MODELLING THE THERMOELASTIC PROPERTIES OF SHORT FIBRE COMPOSITES WITH ANISOTROPIC PHASES

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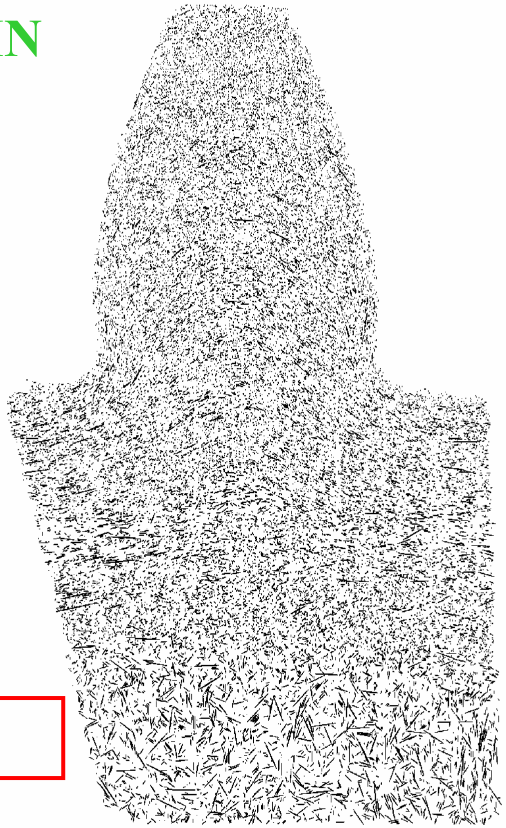
COMPTEST 2004

MOTIVATION

STRUCTURE PROPERTY INVESTIGATIONS IN FIBRE REINFORCED POLYMERS



Injection moulding

Complicated shapes and a fast/cheap process

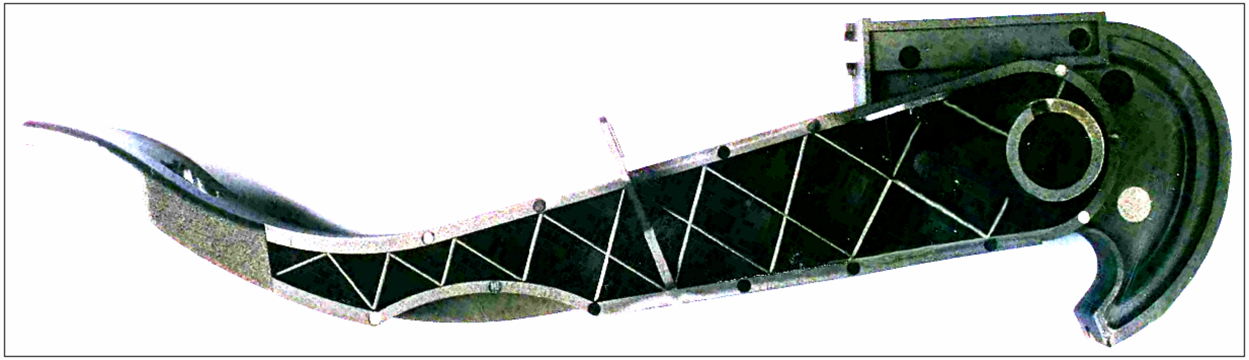
Add short fibre reinforcement

Enhanced stiffness and strength but anisotropic properties

Challenges

- Reliable models for predicting composite properties
  + prediction of fibre orientation due to processing

Computer aided component design and material optimisation



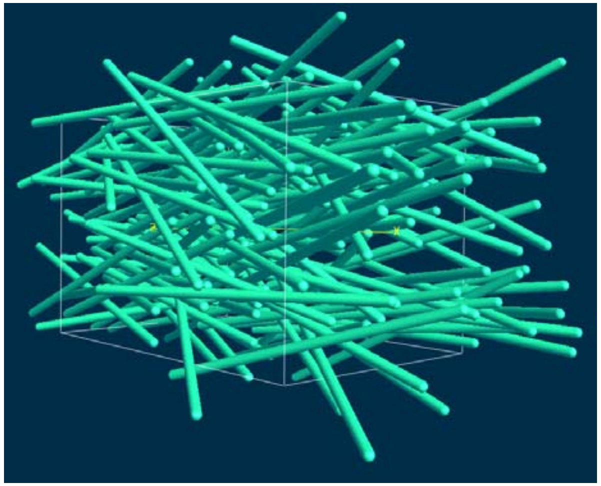
MOTIVATION

Themes

- **Development of analytical models for predicting elastic and thermoelastic properties**

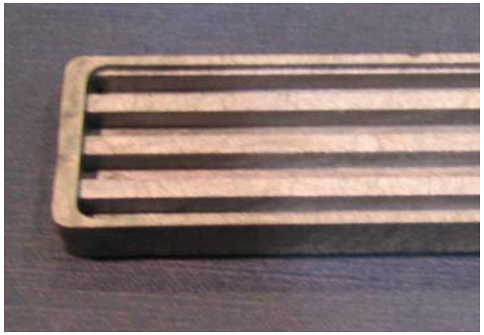
Use of FE techniques to validate/tune analytical models (ETH/Leeds)

P.J.Hine, H.R.Lusti and A.A.Gusev, Comp. Sci and Tech., **2002,** 62, 1445-1453 .



FE model: 100 fibres: periodic boundaries

Compare with actual manufactured components of increasing complexity and with anisotropy in both phases (requires complete description of the orientation structure and phase properties and measurement of mechanical properties).

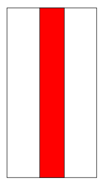


Carbon fibre/LCP ribbed box

MODELLING APPROACHES

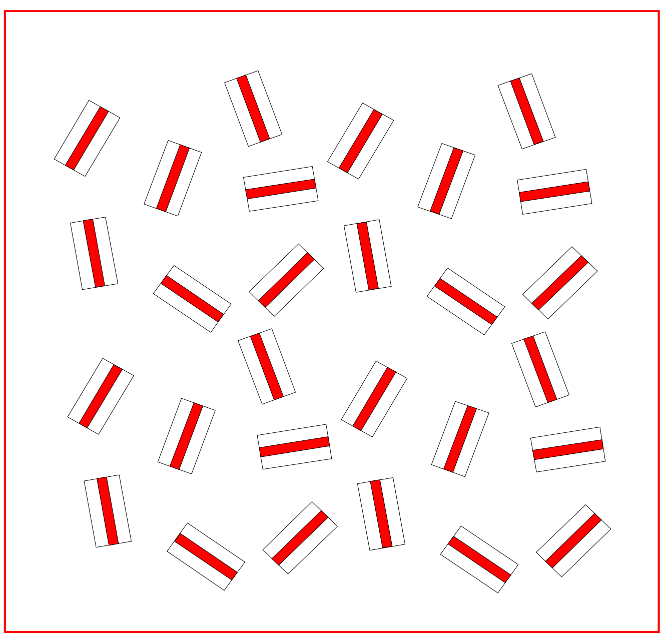
ANALYTICAL

Prediction of elastic properties is split into two components.



