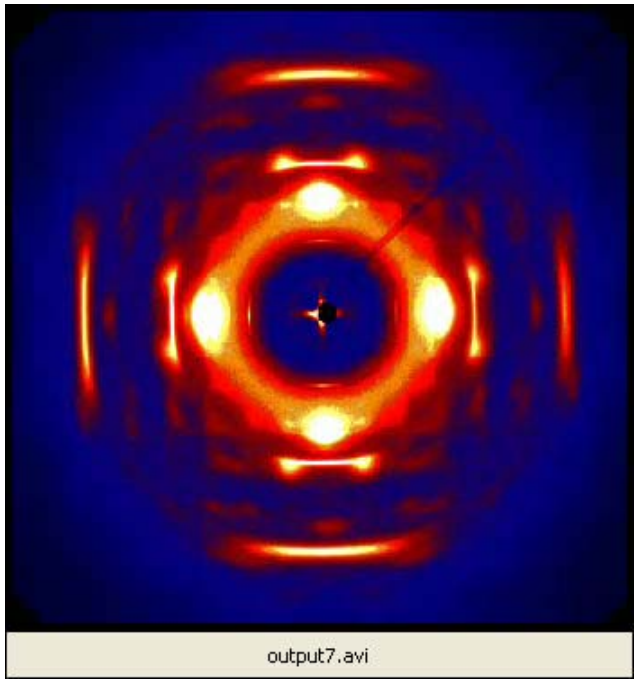
Mapping Fibre Orientation and Alignment

Woven Aramid Satin Weave with Hole Drilled





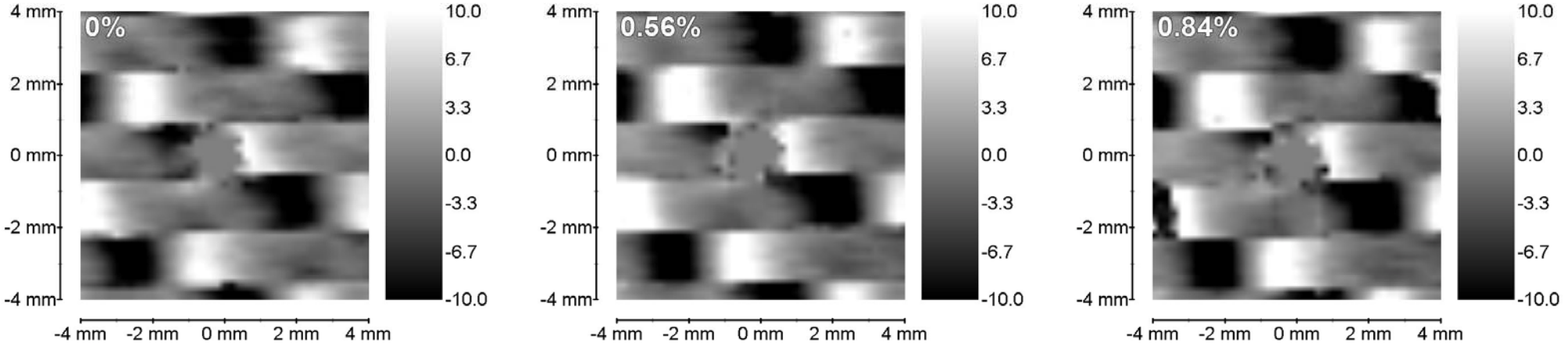
Optical Image



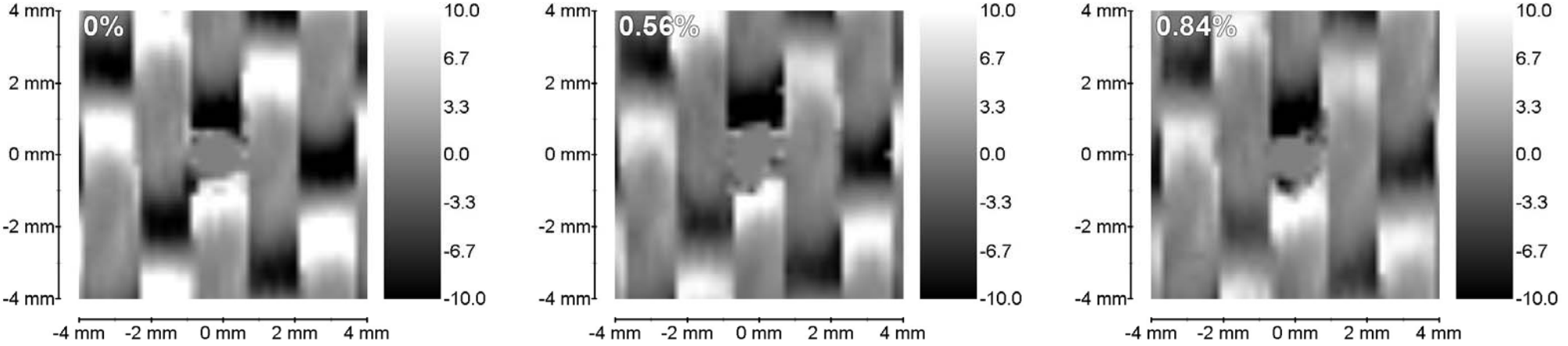
Analysis of the Structure and Deformation of a Woven Composite Lamina using X-ray Microdiffraction, R.J. Davies, S.J. Eichhorn, J.A. Bennett, C. Riekel and R.J. Young, *Journal of Materials Science*, **43,** (2008) 6724-6733.

