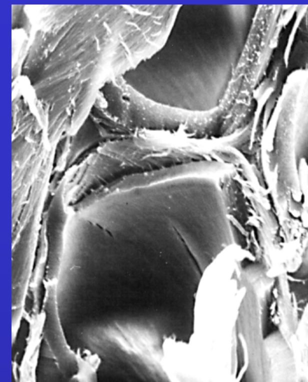
NATURAL CELLULOSE-BASED HIERARCHIES:

CONCEPTS FOR NOVEL MATERIALS AND ADDED FUNCTIONALITY

George Jeronimidis
Centre for Biomimetics
Reading University

- **Cellulose fibres from plants**
- **Advantages and limitations of cellulose fibres/nanofibres**
- **Cellulose fibres/nanofibres as reinforcement in composites**
- **Benefits of hierarchical structures**
- **Conclusions**

Sources of cellulose fibres and nanofibres



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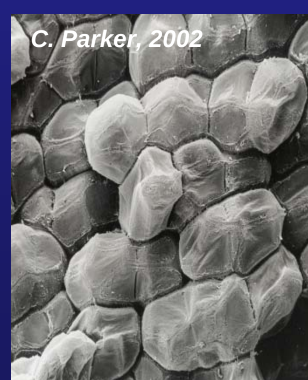
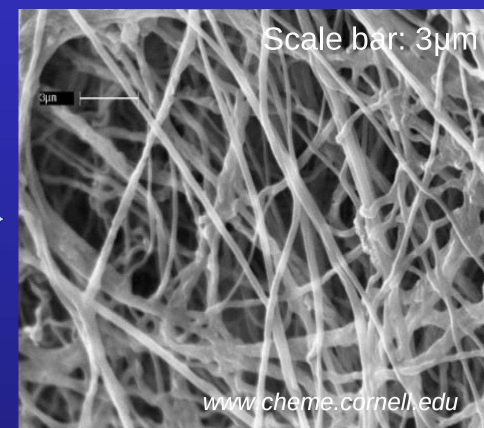
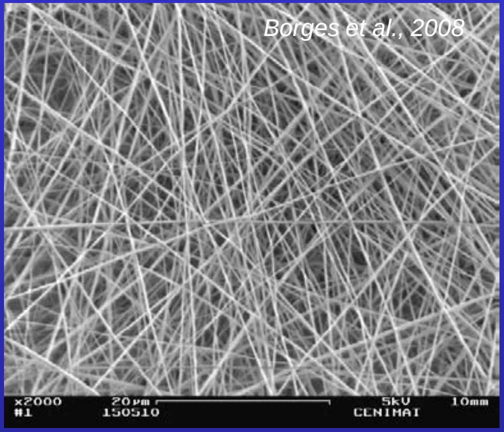
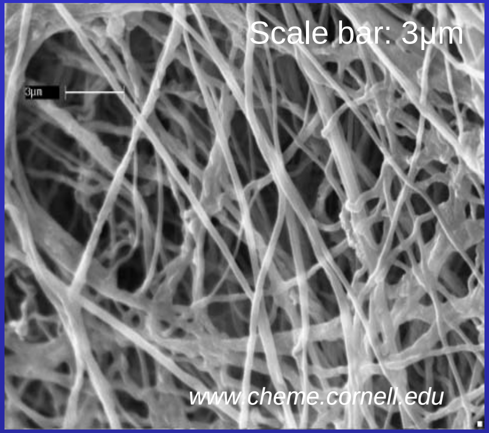


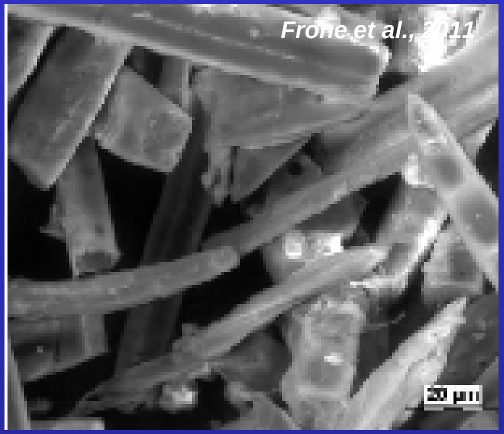


+ Bacterial Cellulose

Typical properties of cellulose nanofibres







Young's modulus (fibre direction)	134 GPa	
Tensile strength	7.5 GPa	
Density	1500 kg/m^3	
Nanofibre diameter	50 ~ 200 nm	*[Frone et al., 2011]*
Nanofibre aspect ratio (L/d)	10 ~ 30	*[Eichorn et al., 2010]*

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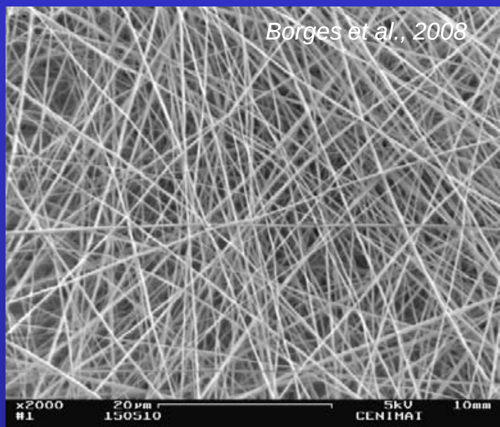

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HOW CAN THESE PROPERTIES BE EXPLOITED EFFECTIVELY ????

Advantages of cellulose nanofibres (CNF)

High modulus and high specific modulus

[compares well with glass, aramid an carbon]

High tensile strength

[theoretical strength of solids is of the order of E/10, CNF has a value of E/18]

Limitations of cellulose nanofibres

length diameter aspect ratio (L/d)

