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School of Chemical Technology

CHEM-E2200: Polymer blends and composites

Fibre architecture and principles of reinforcement

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Outline

- Fibre 'architecture'
- Volume fraction and the rule of mixtures
- Principle of load sharing and reinforcement
- Long or short? The effect of reinforcement geometry on elastic stress transfer and reinforcement processes

Reinforcement architecture
('fibre architecture' or microstructure)

Microstructure: the reinforcement architecture

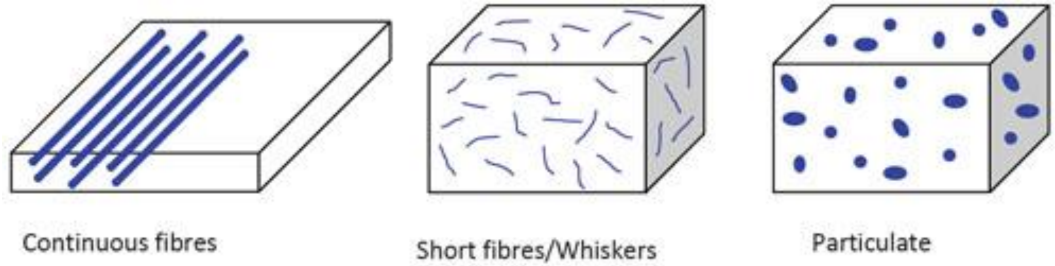
The term reinforcement (fibre) **architecture** includes:

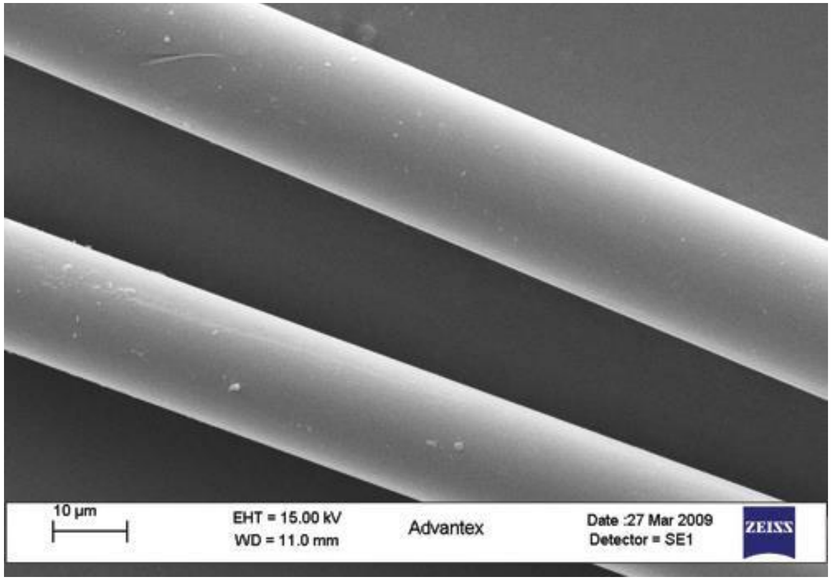
- The **geometry** of the reinforcement (aspect ratio, morphology)
- The **volume** fraction of the reinforcement
- The **orientation** of the reinforcement with respect to applied loads
- The **packing arrangement** of the reinforcement (also related to the orientation) – woven, non-woven textiles, unidirectional fabrics

Geometry, orientation, packing arrangement and volume fraction are all inter-dependent

Geometry of 'reinforcement'

- Fibre, particle or plate
- Scale: micrometre, nanometre
- Continuous or discontinuous
- 'Short' or 'long' fibre
- Aspect ratio of fibrous reinforcement: ratio of length to diameter (assuming reinforcement has a circular cross-section. Not always the case!)





E-glass fibre
(Source: Owens Corning Composite Materials LLC)

Volume fraction

$$V_f = V_{fibre}/V_{composite}$$

V_f = fibre volume fraction
V_{fibre} = volume of fibre in composite
$V_{composite}$ = volume of composite

- One of the most important concepts in composite science
- The volume fraction of the reinforcement, frequently referred to as the "fibre volume fraction", strongly affects many composite properties
- Varies from a "few" per cent (<10%) to up to around 70% (above this value, the reinforcement will be in contact and so the matrix cannot completely surround the reinforcement)

Packing arrangement and volume fraction

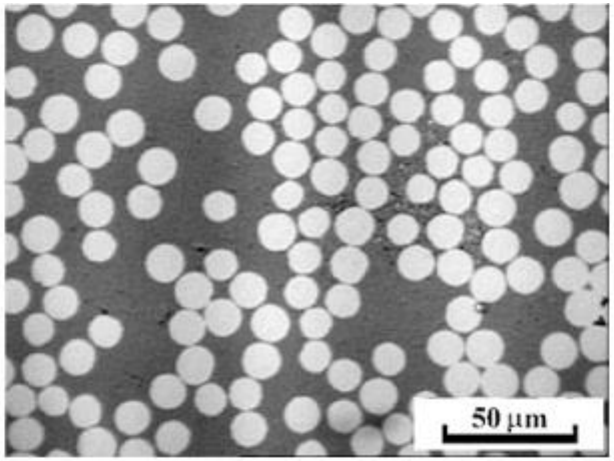
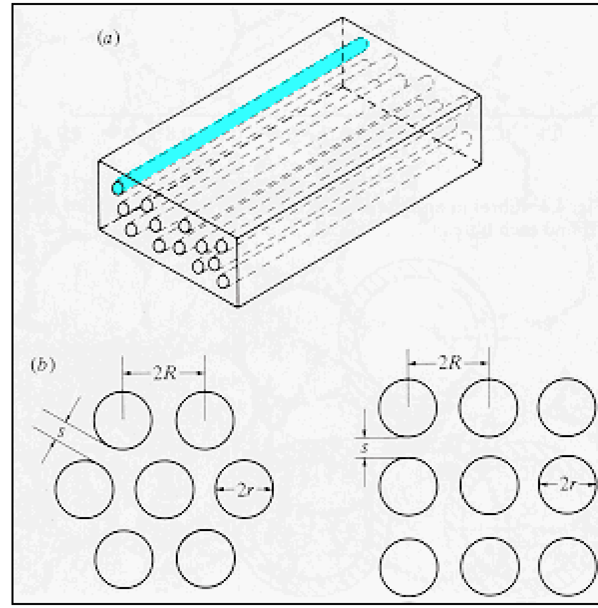


Figure 2. (*a*) Overall aspect of the microstructure of the composites, showing a regular fiber spacing and low void content; (*b*) Detail of the fiber distribution inside a tow.

(Source: de Morais et al, 2003)



(Source: Hull and Clyne 1992)

Circular cross-sectional fibres:

- Upper limit of volume faction when fibres just touch (we assume a continuous matrix)
- Square or hexagonal array
- Theoretical upper limit: 78,5% (square); 90,7% (hexagonal)
- Unlikely in real-life applications (60% upper limit?)
- BUT, this is for UD composites: is this what is required?