Out-of-plane fibre tilt angle

Woven Aramid Satin Weave with Hole Drilled



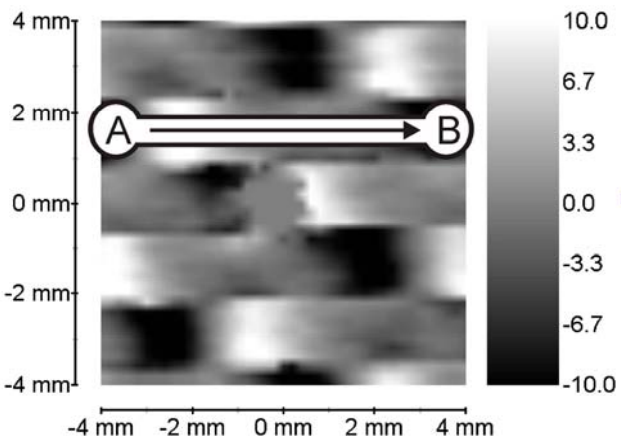
Horizontal tows

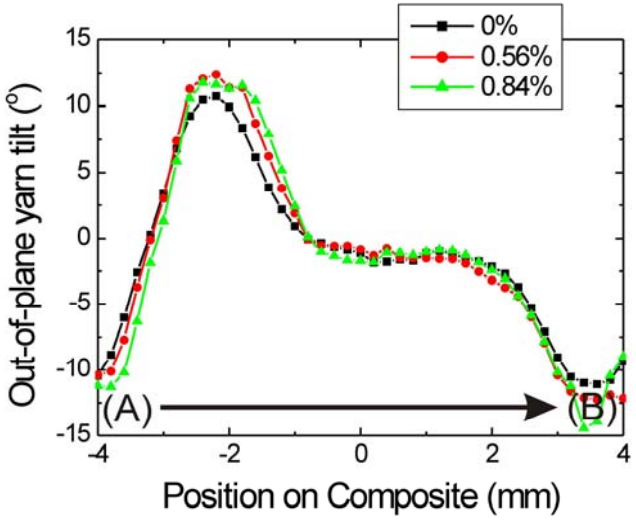


Vertical tows

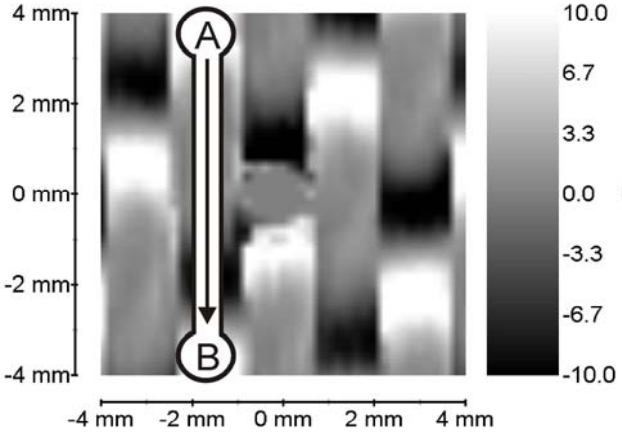
Changes in out-of-plane tilt angle

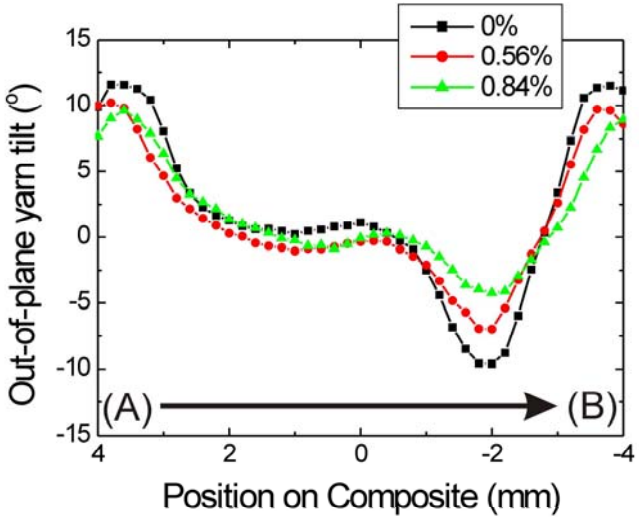
Stress