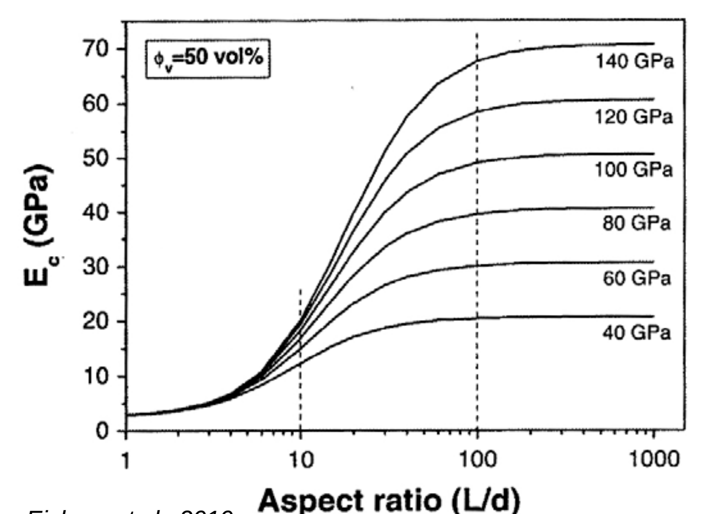
surface chemistry (compatibility with polymer matrix systems for composites)

loss of hierarchical organisation and limited control of fibre orientation (benefits of cell wall structure/density)

limited compressive strength because of fibre buckling

Length-diameter aspect ratio

$$L_i = \left(\frac{d}{\tau_y}\right)\left(\frac{E_f \sigma_c}{E_c^{continuous}}\right)$$



Eichorn et al., 2010

d = diameter

τ_y = matrix shear strength

E_f = fibre modulus

E_c = composite modulus

σ_c = composite tensile strength

Composite modulus for a unidirectional fibre composite as a function of cellulose nanofibre aspect ratio at a volume fraction of fibres of 50% (PP matrix)

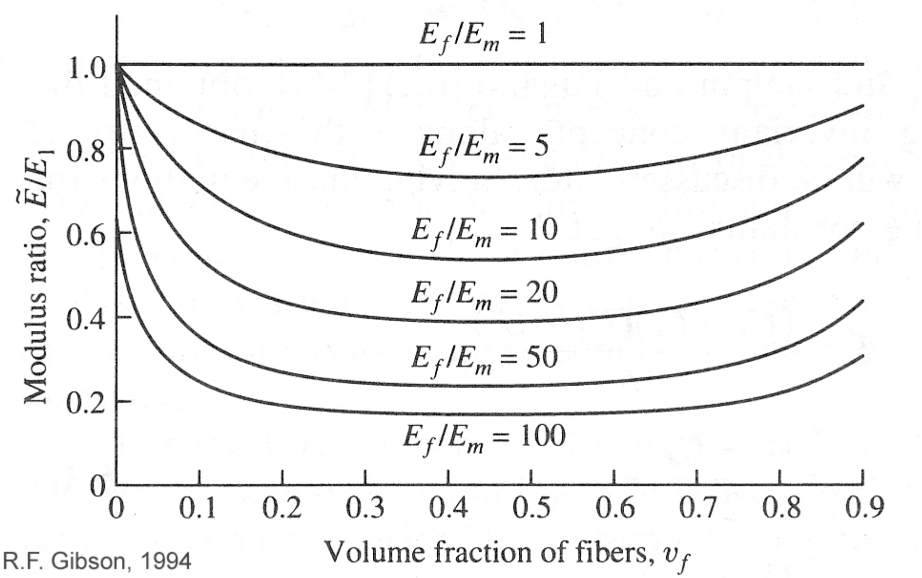
Fibre orientation

Cox Model (2D), 1952:	$\bar{E} = \frac{E_f v_f}{3}$	$\bar{G} = \frac{E_f v_f}{8}$	$\nu = \frac{1}{3}$
Cox Model (3D), 1952:	$\bar{E} = \frac{E_f v_f}{6}$	$\bar{G} = \frac{E_f v_f}{8}$	$\nu = \frac{1}{4}$
Tsai - Pgano Model (2D), 1968:	$\bar{E} = \frac{3}{8}E_1 + \frac{5}{8}E_2$	$\bar{G} = \frac{1}{8}E_1 + \frac{1}{4}E_2$	

E_f = Fibre modulus

E_1, E_2, G_{12} = Elastic and shear moduli of unidirectional discontinuous fibre composite

Fibre orientation, volume fraction and fibre/matrix modulus ratio

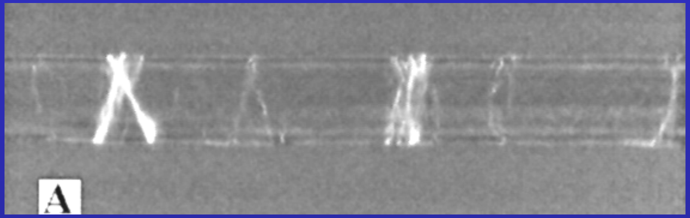


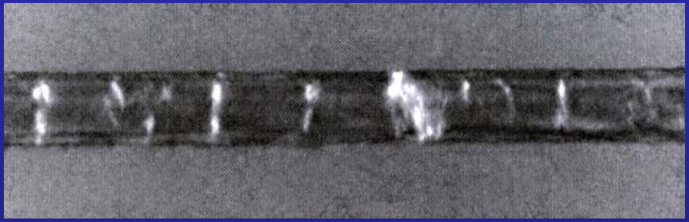
R.F. Gibson, 1994

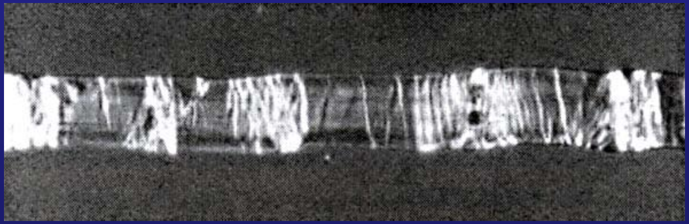
Dependence of Normalised Composite Modulus (random fibres) on fibre/matrix modulus ratio and fibre volume fraction.

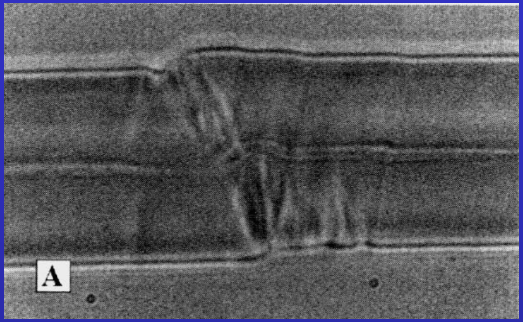
E_1 is the Young's modulus of a continuous unidirectional fibre composite in the fibre direction