UNIT

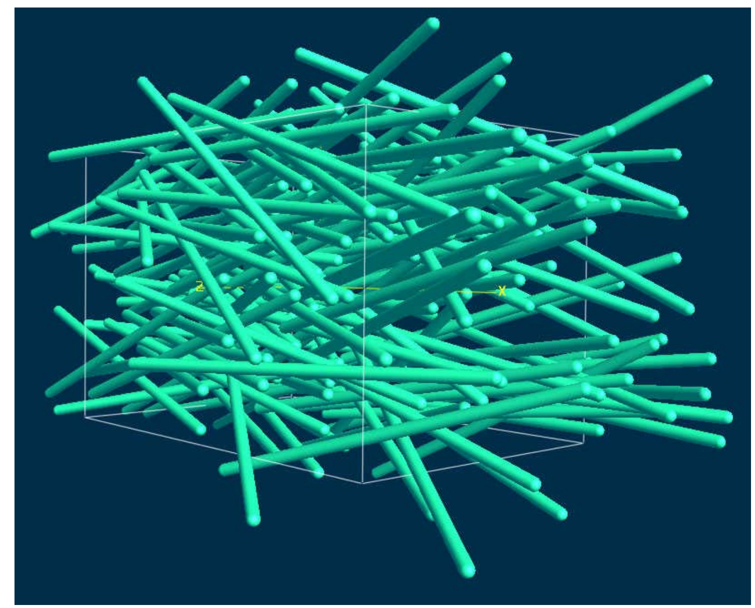
+



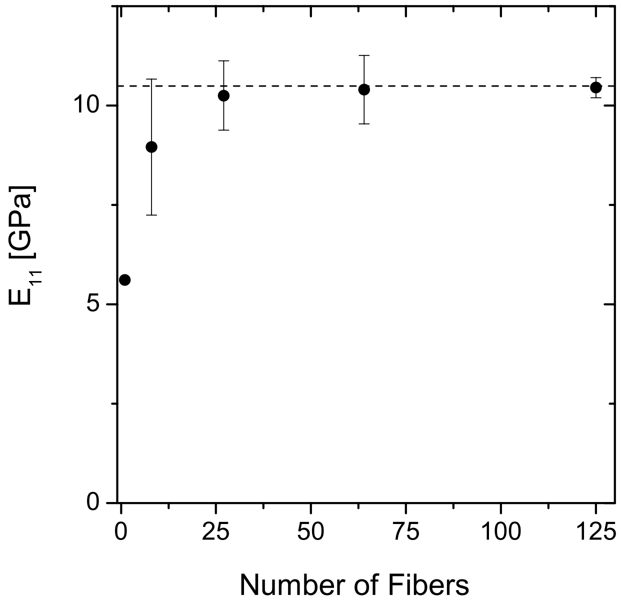
AGGREGATE

FINITE ELEMENT

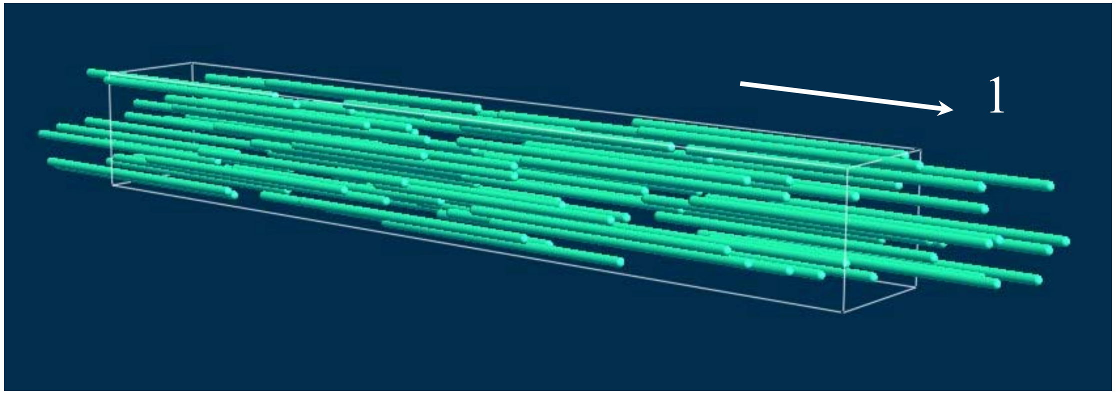
Prediction of elastic properties is carried out in one process.



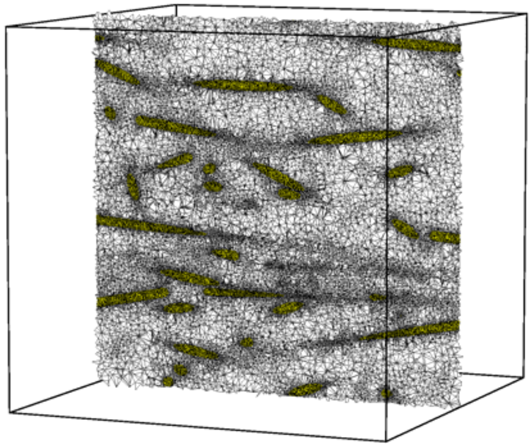
FE MODELLING APPROACH



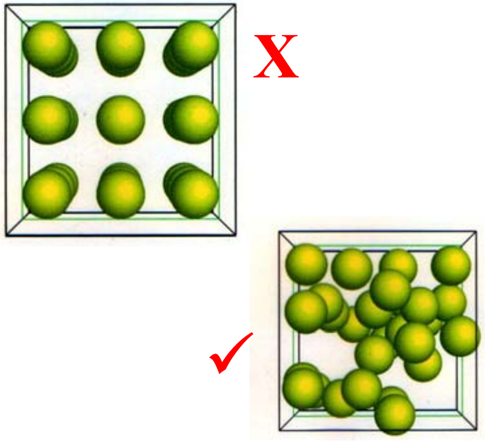
- Finite element based approach of Gusev
- 100/250 sphero-cylinders required for reliable predictions depending on the orientation state.
- Monte Carlo techniques used to generate random microstructures.
- Periodic boundary conditions used.