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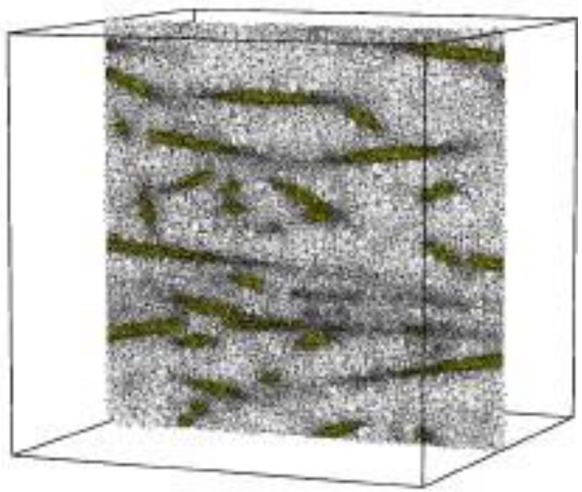
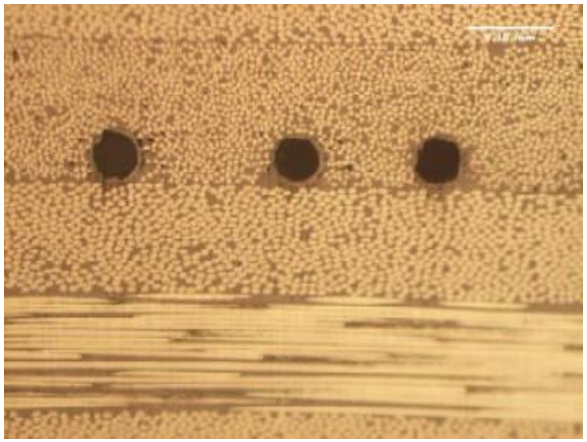
Effect of fibre architecture on volume fraction

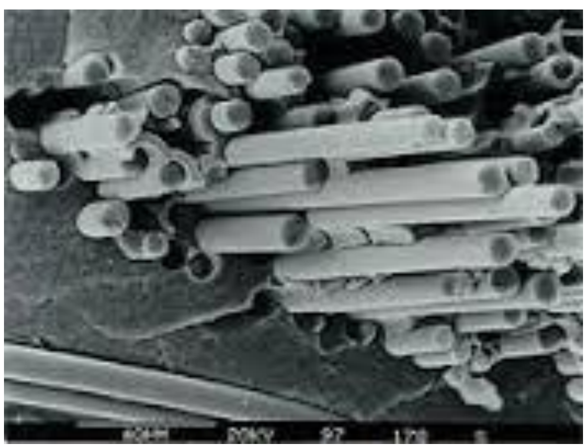
- 3-D volumes do not pack to high volume fractions
- **<u>To obtain high volume fractions, organised packing arrangements are needed</u>**



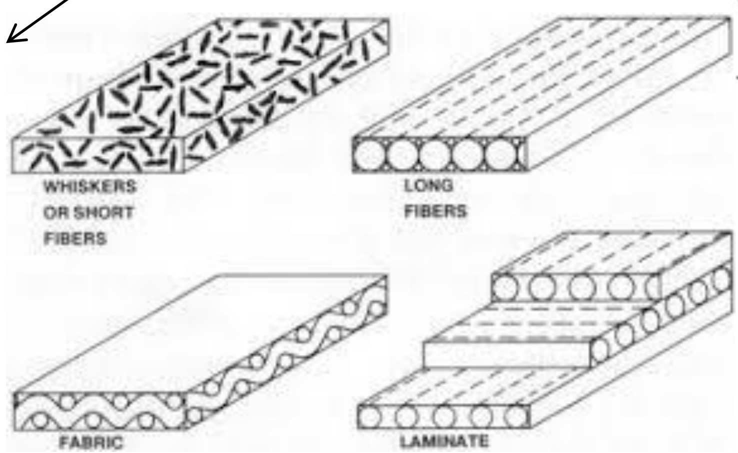
Computer model consisting of 150 fibres with an aspect ratio of 37. Volume fraction 8% (Source: ETH Zurich: http://www.mat.ethz.ch/about_us/material_world/success_stories/numerical_simulation)

Microstructures of natural and synthetic composites

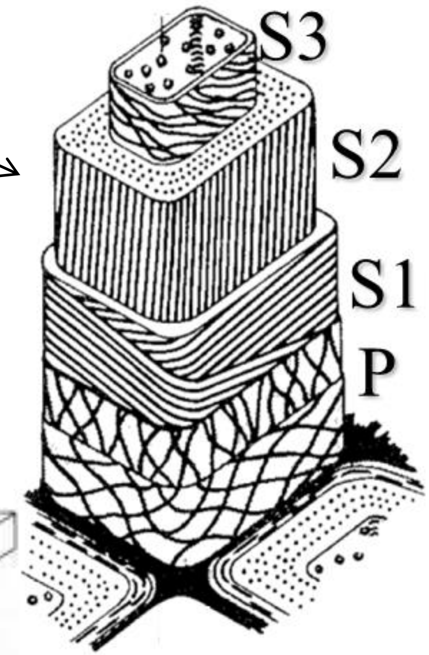




Manmade laminates



Wood fibre



Laminate examples

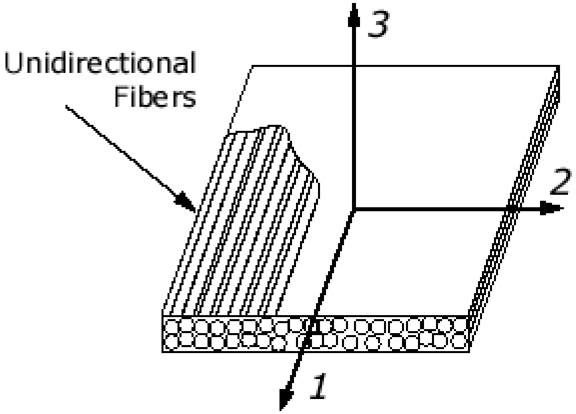
Fibre architecture - orientation

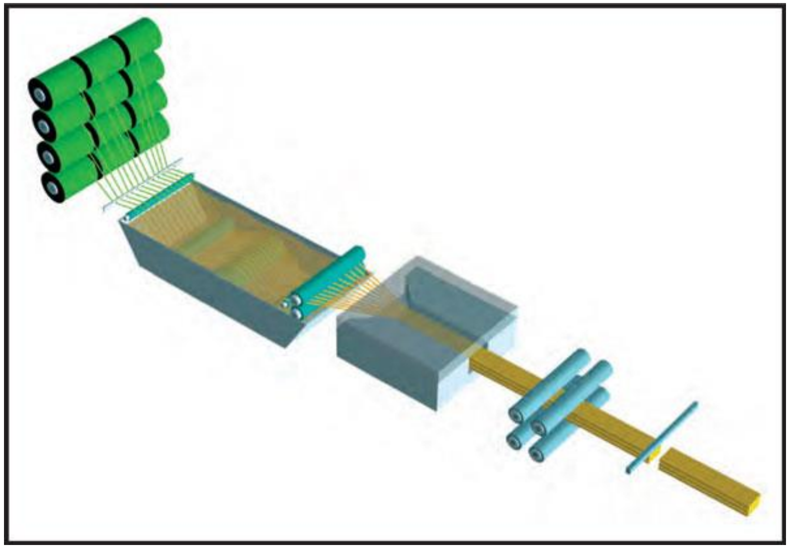
1. **Unidirectional** – UD (all fibres are aligned with the same orientation)
2. **Cross-ply** laminates (similar to plywood) where alternate UD plies are perpendicular to each other
3. **Multi-directional** laminate structures where **alternate plies** are at different orientation (e.g. at 45^{o} to the adjacent ply)
4. **Bi-directional woven structures** (many different weave types)
5. **Planar random chopped strand mat** – C.S.M. (almost a random orientation of fibre in one plane (similar to paper)
6. **3-D random** arrangement