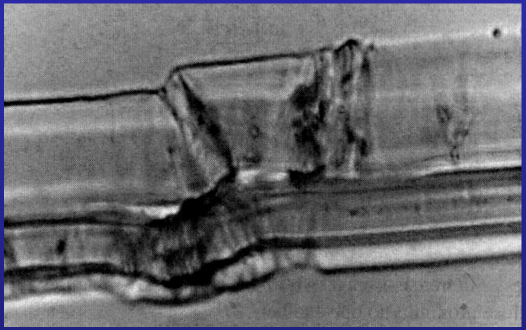
Fibre buckling in plant cell walls

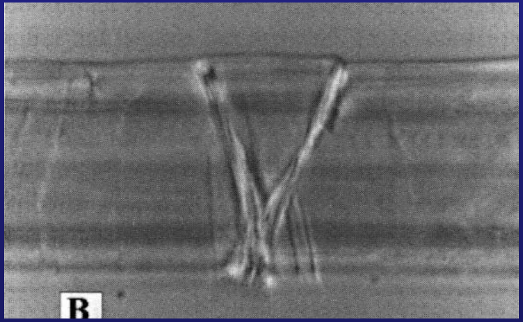


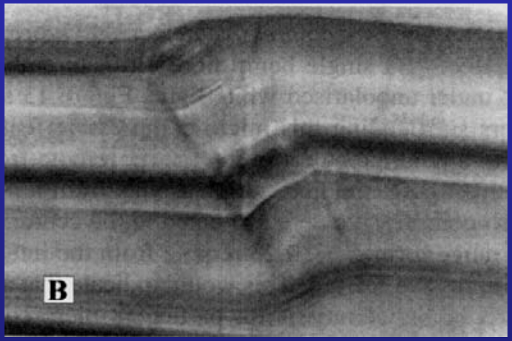










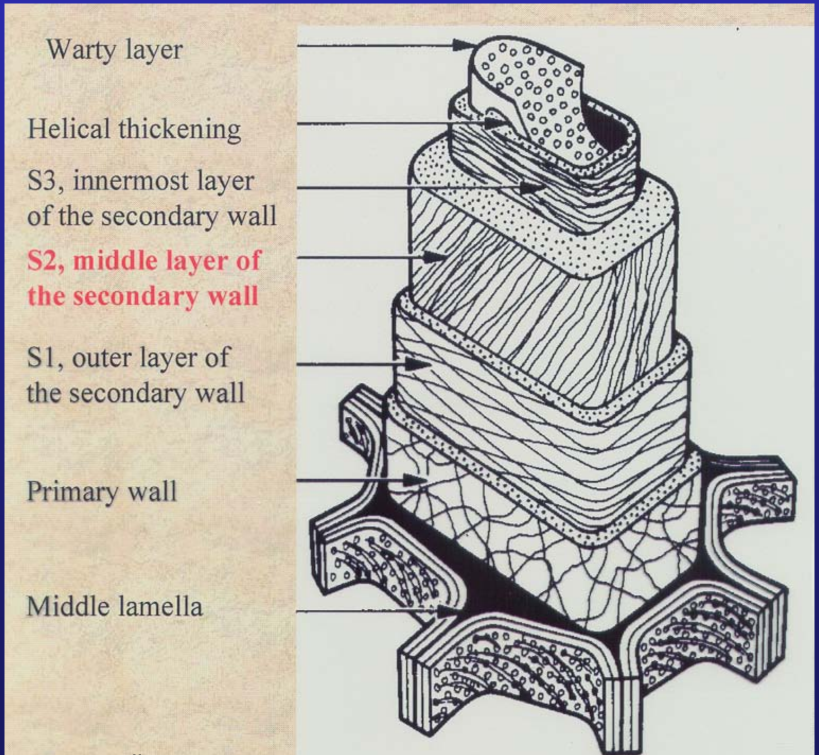


Hugues (1979)

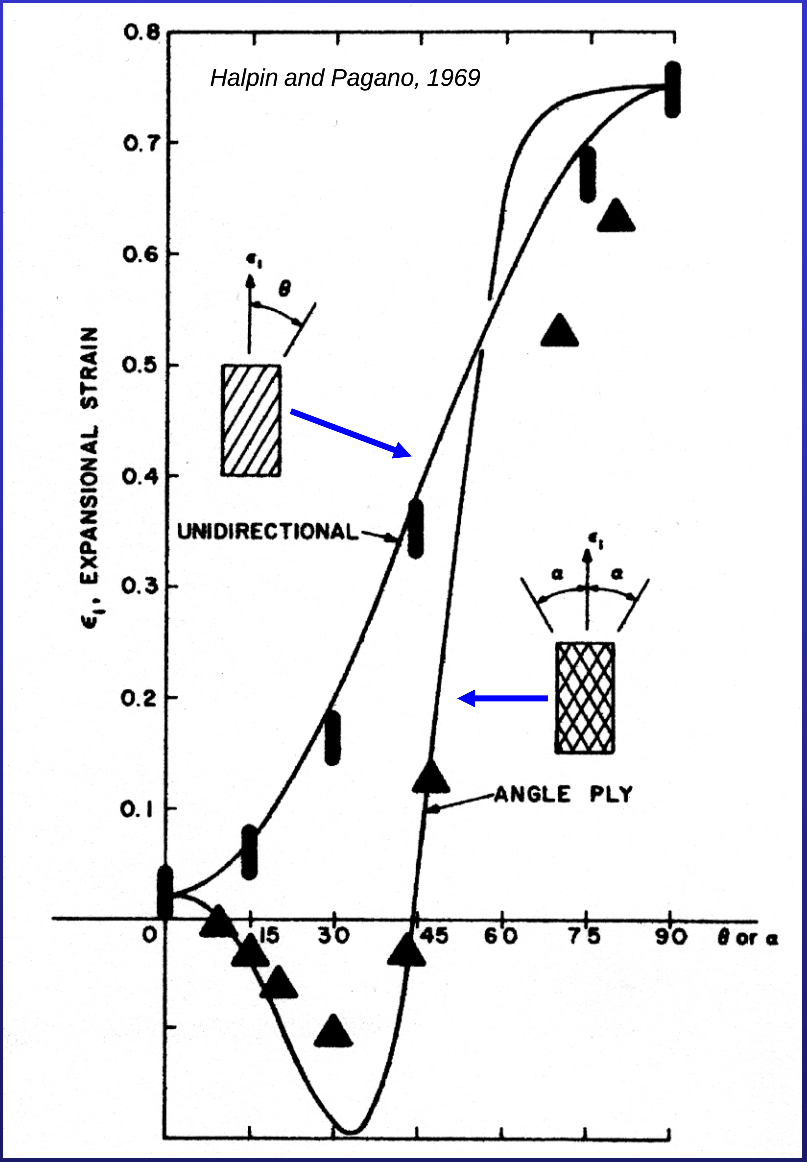
Benefits from hierarchical structures

- Compensation for limitations of unidirectional composite
- Cellular structures possible (low density)
- Beneficial fibre pre-stressing in tension (buckling)
- Control of swelling
- Multiple energy absorption mechanisms against fracture
- Modulation of multiple interfaces