MESHING



- Periodic morphology – adaptive meshing
- tetrahedra based
- quality refinement
- typically 3 million nodes
- random microstructures



ISOTROPIC/ANISOTROPIC FIBRE

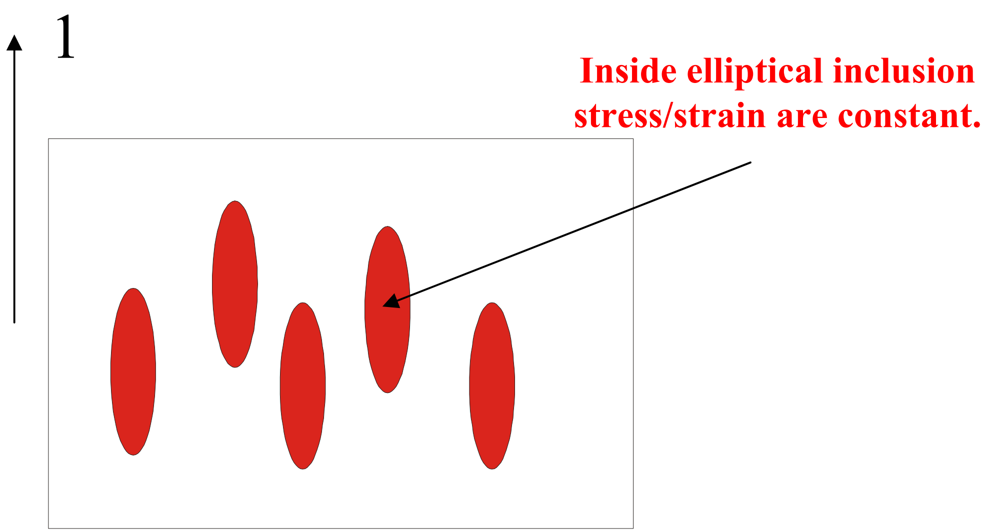
+

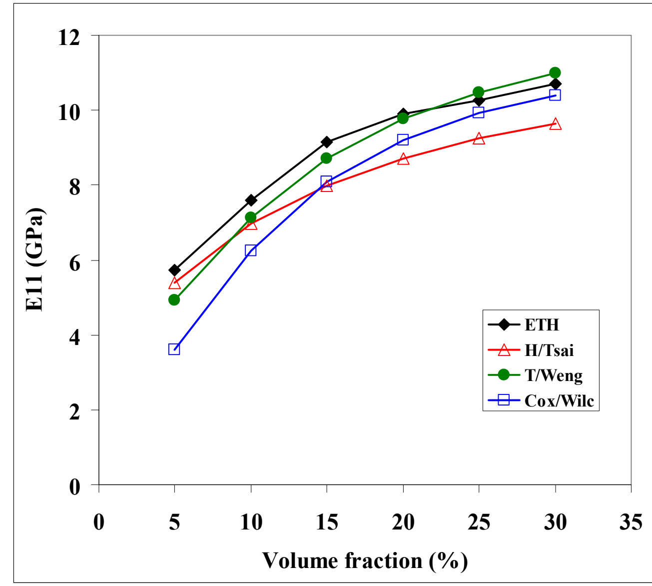
ISOTROPIC MATRIX

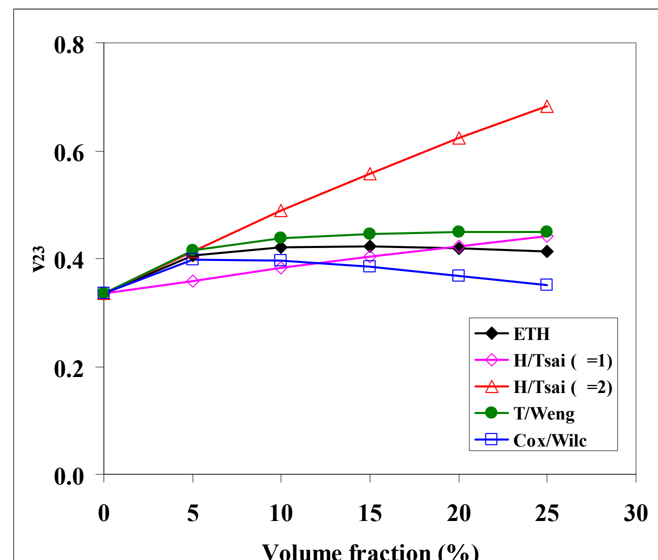
ANISOTROPIC FIBRE/ISOTROPIC MATRIX

Tandon/Weng

Based on Eshelby (equivalent inclusion method) and Mori Tanaka (average stress theory).
Can cope with anisotropic fibres (modification by Qui and Weng).







The best model for the prediction of elastic properties of the unit is that of Tandon and Weng.

Halpin-Tsai doesn’t capture the physics

Y. P. Qiu, G. J. Weng, *J. Engng. Sci.* **1990**, *28*, 1121.

ANISOTROPIC FIBRE/ISOTROPIC MATRIX

The best model for the prediction of thermal expansion properties of the unit is that of Levin (Christensen/Rosen).

This is based on the elastic and thermal properties of the phases and the elastic properties of the unit.

$$\alpha_i = (\alpha_k^{(1)} - \alpha_k^{(2)})(S_{kl}^{(1)} - S_{kl}^{(2)})^{-1}(S_{li} - S_{li}^{(2)}) + \alpha_i^{(2)}$$

where subscripts 1 and 2 stand for the fibre and matrix phases

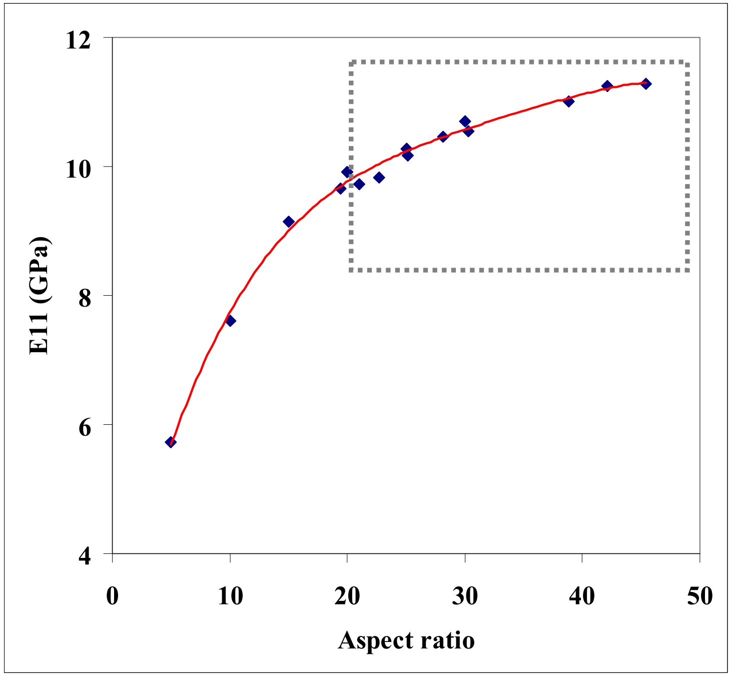
V. M. Levin, *Mech. Tverd. Tela* 1968, *88*, 25.