Volume fraction and mechanical properties increase.
BUT so does the degree of anisotropy

- 1-4 long fibre; 5 'long' short fibre; 6 short fibre randomly oriented

Unidirectional





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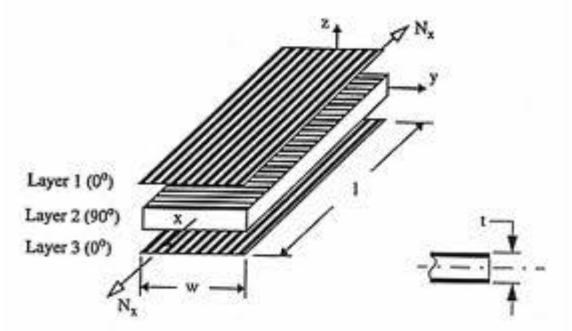
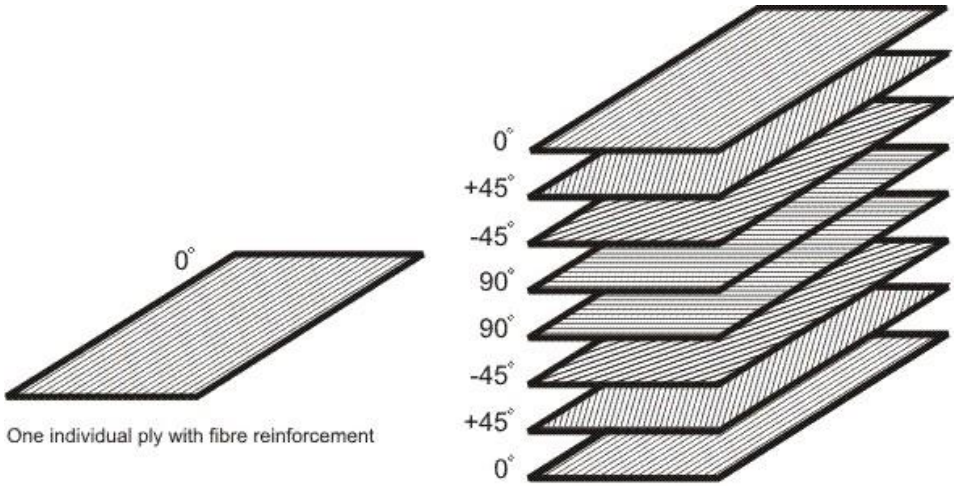
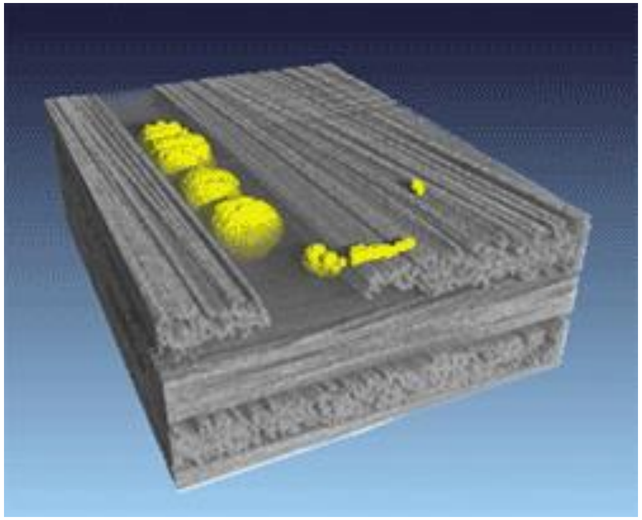
Cross-/multi-ply

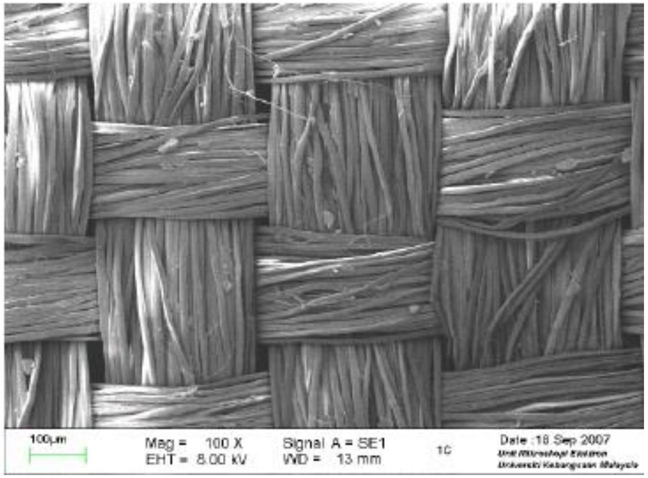


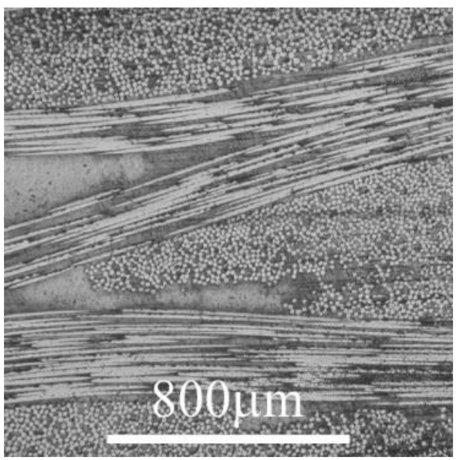




CLT: cross-laminated timber

Woven-structures





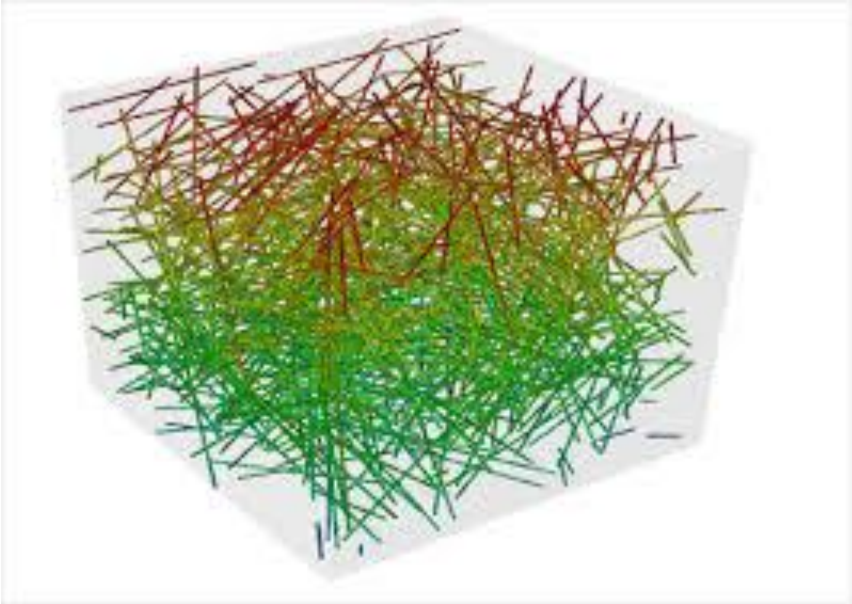
- ‘Resin rich’ pockets in between weave
- Non-optimal arrangement due to ‘crimp’ in textile