Layered composite structures



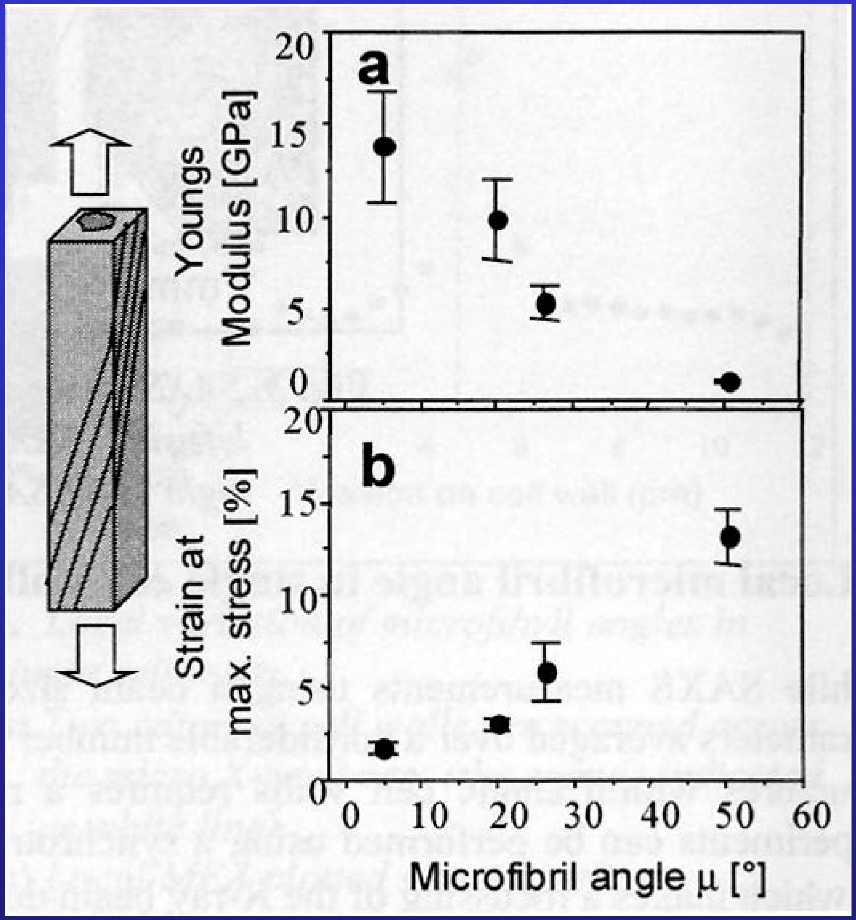
M. Bramwell, 1976



Hygro- or thermal expansion of angle-ply composite structures

Individual plies with non-zero coefficients of thermal expansion can create a laminate structure with zero thermal expansion coefficient

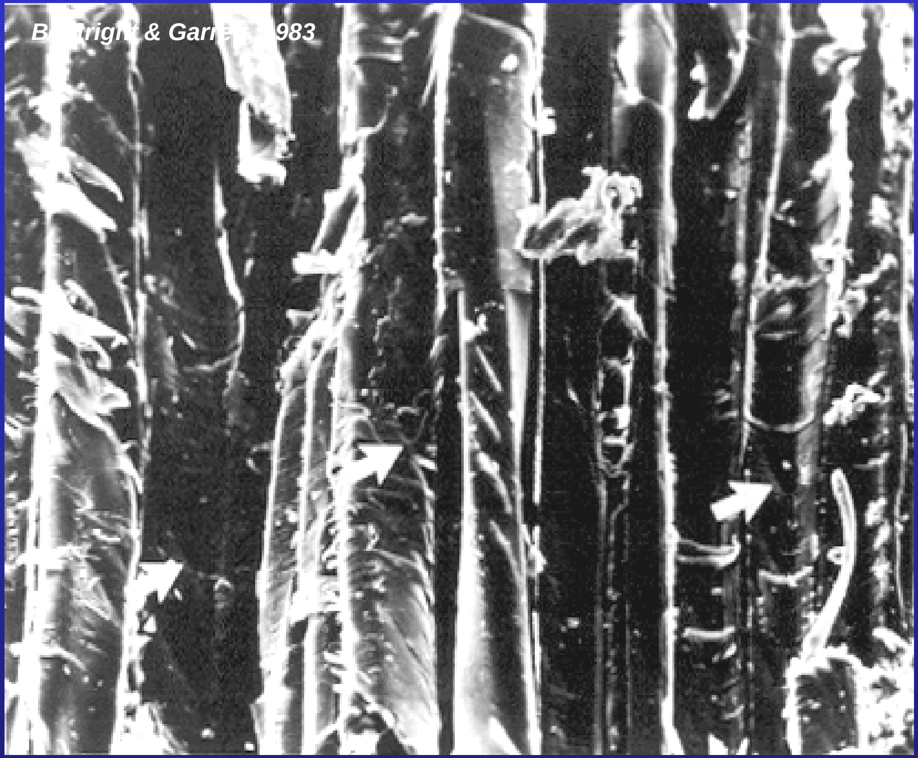
Similar effects are possible with hygro-expansivity



Energy absorption $\propto E\varepsilon^2_{failure}$

Dependence of Young' s modulus and failure strain in wood as a function of microfibrillar angle in S2