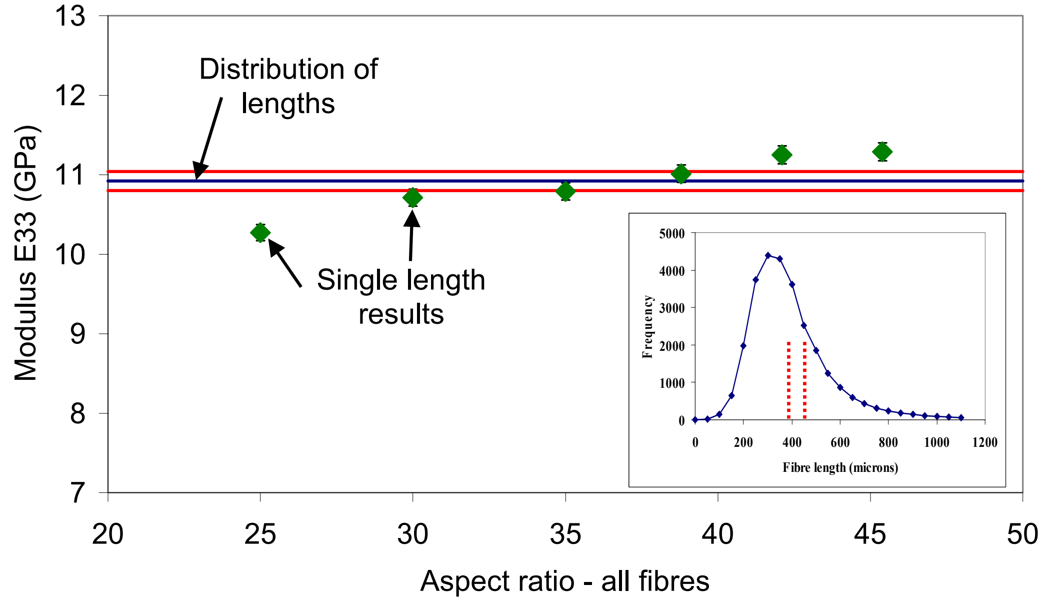
R.M. Christensen, *Mechanics of Composite Materials*, Krieger Publishing Company, Mala-bar, Florida, 1991

B.W. Rosen and Z. Hashin, International Journal of Engineering Science **1970,** 8, 157-173.

ANISOTROPIC FIBRE/ISOTROPIC MATRIX

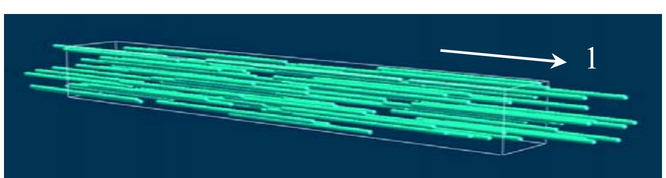
Aligned fibres, Fixed volume fraction (15%) isotropic phases





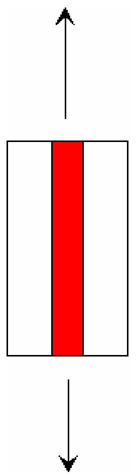
Results determined using a single aspect ratio

Single value to match distribution	Number Average L_N	Weight Average L_W	Skewed Average L_S	RMS Average L_{RMS}
36.6 ± 2.5	38.8	45.4	41.9	33.2
	$\langle a \rangle$		$\langle 1/a \rangle^{-1}$	$\langle a^2 \rangle^{-1/2}$



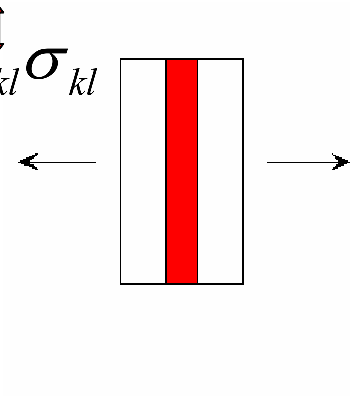
The best measure for the fibre length is the number average length.

ANISOTROPIC FIBRE/ISOTROPIC MATRIX

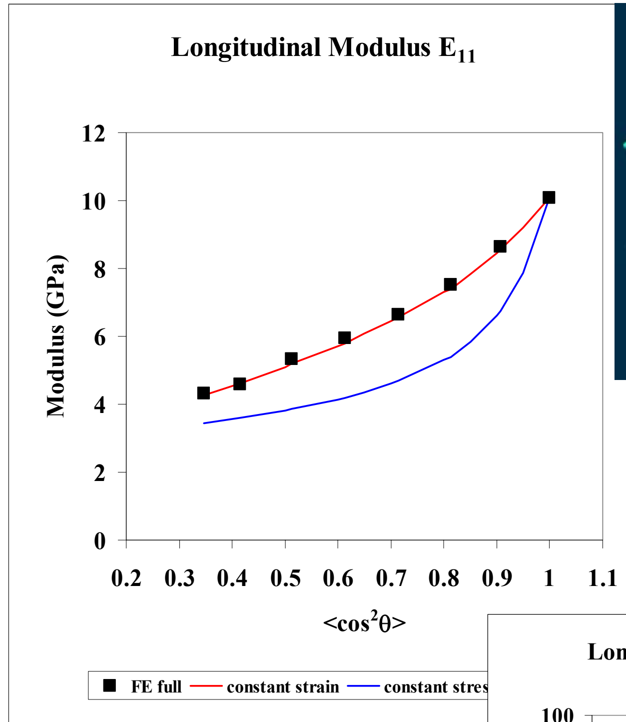


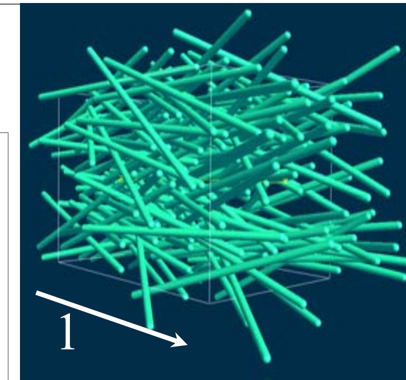
$$\sigma_{ij} = C_{ijkl}\varepsilon_{kl}$$

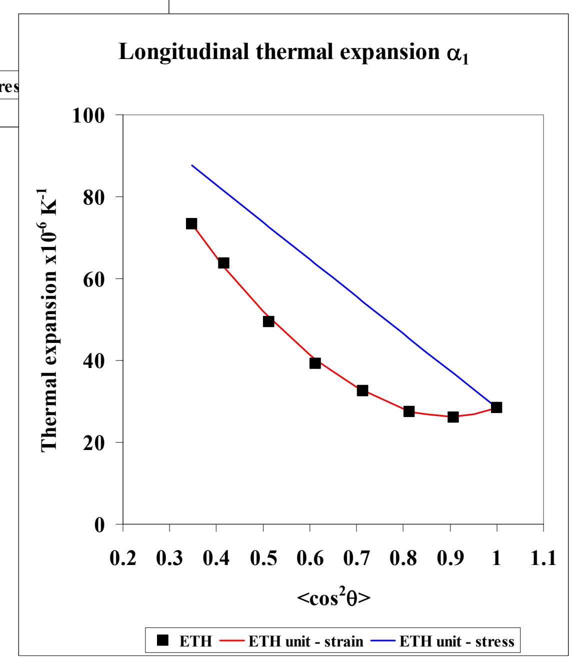
$$\varepsilon_{ij} = S_{ijkl}\sigma_{kl}$$