Source: Department of Materials Science and Metallurgy, University of Cambridge

2-D and 3-D random

Above: Chopped Strand Mat (CSM) reinforcement. A 2-D random arrangement of fibres

3-D random fibre arrangement



Packing arrangement

- In UD composites the volume fraction (V_f) is theoretically up to 90%, but in practice the maximum is generally around 60%
- Cross-ply structure – layers of UD reinforcement layers (similar V_f to normal UD composites)
- Woven materials, lower V_f due to the ‘crimp’ in the textile structure, therefore the fibres cannot conform as easily
- CSM: Chopped Strand Mat. Lower V_f still as the fibres cannot align as easily
- 3-D lowest since the fibres need to occupy space three dimensionally

Long fibre textiles

- There is a large range of reinforcement types available for manmade fibres.
- For synthetic fibre, textiles include:
  - Unidirectional
  - Woven
  - Multi-axial
  - Other/random
- See: e.g. https://www.owenscorning.com/composites/ for further information

Principles of reinforcement

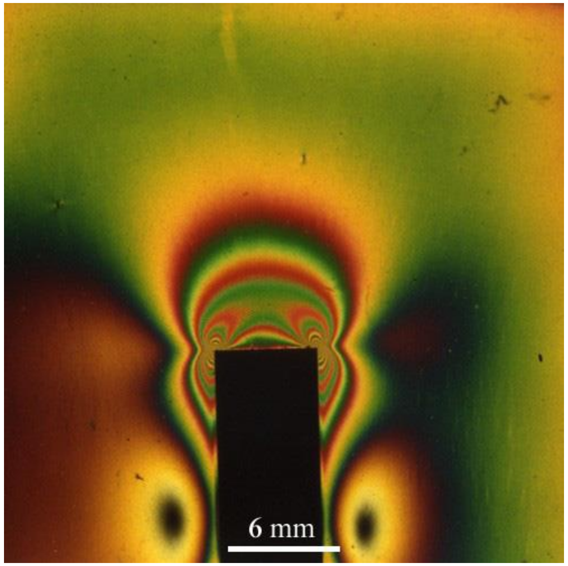
Micromechanical model: single filament/fibre composite (SFC)

- Consider a simple, "ideal" composite (Fig. 1), consisting of a single element of reinforcement (fibre), of finite length, uniform geometry and having homogeneous properties embedded in a matrix material
- Single Filament/Fibre Composites (SFC) are often used in the study of composite micromechanics

Fig. 1: Single filament composite

Load sharing

Whilst stress may vary sharply from point to point along the fibre (particularly in short fibres), the proportion of the external load carried by each of the individual constituents can be assessed by volume-averaging the loads associated within them….



DoITPoMS, University of Cambridge

Rule of Mixtures

- The volume weighted average of the properties of each constituent comprising the composite can be used to describe a number of material properties
- In general terms, this relationship is known as the "Rule of Mixtures" and may be expressed as follows:

$$X_c = V_f X_f + V_m X_m$$

X_c	is the composite property
X_f	is the fibre property
X_m	is the matrix property
V_m	is the volume fraction of matrix. This is the volume of matrix in the composite as a fraction of the total volume of the composite. Assuming that the composite consists of two phases only (with no voids), V_m may be expressed alternatively as $\left(1-V_f\right)$

Load sharing

$$\sigma_c = V_f \bar{\sigma}_f + (1 - V_f)\bar{\sigma}_m$$

σ_c	is the composite applied stress
$\bar{\sigma}_f$	is the volume averaged fibre stress
$\bar{\sigma}_m$	is the volume averaged matrix stress
V_f	is the *volume fraction* of reinforcement. This is the volume of fibre present in the composite as a fraction of the total volume of the composite

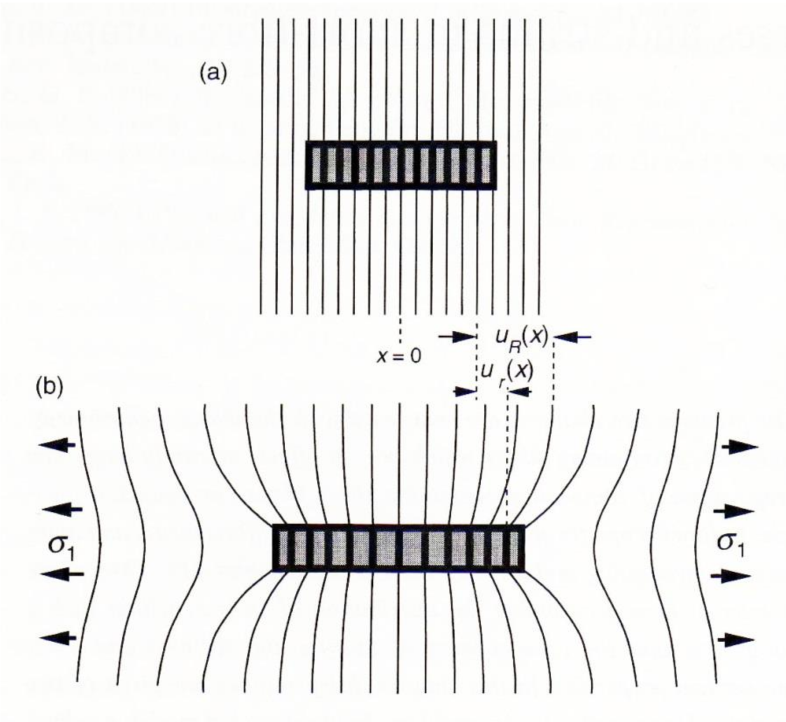
Reinforcement principles

- For a two phase composite, a certain proportion of the load will be carried by the fibre and the remainder by the matrix
- The proportion of the load carried by each constituent will depend upon the microstructural arrangement (architecture)
- The ***reinforcement may be considered to be acting efficiently if it carries a relatively large proportion of the externally applied load***
- A high reinforcing efficiency can lead to greater composite strength and stiffness, since the reinforcement is usually both stronger and stiffer than the matrix

Reinforcement processes: elastic stress transfer

- In order for the composite to support an externally applied load, it is a requirement that the loads are transmitted to the reinforcement
- This is achieved through **shear stresses** that operate at the interface
- Stress transfer is influenced by:
  - The elastic properties (i.e. Young's modulus) of the constituents
  - The geometry and orientation (relative to the applied stress) of the reinforcement
- A model proposed by Cox in 1952, known as the "shear-lag" model, is often used to describe composite micromechanical behaviour

Shear-lag model: thought experiment!