H. Lichtenegger et al., 2000



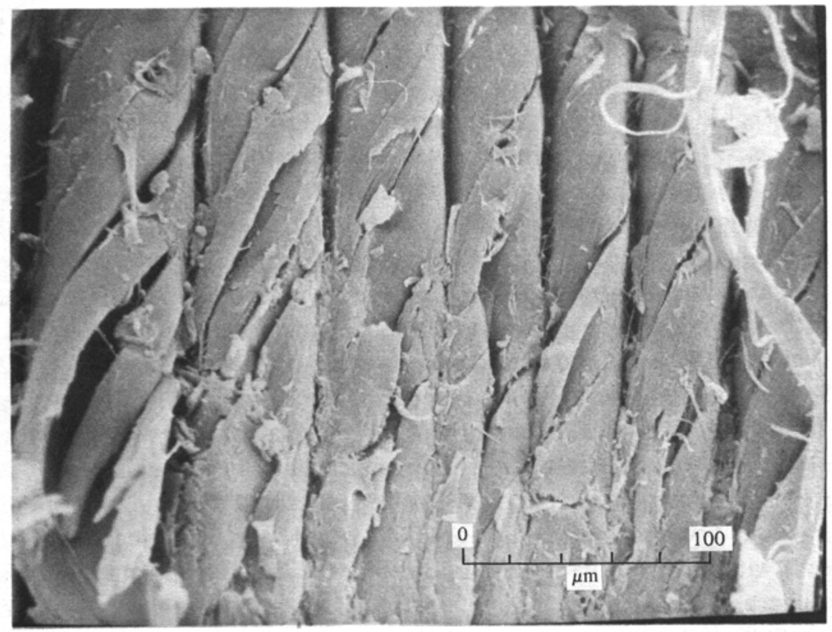
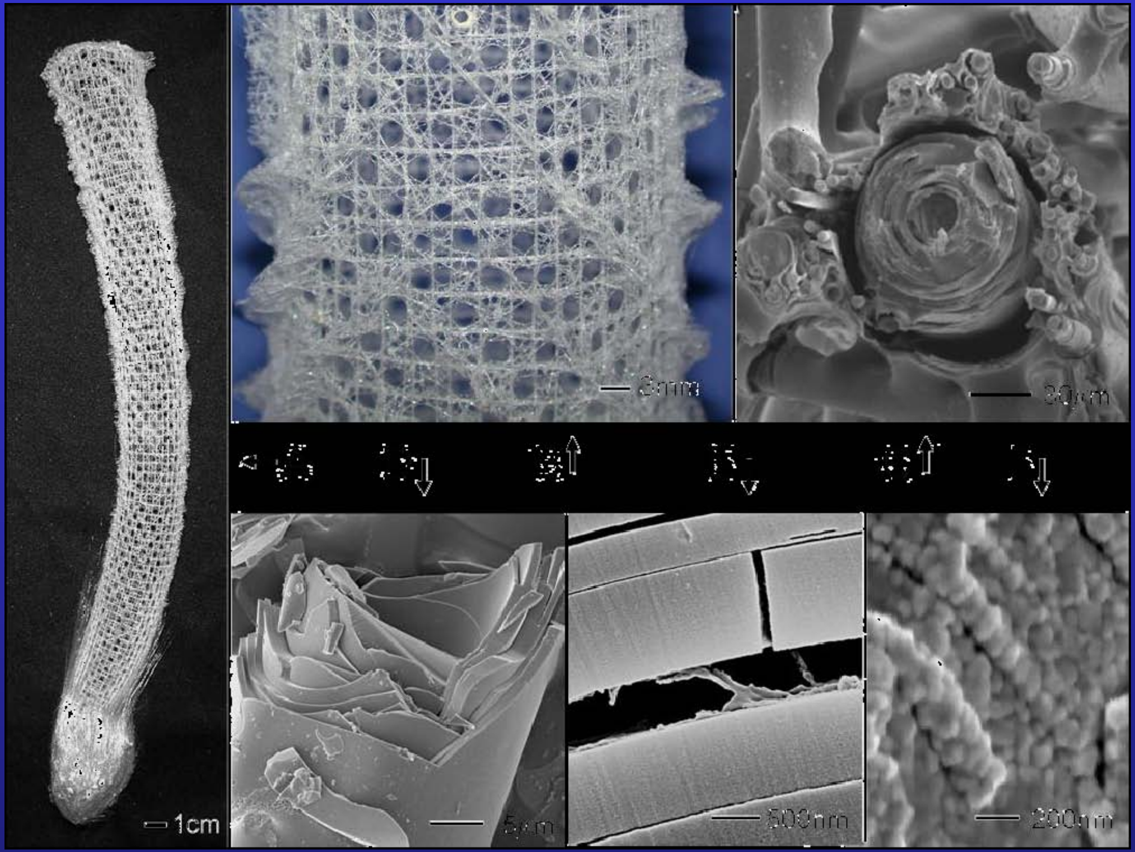


Fig. 4. Tensile failure in Sitka spruce (*Picea sitchensis*). Folding inward of the S2 wall as a result of cracks parallel to the microfibrillar direction.