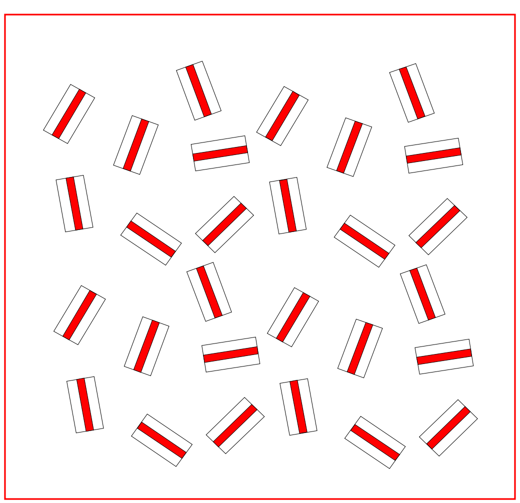


CONSTANT STRAIN (Average C's) **OR** **CONSTANT STRESS (Average S's)**





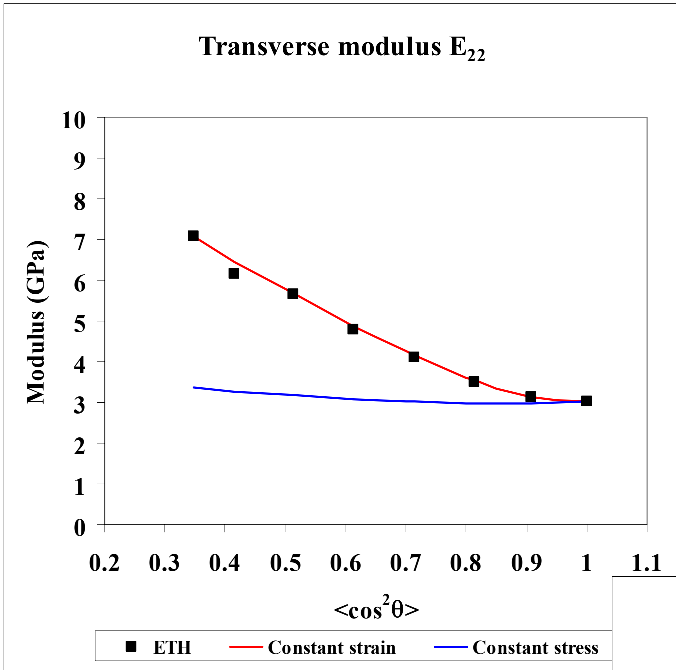




Brody H and Ward IM. Polymer Engineering and Science 1971;11:139-151.

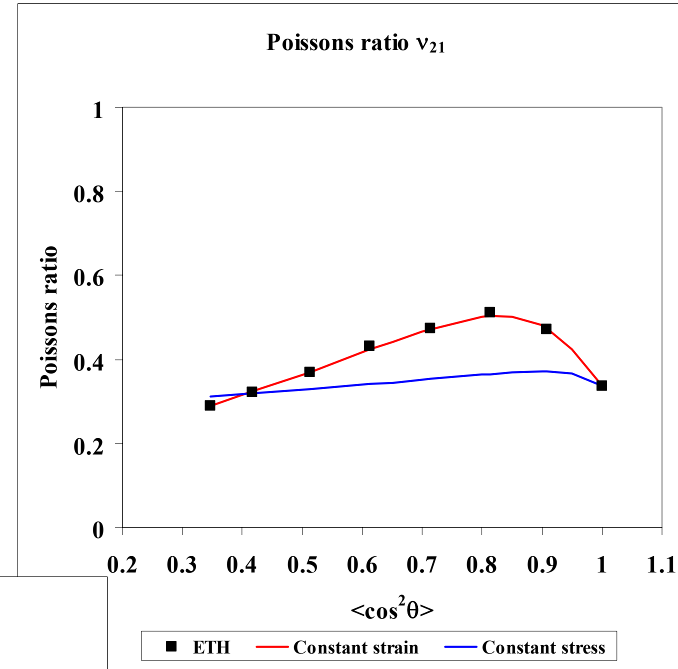
C.W. Camacho and C.L. Tucker III Polymer Composites 1990, 11, 229-239.

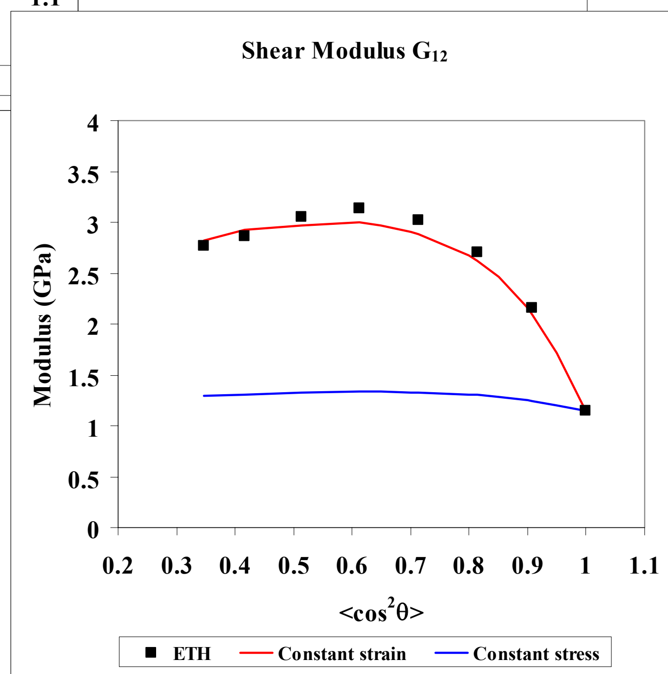
ANISOTROPIC FIBRE/ISOTROPIC MATRIX

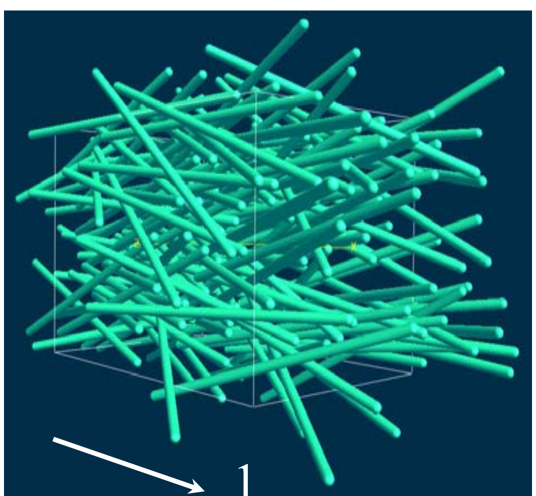


Carbon fibres/PP

E_{11} Carbon 370GPa
α_1 Carbon $-1.3e^{-6}$ K^{-1}
E_{11} PP 2.28GPa
α_1 PP $117e^{-6}$ K^{-1}







The best approach determining the aggregate properties is to use the tensor averaging approach and a constant strain prediction

ANISOTROPIC FIBRE

+

ANISOTROPIC MATRIX

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SAMPLES AND MATERIALS

	Description	Grade	Fibre	Matrix	Weight fraction
1	Carbon fibre filled Nylon	Solvay IXEF 300/6/9019	Anisotropic	Isotropic	30%
2	Unfilled LCP	Hoechst Celanese Ticona B950		Anisotropic	
3	Glass fibre filled LCP	Hoechst Celanese Ticona B130	Isotropic	Anisotropic	30%
4	Carbon fibre filled LCP		Anisotropic	Anisotropic	30%