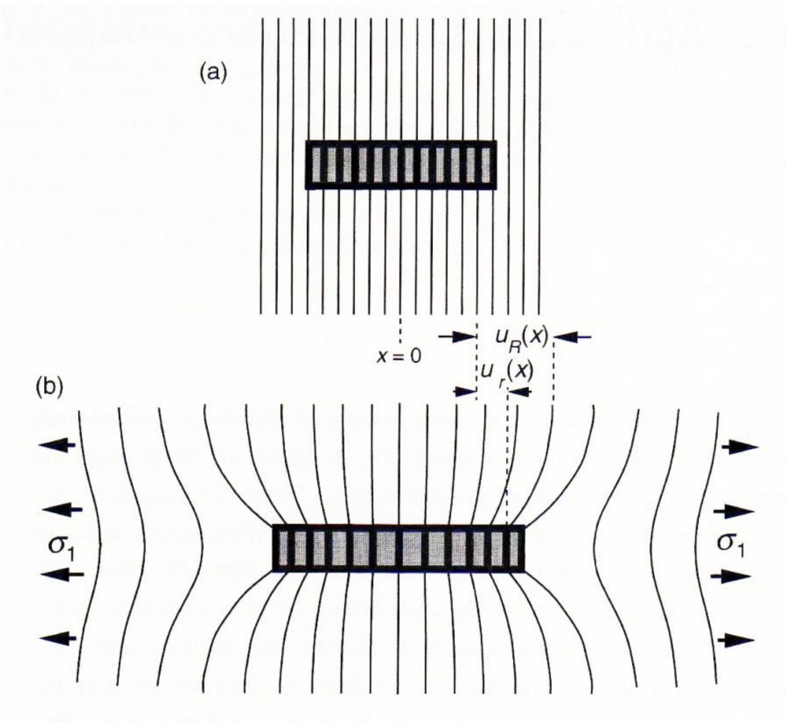
(Source: Hull & Clyne 1996)

stiff reinforcement

compliant matrix

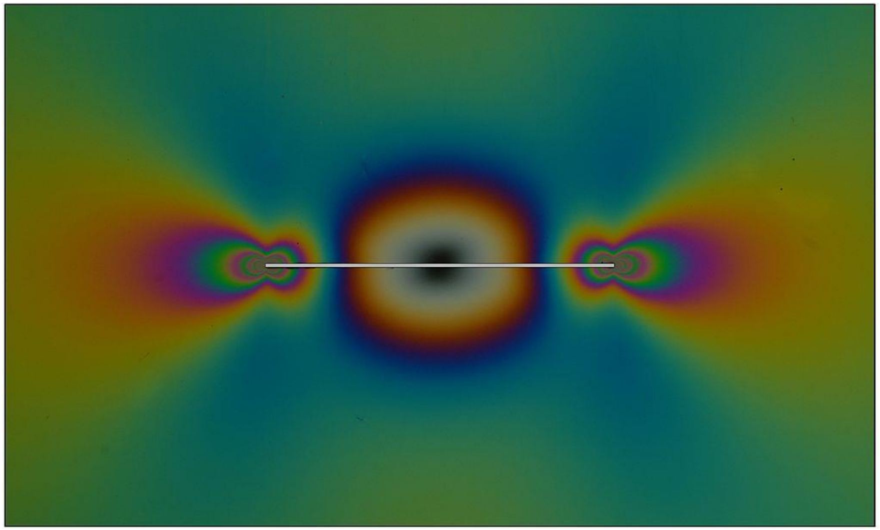
- Distortion of **compliant** matrix around **stiff** reinforcement
- Assumes a 'perfect' interface – i.e. no slippage between phases

Shear-lag model



(Source: Hull & Clyne 1996)

In a photoelastic model shear stress can be visualised as the change in optical properties



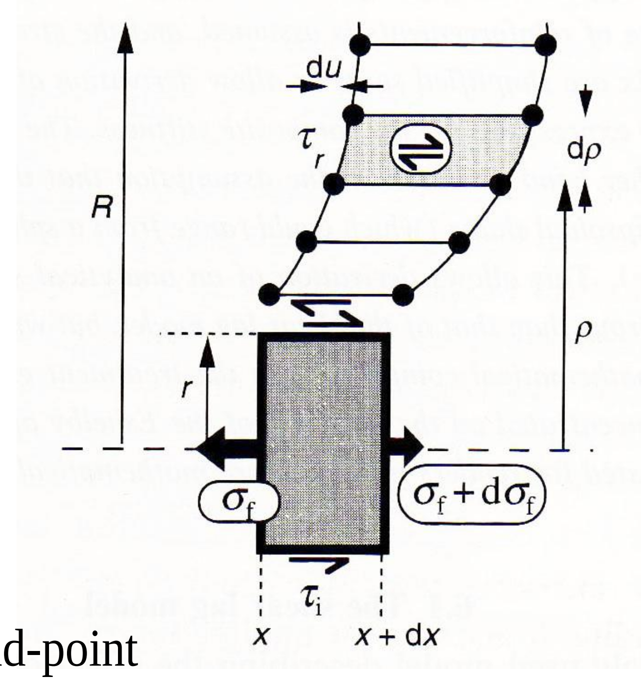
SSMG-ITALY - Laboratory for Physical Modelling of Structures and Photoelasticity (University of Trento, Italy)

Distortion of **compliant** matrix around **stiff** reinforcement

Interfacial shear stresses

- Interfacial shear stress (τ_i) operates at the interface, parallel to the fibre surface
- Using a force-balance approach it can be shown that:

$$\frac{d\sigma_f}{dx} = -\frac{2\tau_i}{r}$$



Where: x is the axial distance from the fibre mid-point

r is the fibre radius

(Source: Hull & Clyne 1996)

Variation of fibre stress along the length

- It can be shown that the axial stress distribution, due to elastic stress transfer in a fibre, may be given by:

$$\sigma_f = E_f \varepsilon_1 \left[1 - \cosh(nx/r)\,\mathrm{sech}(ns)\right]$$

E_f is the fibre Young's modulus

ε_1 is the applied composite strain

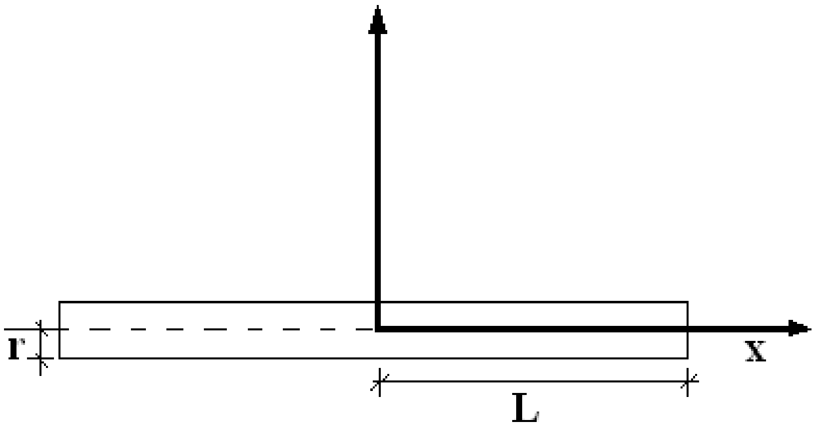
s is the fibre aspect ratio, defined as L/r (where L is the fibre half length)

n is a dimensionless constant given by:

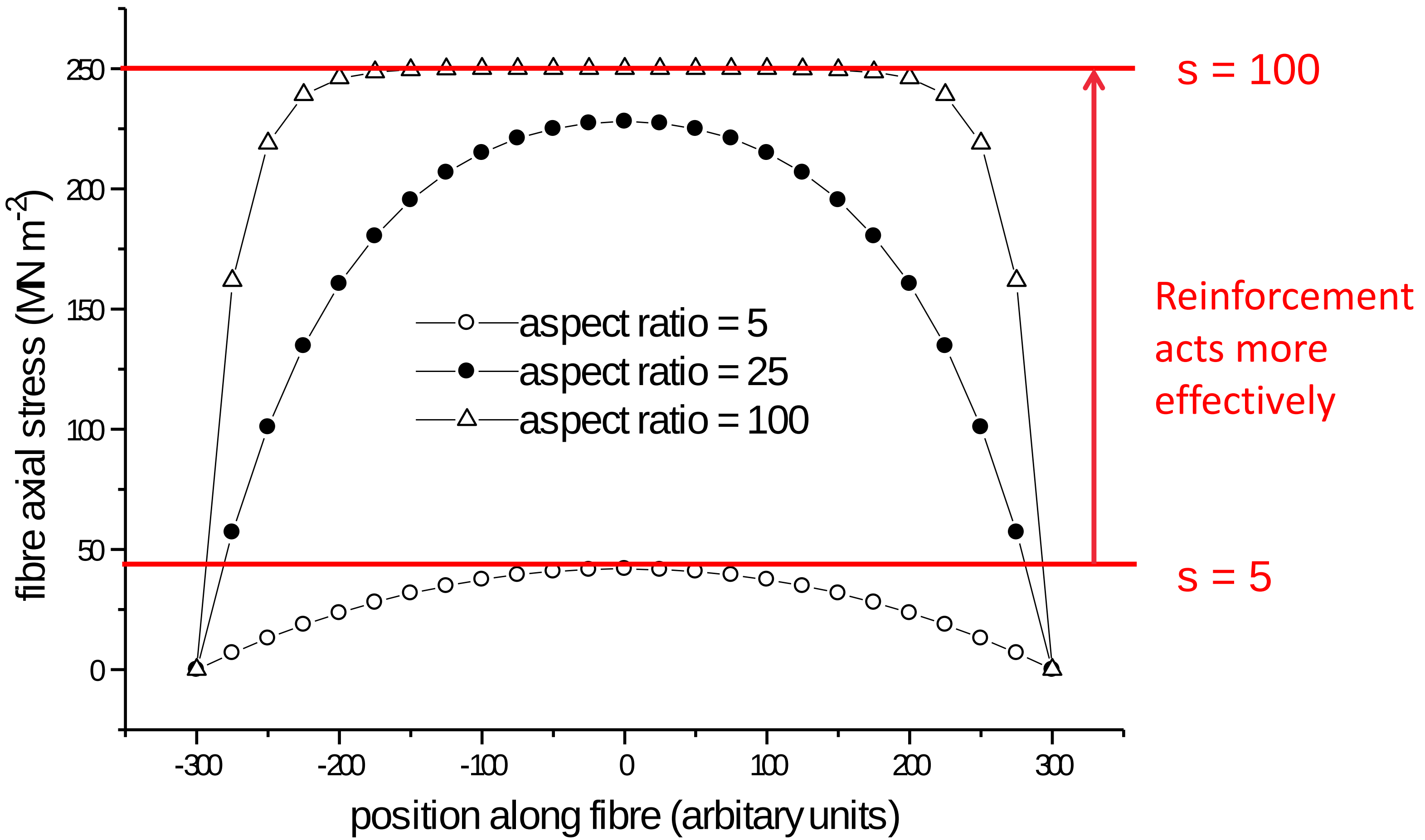
$$n = \left[\frac{2E_m}{E_f(1+\nu_m)\ln(1/V_f)}\right]^{1/2}$$

E_m is the matrix Young's modulus

ν_m is the matrix Poisson's ratio

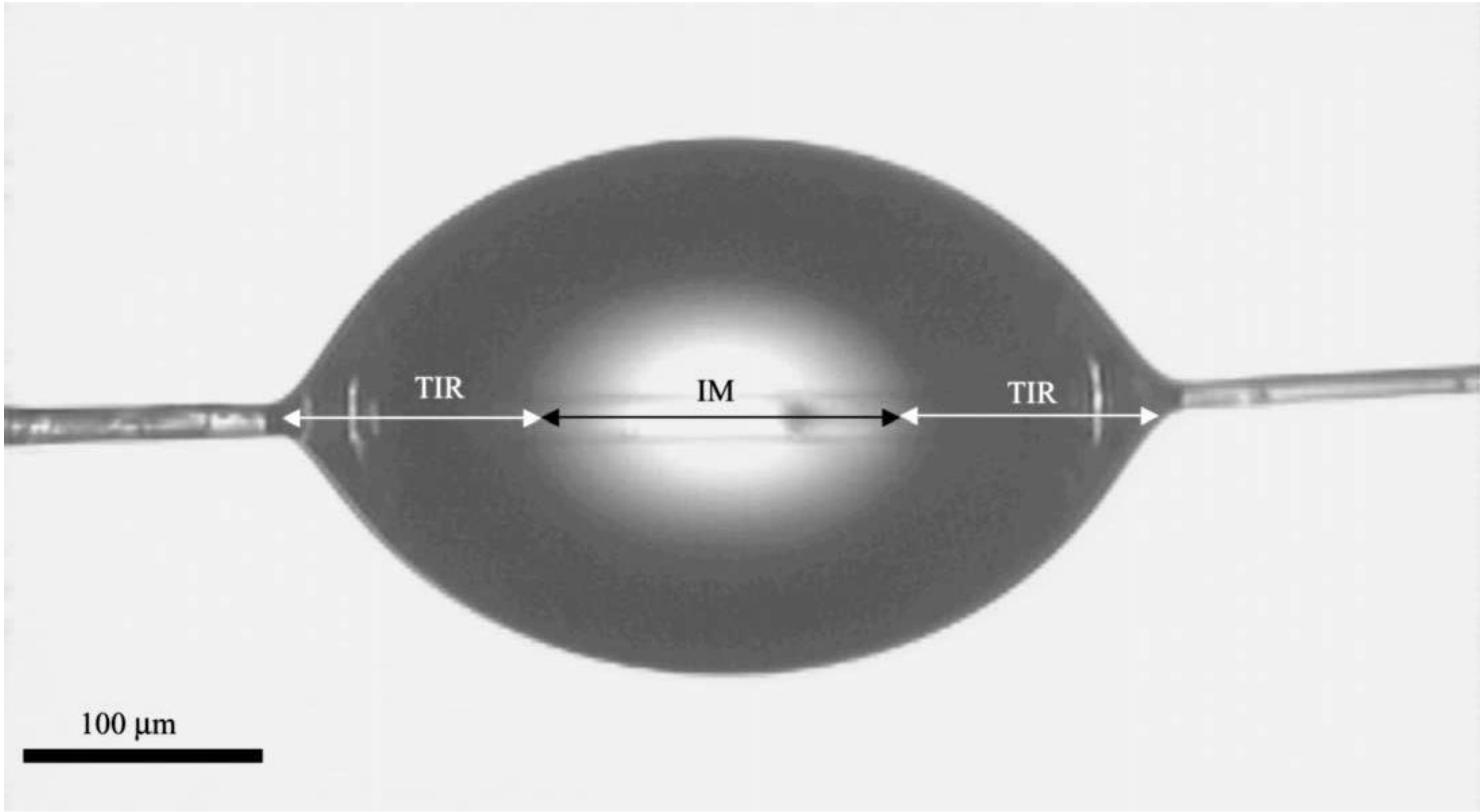


Effect of aspect ratio



Assumptions: fibre modulus: 50 GPa; matrix modulus: 3.5 GPa; axial strain: 0.5%

Experimental validation



Microdroplet test: hemp fibre embedded in epoxy

(Source: Eichhorn and Young, 2004)