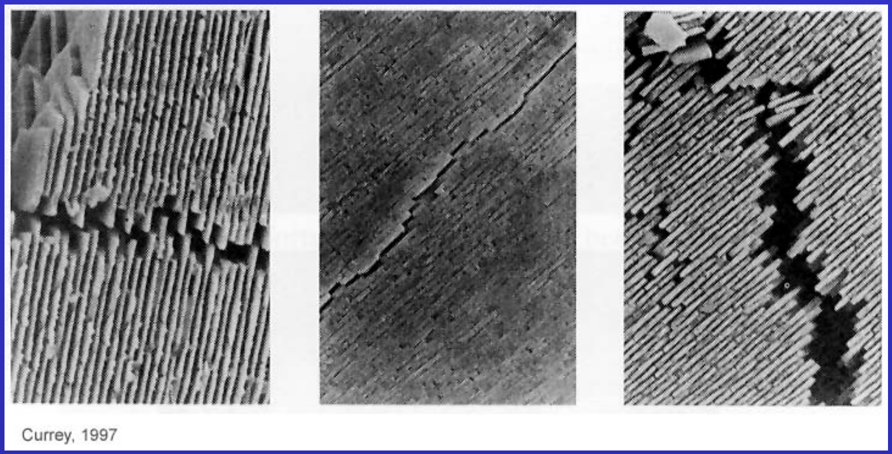
Jeronimidis, 1978

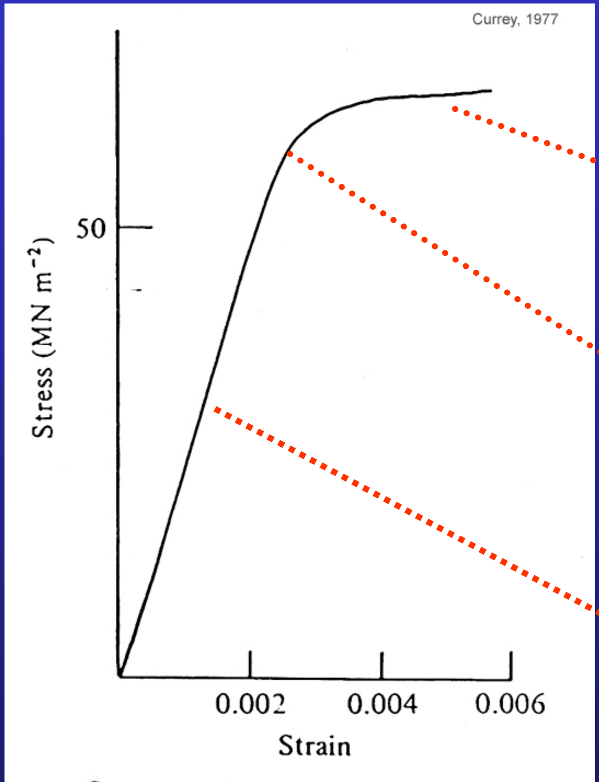


Glass sponge Euplectella – hierarchical architecture

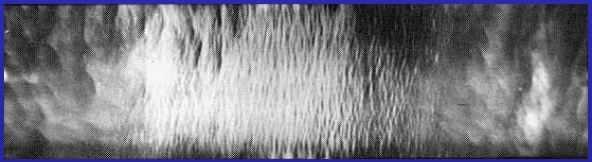
Layered structure as a defense against brittle fracture

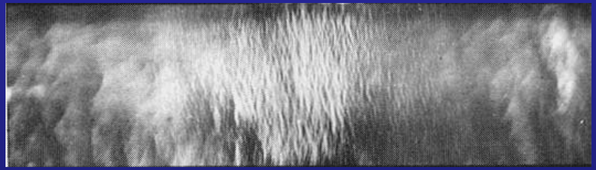
Aizenberg et al., 2005; Weaver et al., 2007; Fratzl,2010

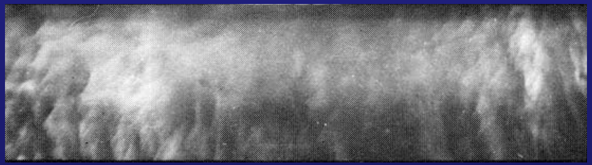




Stress–strain curve of nacre in tension.

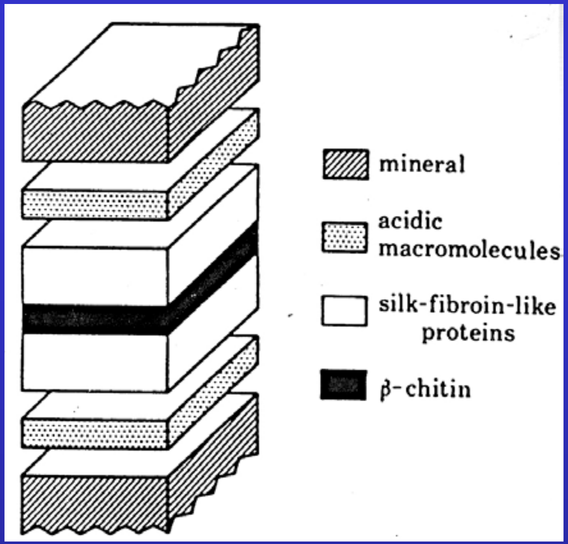


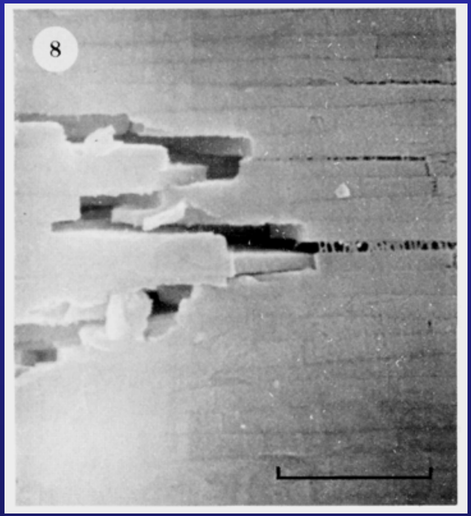


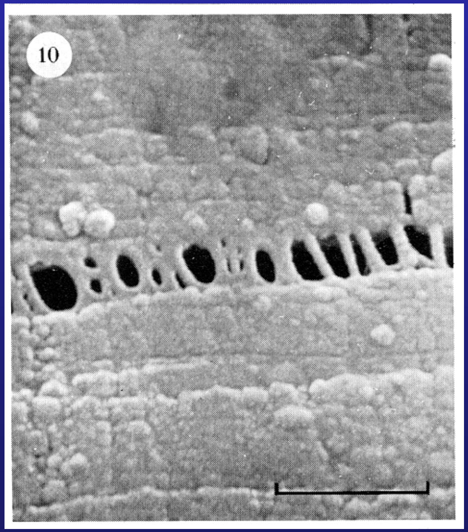


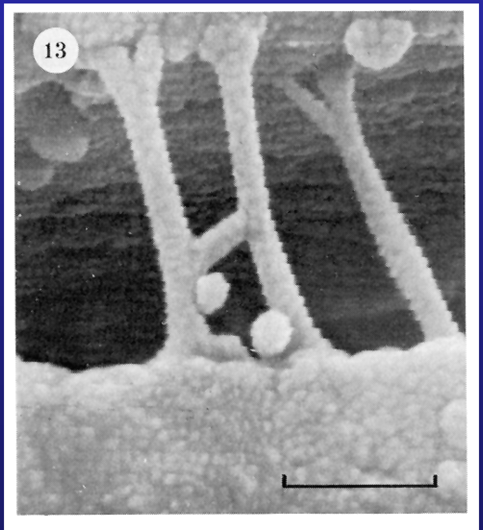
Semi-ductile fracture of nacre in tension (95% brittle ceramic) resulting from hierarchical organisation and control of interfaces