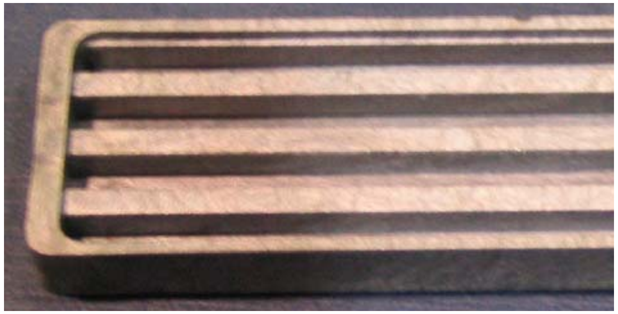
Injection moulded dumbbells made by the University of Minho

Materials 1,2,3,4

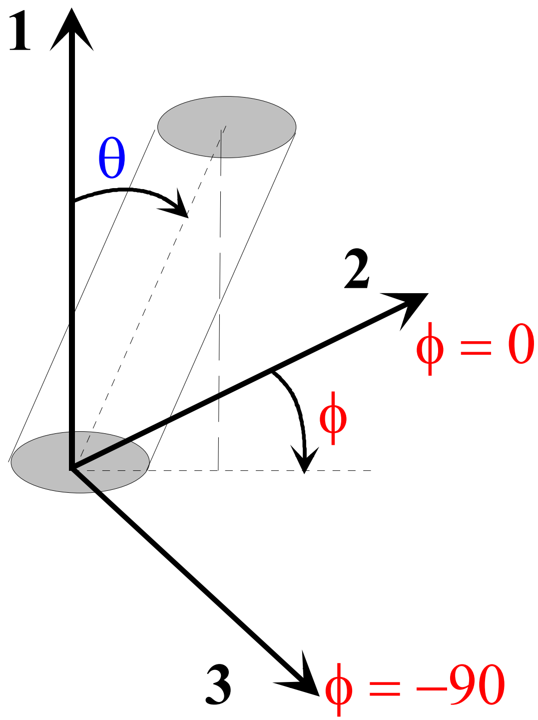
Injection moulded demonstrator component made by the University of Bradford

Material 4

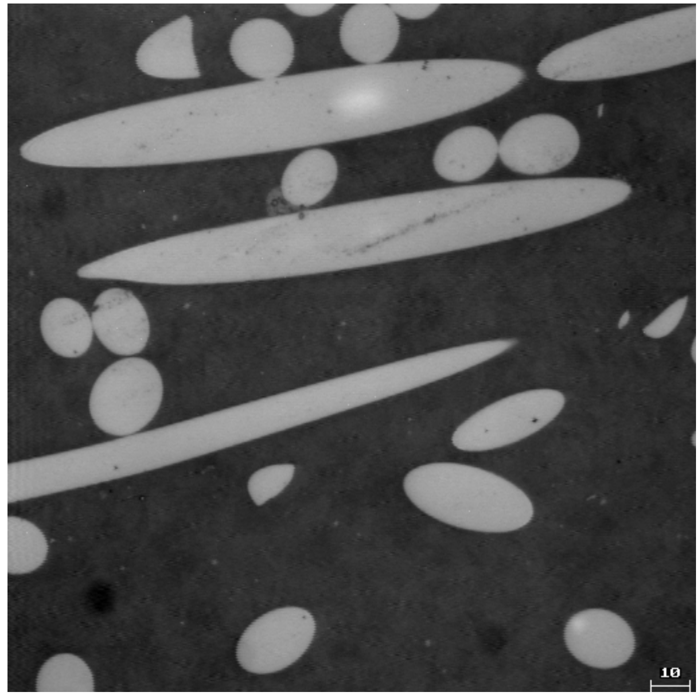
Picture of dumbbell



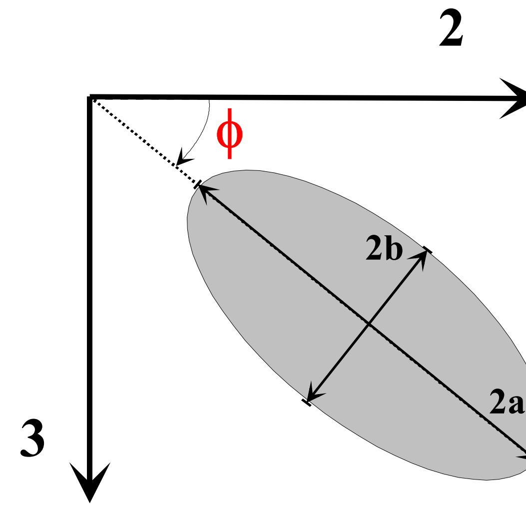
MEASURING FIBRE ORIENTATION



Definition of the orientation angles θ and φ



Best technique for measuring fibre orientation (when fibre diameters ~μm's) is from polished 2D sections taken from the composite.



$$\theta = \cos^{-1}\left(\frac{b}{a}\right)$$

Calculation of θ and φ from the fibre elliptical footprint

RESULTS - DUMBBELL

Injection moulded dumbbell – Carbon/Nylon

		Theoretical predictions			
		Fully aligned fibres Infinite fibre length	Fully aligned fibres AR=25 (measured)	Actual alignment AR = 25	Experimentally measured
E_{11}	GPa	49.9	25.8	**21.8**	**23.9**
E_{22}	GPa	3.24	3.21	**4.15**	**3.60**
α_1	$X\ 10^{-6}\ K^{-1}$	1.92	4.56	**7.25**	**5.50**
α_2	$X\ 10^{-6}\ K^{-1}$	80.7	79.6	**67.4**	**60.0**

Volume fraction	**0.21**
Aspect ratio	**25**
$<\cos^2\theta>$	**0.856**
$<\cos^4\theta>$	**0.820**

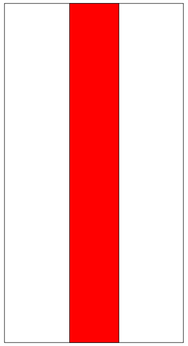
Dumbbells are transversely isotropic

- A full description of the carbon fibre properties is difficult to obtain.
- Within these constraints the agreement is excellent.
- The correction for finite length is more important than for misalignment.