Tilt increases

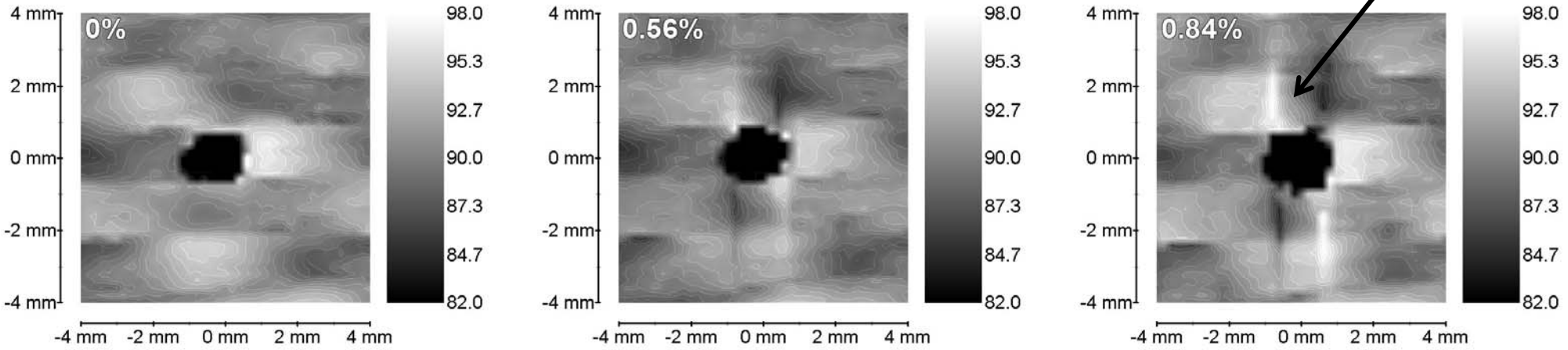




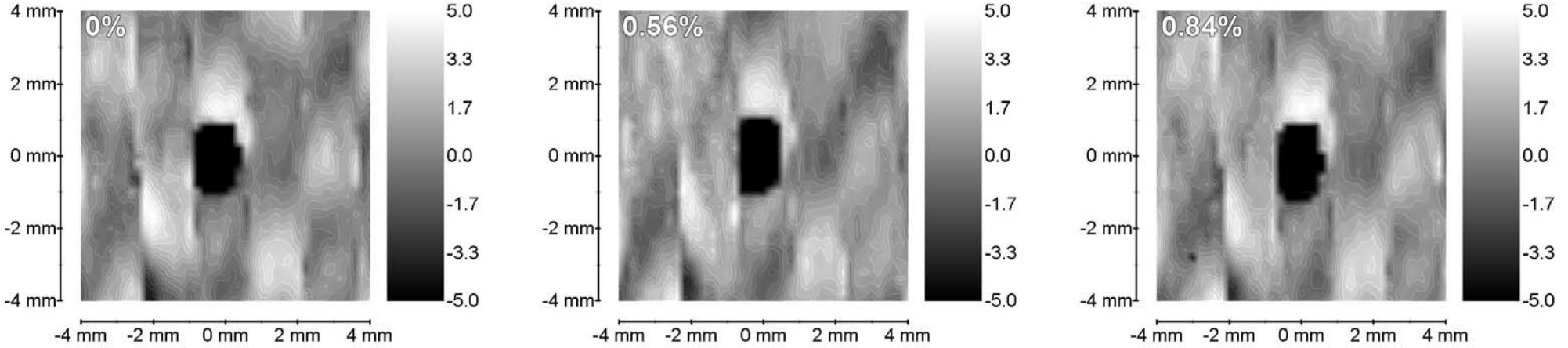
Tilt decreases

In-plane fibre orientation

Fibre orientation affected by hole



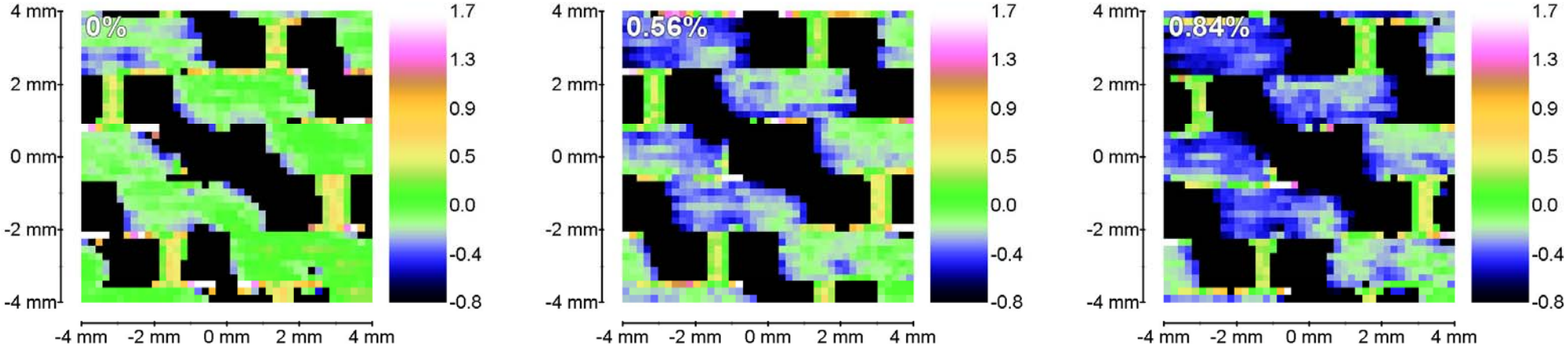
Horizontal tows



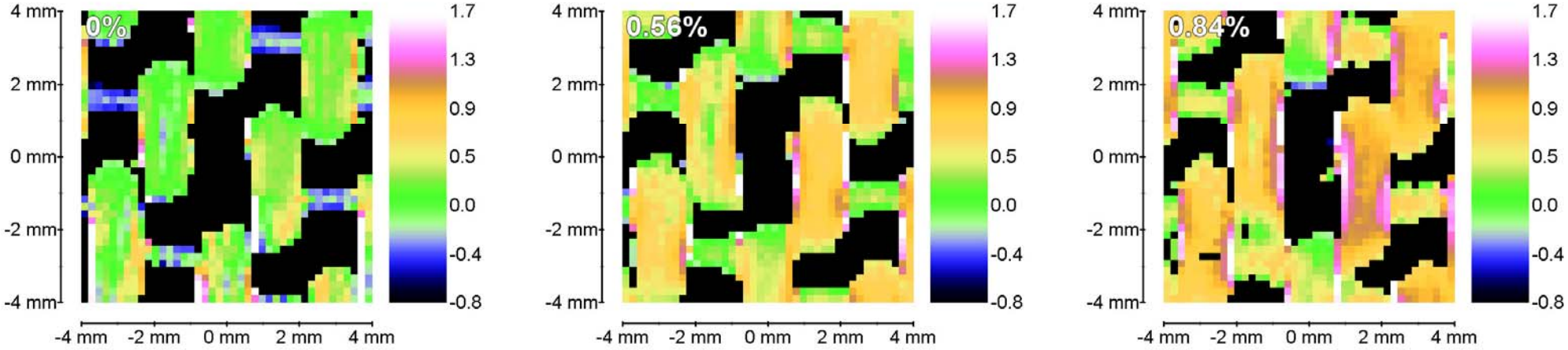
Vertical tows

Development of axial fibre stress