Hierarchy of nacre

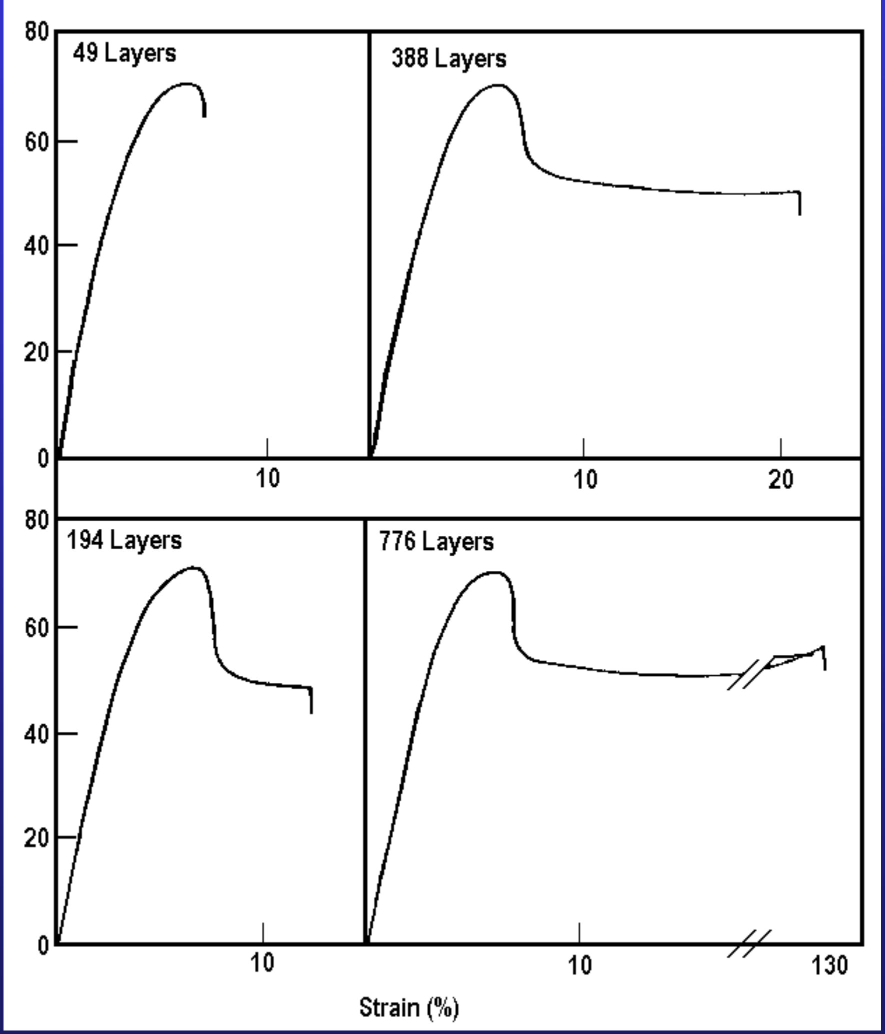








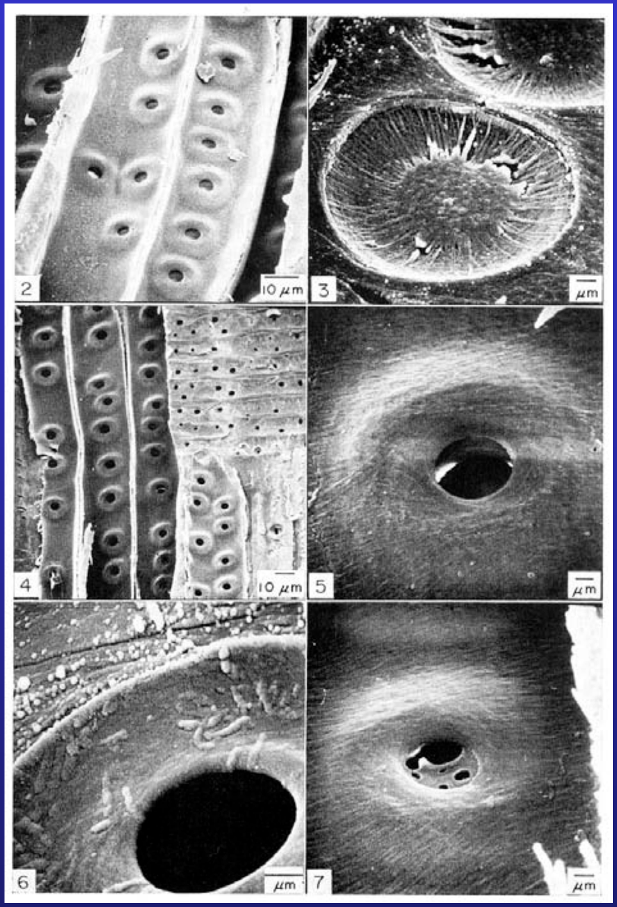
A. Jackson and JFV Vincent, 1980



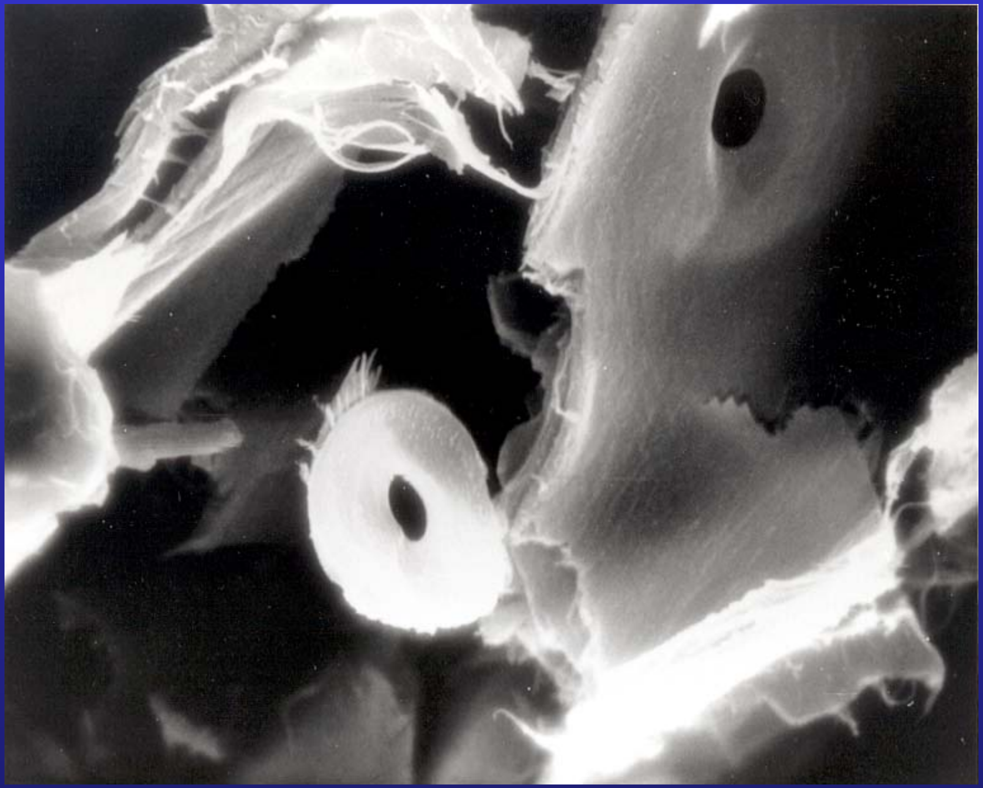
POLYMER MATERIAL IN TENSION

Transition from semi-brittle to ductile fracture induced by layered hierarchies

E.Baer, 1987



Bolton & J.A. Petty, 1975