RESULTS - DUMBBELL

Injection moulded dumbbell – Glass/LCP

Predictions of the fully aligned unit			
		Analytical	FE
E_{11}	GPa	**33.9**	**33.8**
E_{22}	GPa	**2.01**	**2.34**
ν_{12}		**0.427**	**0.421**
ν_{23}		**0.686**	**0.642**
G_{12}	GPa	**1.63**	**1.90**
α_1	$\times 10^{-6}$ K^{-1}	**-1.04**	**-0.9**
α_2	$\times 10^{-6}$ K^{-1}	**63.2**	**61.9**

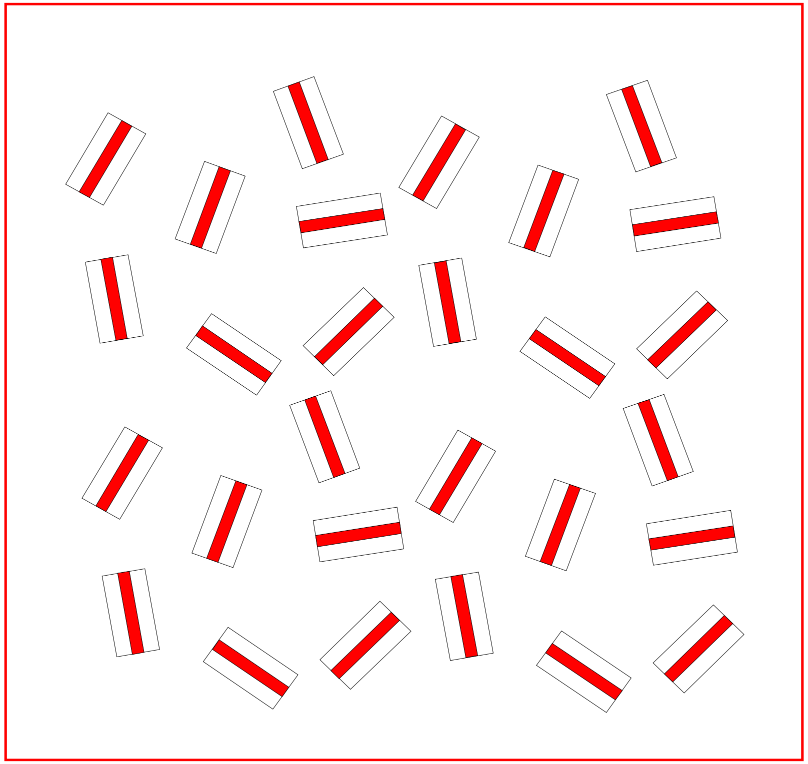


- Confirms analytical approach gives excellent agreement with FE predictions

T. Mura, *Mechanics of Elastic and Inelastic Solids*. **1982**, The Hague: Nijhoff.

RESULTS - DUMBBELL

Injection moulded dumbbell – Glass/LCP



Composite			
		Theory	Measured
E_{11}	GPa	29.1	25.6
E_{22}	GPa	2.86	1.95
α_1	x 10^{-6} K^{-1}	-1.20	-0.43
α_2	x 10^{-6} K^{-1}	55	60

Volume fraction	0.19
Aspect ratio	25
$\langle\cos^2\theta\rangle$	0.904
$\langle\cos^4\theta\rangle$	0.865

RESULTS - DUMBBELL

Injection moulded dumbbell – Carbon/LCP

		Fully aligned fibres Infinite fibre length	Fully aligned fibres AR=25 (measured)	Actual alignment AR = 25	Experimentally measured
E_{11}	GPa	74.6	62.7	**51.73**	**43.2**
E_{22}	GPa	2.09	2.09	**2.54**	**2.45**
α_1	$\times 10^{-6}\ K^{-1}$	-1.65	-1.89	**-5.0**	**-1.0**
α_2	$\times 10^{-6}\ K^{-1}$	60.9	61.0	**58.2**	**49.0**

Volume fraction	**0.21**
Aspect ratio	**25**
$\langle \cos^2\theta \rangle$	**0.856**
$\langle \cos^4\theta \rangle$	**0.820**

Dumbbells are transversely isotropic

- A full description of the carbon fibre properties is difficult to obtain.
- Within these constraints the agreement is excellent.
- The correction for misalignment is more important than fibre length for this material.

RESULTS – RIBBED BOX

Injection moulded dumbbell
Carbon/LCP

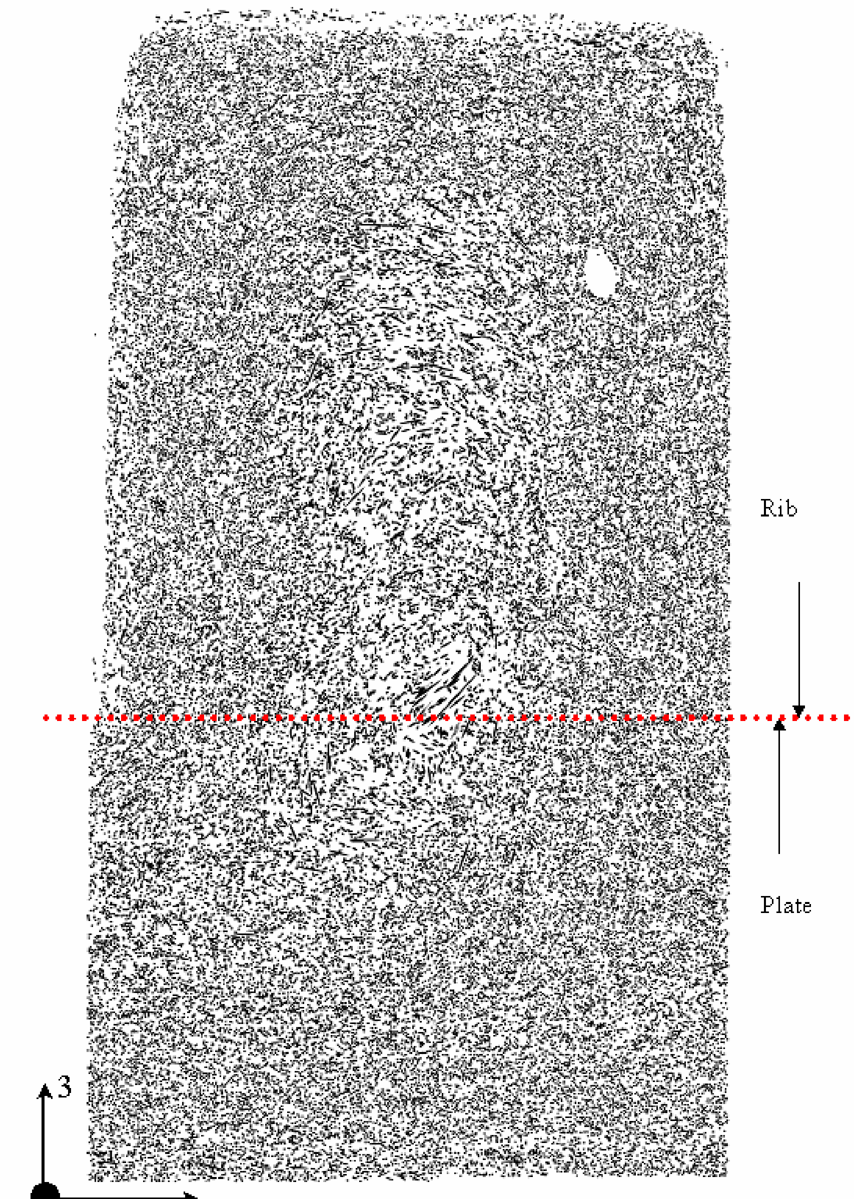
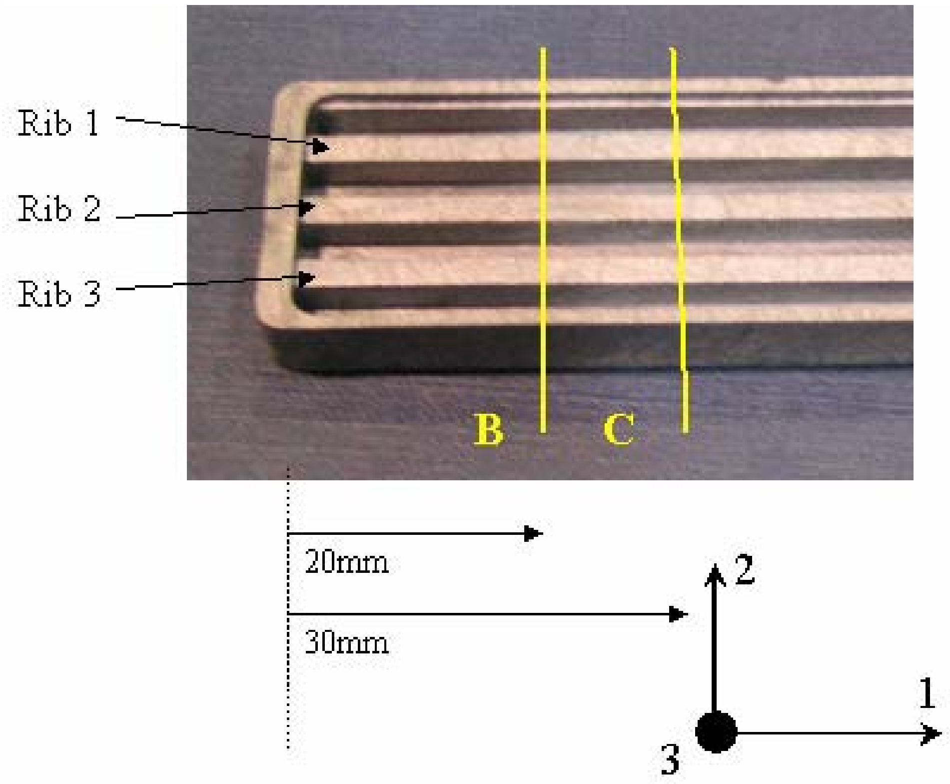