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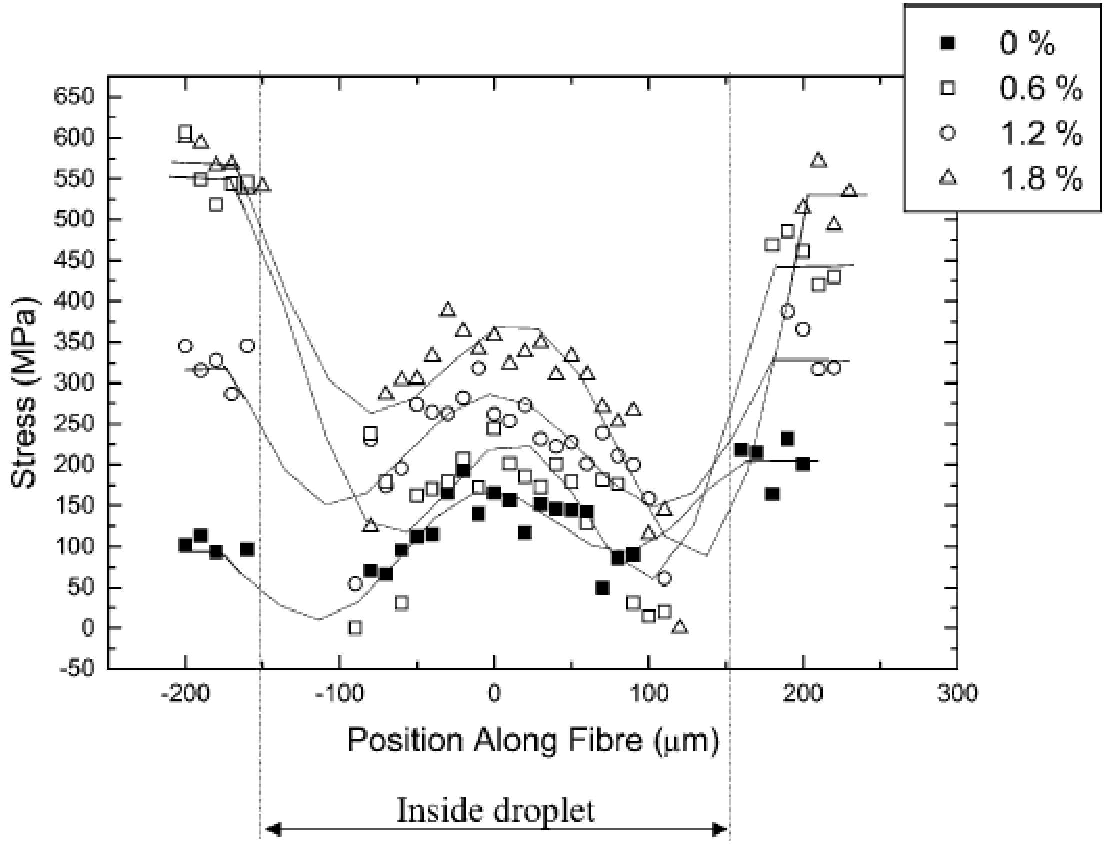
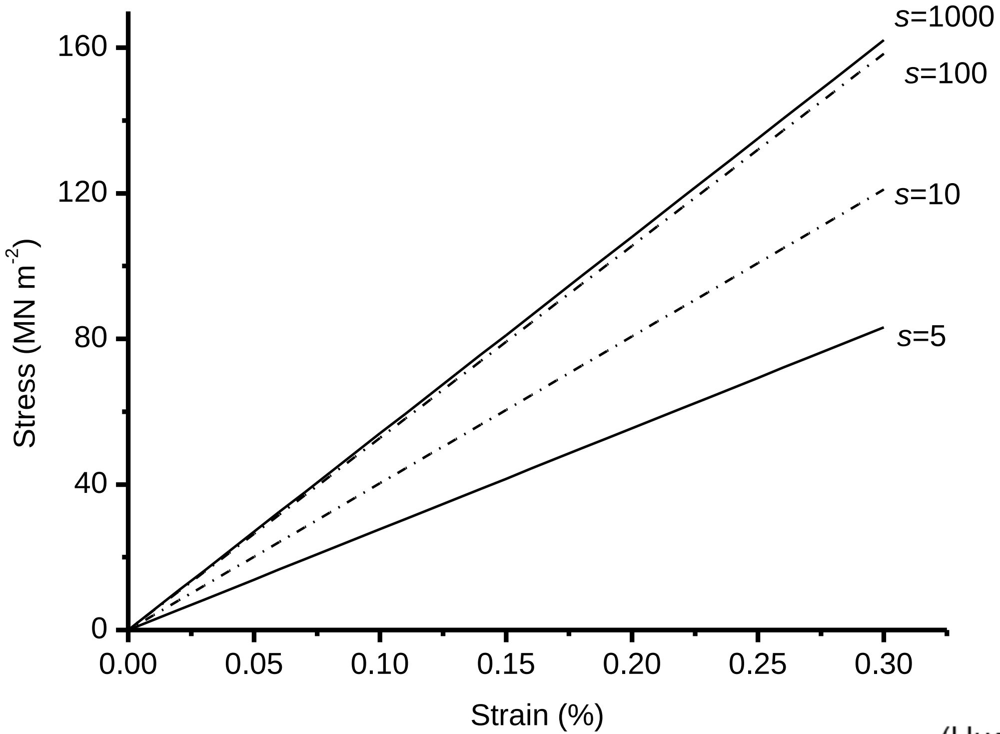
Experimental validation



Axial stress along fibre, measured using Raman spectroscopy

(Source: Eichhorn and Young, 2004)

Influence of aspect ratio on axial stiffness



(Hughes et al. 2007)