Woven Aramid Satin Weave with Hole Drilled



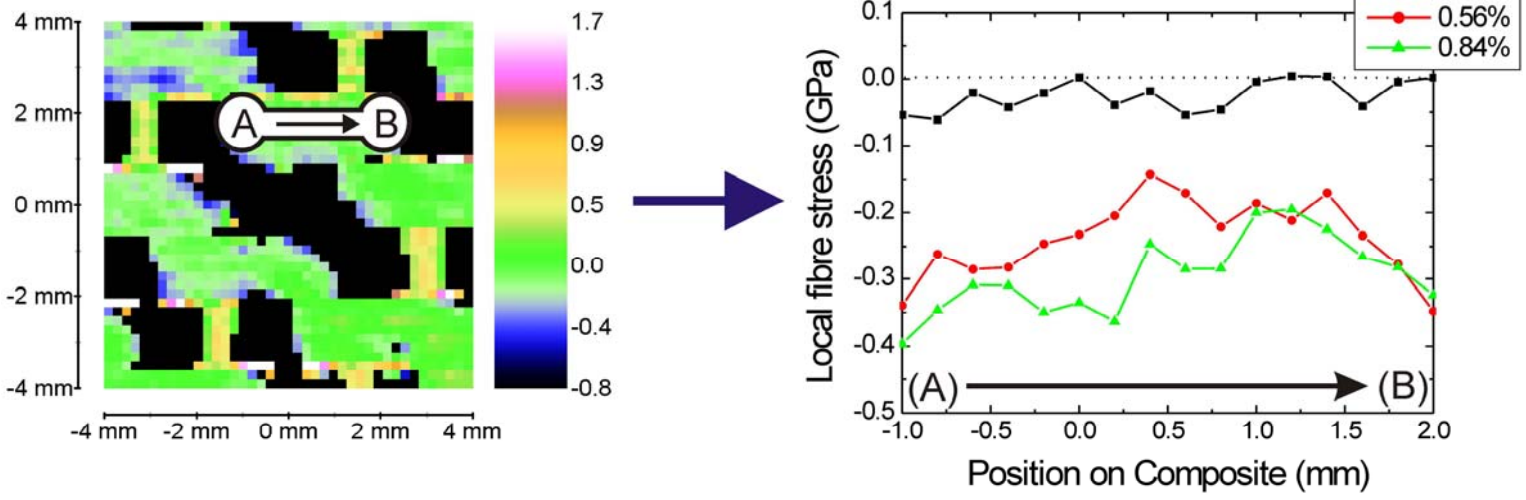
Horizontal tows

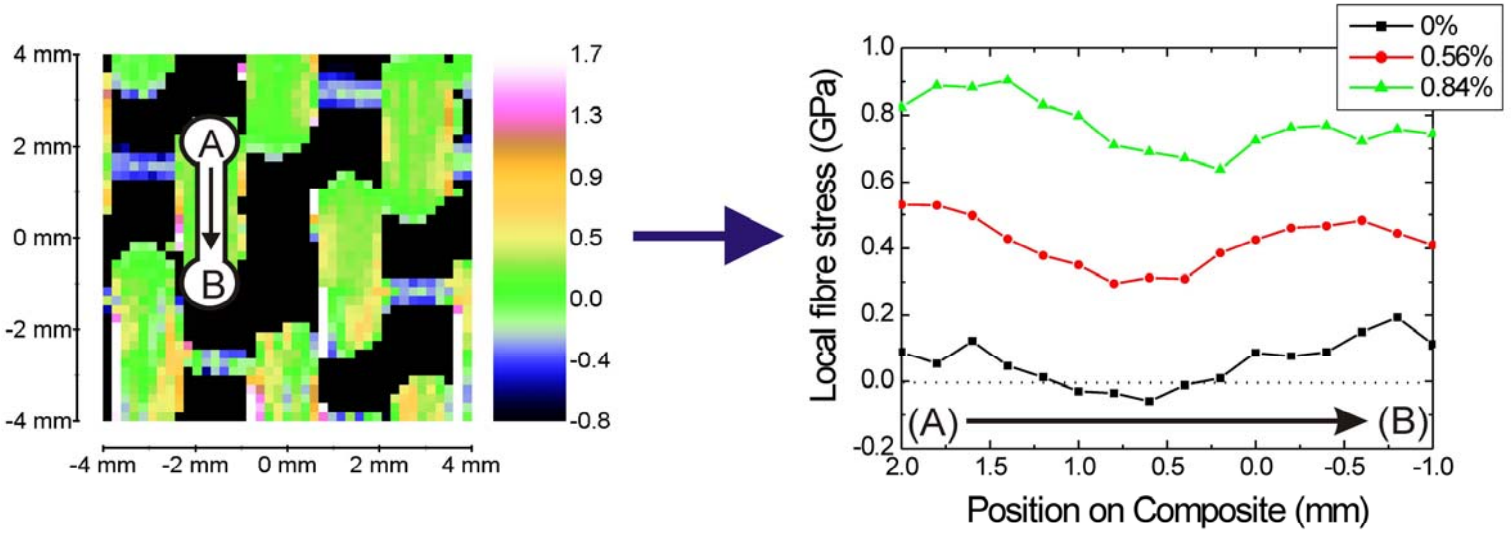


Vertical tows

Development of axial fibre stress

Stress





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Conclusions

- Microfocus x-ray diffraction allows on the micron level:
  - the evaluation of local composite geometry
  - the determination of local fibre stress
- Tremendous scope for further analysis and exploitation:
  - cross-ply aramid/epoxy
  - woven aramid/epoxy

Acknowledgements

- EPSRC – funding of the research project
- Dr. D. J. Bannister of SP Systems Ltd for supplying the materials