Figure 5: Rib 2: position C

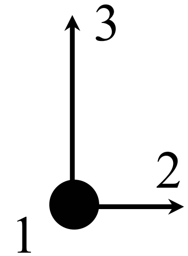


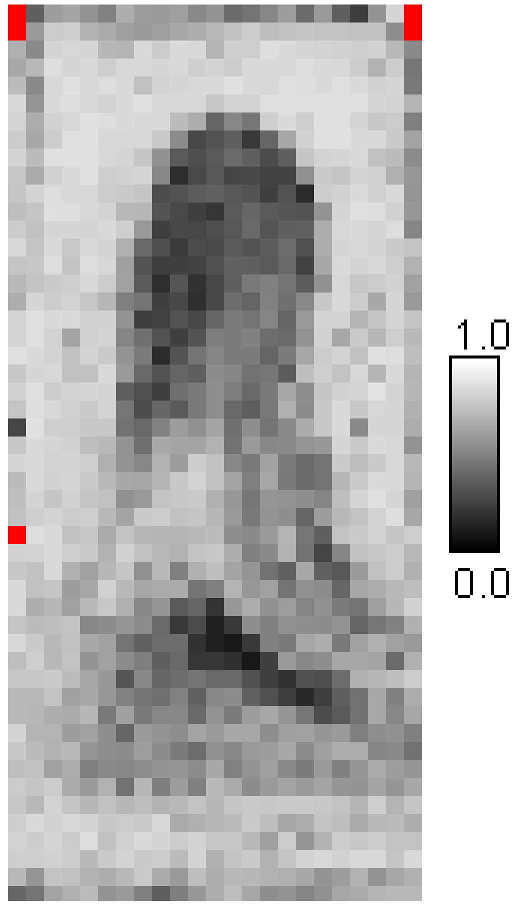
RESULTS – RIBBED BOX

Injection moulded ribbed box - Carbon/LCP

	Measured
$\cos^2\theta_1$	0.675 ± 0.029
$\cos^2\theta_2$	0.157 ± 0.020
$\cos^2\theta_3$	0.168 ± 0.028
$\sin^2\theta$	0.325 ± 0.029
$\sin^2\theta\cos^2\theta$	0.141 ± 0.004
$\cos^4\theta$	0.534 ± 0.030
$\sin^4\theta$	0.185 ± 0.028
$\cos^4\phi$	0.404 ± 0.033
$\text{Cos}^2\phi$	0.516 ± 0.032
$\sin^4\theta\cos^4\phi$	0.075 ± 0.021
$\sin^2\theta\cos^2\phi$	0.168 ± 0.028
$\sin^4\theta\cos^2\phi$	0.096 ± 0.023
$\sin^2\theta\cos^4\phi$	0.132 ± 0.026

Results averaged for Ribs 1,2,3 at B and C





RESULTS – RIBBED BOX

Injection moulded ribbed box - Carbon/LCP

			Best analytical	
		Measured	**Matrix = fibre orientation**	**Isotropic matrix orientation**
E_{11}	GPa	**25 ± 2**	**29.7 ± 1.7**	**24.2 ± 1.4**
α_1	x 10^{-6} K^{-1}	**-0.9 ± 1.8**	**-5.02 ± 0.25**	**1.25 ± 0.1**
α_2	x 10^{-6} K^{-1}	**52 ± 3**	**37.5 ± 1.9**	**31.9 ± 1.6**

Volume fraction	0.21
Aspect ratio	40.2

- Longitudinal stiffness and thermal expansion best predicted by an isotropic LCP matrix and misoriented fibres for the rib.
- Even better agreement could be possible if the matrix orientation was measured directly by X ray scattering.

MODELLING STRATEGY

		UNIT		AGGREGATE	
Fibre	Matrix	Elastic	Thermal Expansion	Elastic	Thermal expansion
Isotropic Glass	Isotropic	Qui and Weng Eshelby	Christensen	Camacho + Tucker	Camacho + Tucker
Anisotropic Carbon	Isotropic	Qui and Weng Eshelby	Christensen	Camacho + Tucker	Camacho + Tucker
Isotropic Glass	Anisotropic LCP	Qui and Weng Mura	Christensen	Camacho + Tucker	Camacho + Tucker
Anisotropic Carbon	Anisotropic LCP	Qui and Weng Mura	Christensen	Camacho + Tucker	Camacho + Tucker

Y. P. Qiu, G. J. Weng, *J. Engng. Sci.* **1990**, *28*, 1121.

T. Mura, *Mechanics of Elastic and Inelastic Solids*. **1982**, The Hague: Nijhoff

R.M. Christensen, *Mechanics of Composite Materials*, Krieger Publishing Company, Mala-bar, Florida, **1991**

C.W. Camacho and C.L. Tucker III, Polymer Composites **1990,** 11, 229-239.