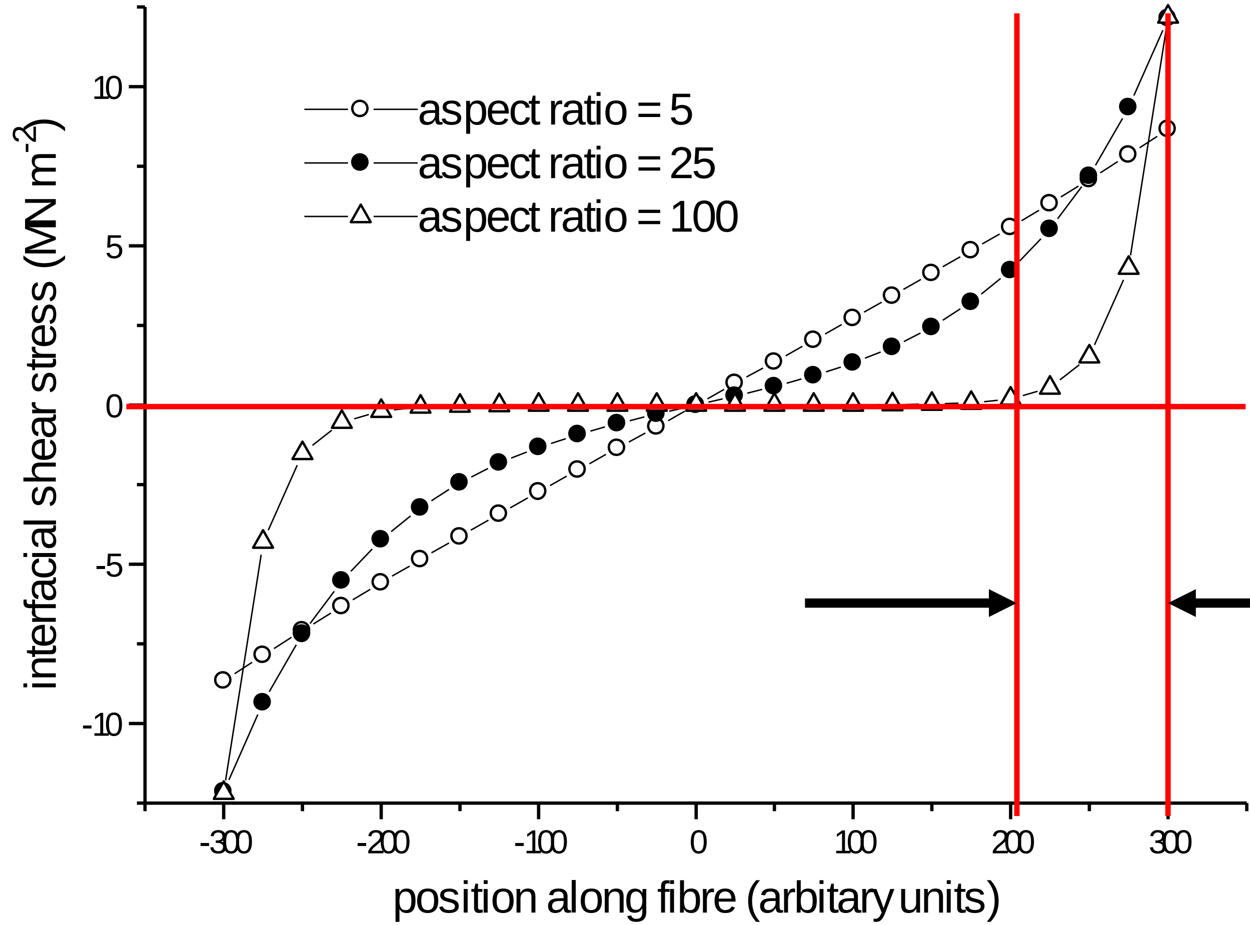
- Theoretical stress-strain curves for a polymer matrix composite containing fibres of varying aspect ratio, based on shear-lag theory
- Material parameters: fibre modulus = 50 GPa; matrix modulus = 3,5 GPa

Variation of interfacial shear stress

- It may be shown that the variation of shear stress along the fibre can be given by:

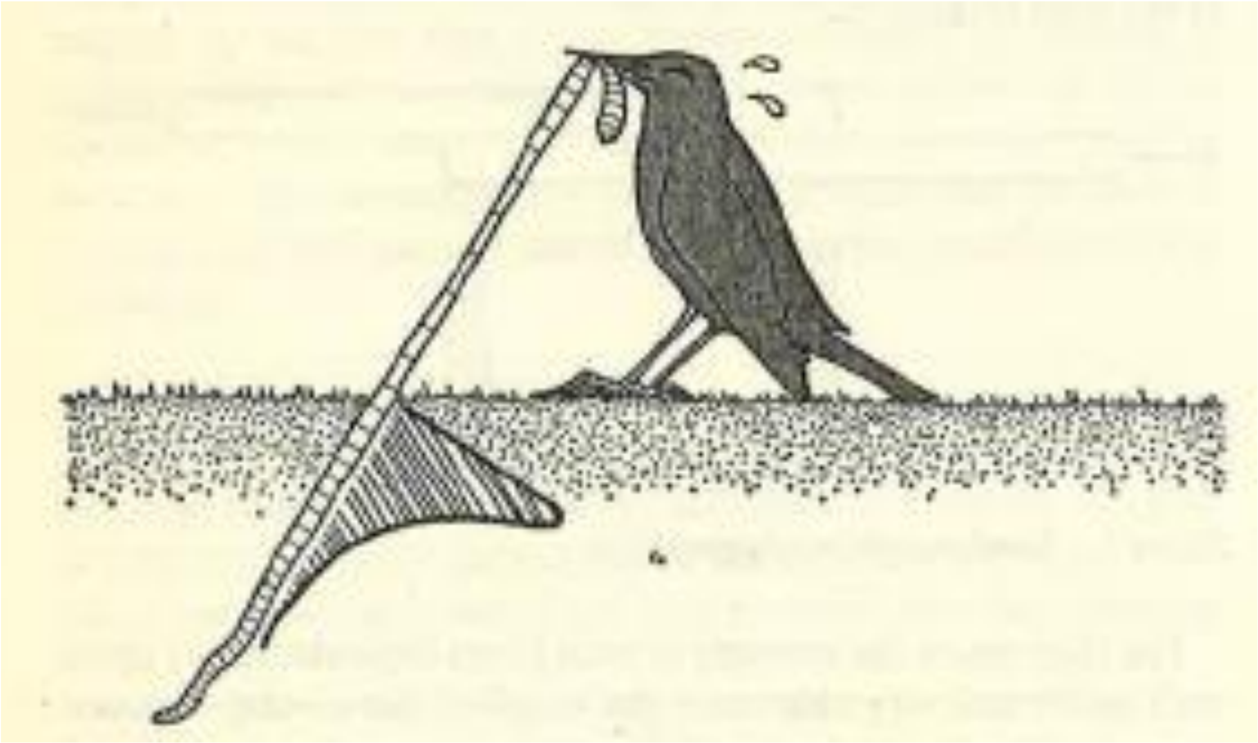
$$\tau_i = \frac{n\varepsilon_1}{2} E_f \sinh\left(\frac{nx}{r}\right) \operatorname{sech}(ns)$$

Shear stress distribution



Stress-transfer takes place here

Assumptions: fibre modulus: 50 GPa; matrix modulus: 3.5 GPa; axial strain: 0.5%



“*Thus the difficulty which a thrush has in pulling a worm out of the lawn does not depend on the length of the worm: a short worm is just a hard to extract as a long one*.”

J.E Gordon: Structures or Why Things Don’t Fall Down

“Cox-type” stress transfer

- As the aspect ratio increases, the efficiency of stress-transfer increases to a point where a “plateau” fibre stress is reached
- For a given set of fibre and matrix properties and applied strain, a maximum axial fibre stress and interfacial shear stress will be attained
- As aspect ratio increases no further axial stress in the fibre will be achieved, i.e. there is no stress transfer, except at the end of the fibre
- So, in long fibre composites, it can be assumed that fibre and matrix undergo **equal strain**, when a stress is applied parallel to the fibre axis

Literature

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