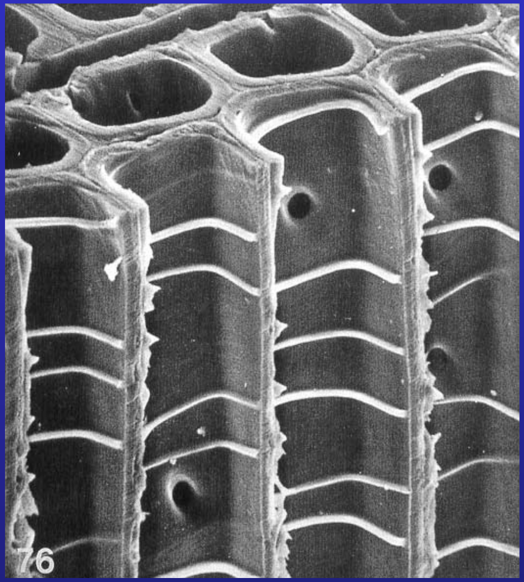


Jeronimidis, 1978

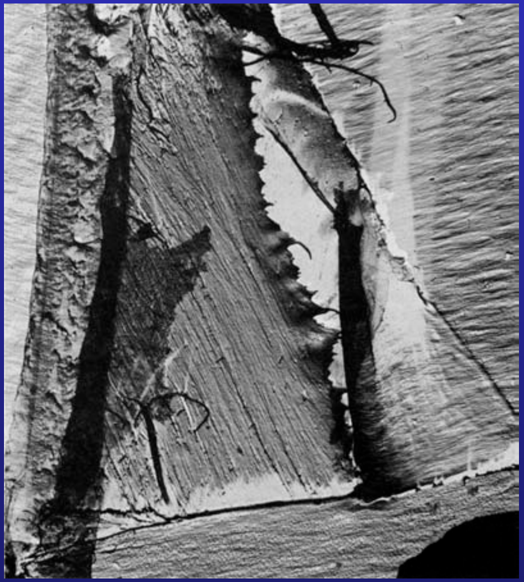
Preventing fracture from bordred pits via modulation of fibre orientation

GROWTH AND HIERARCHICAL STRUCTURES

(a)

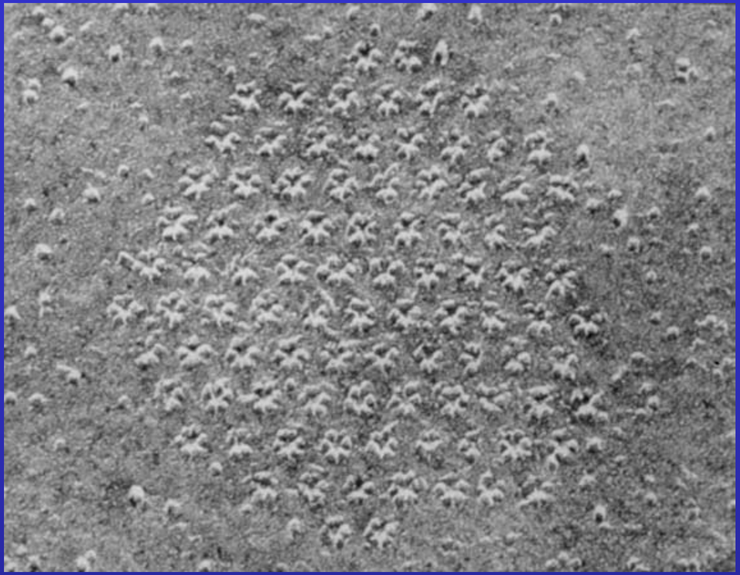


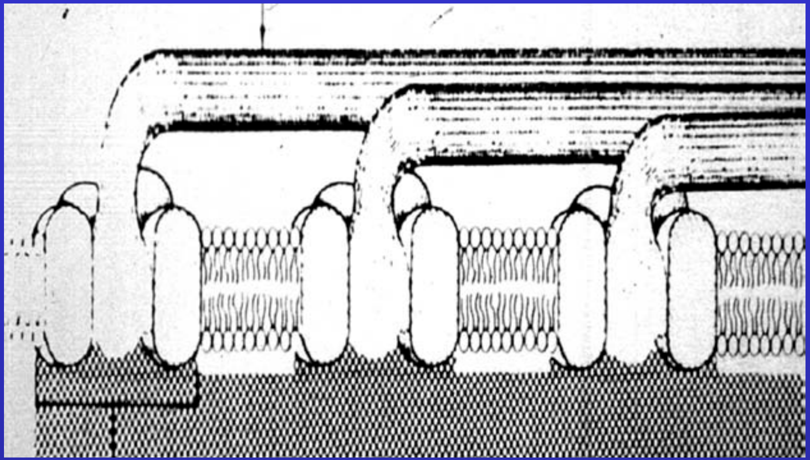
(b)

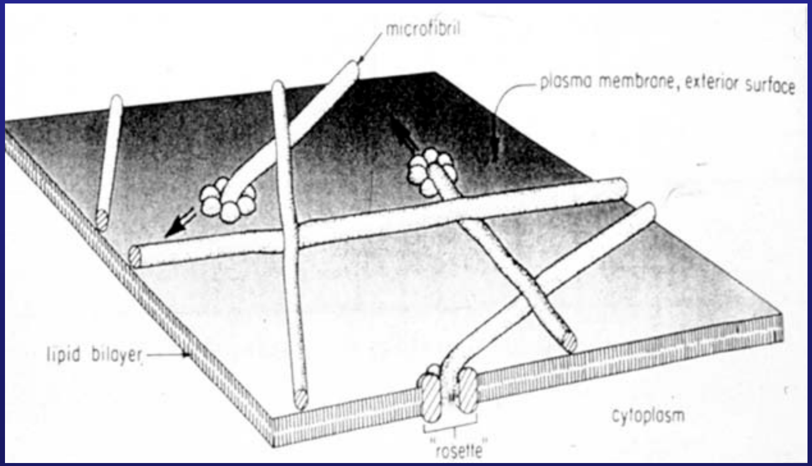


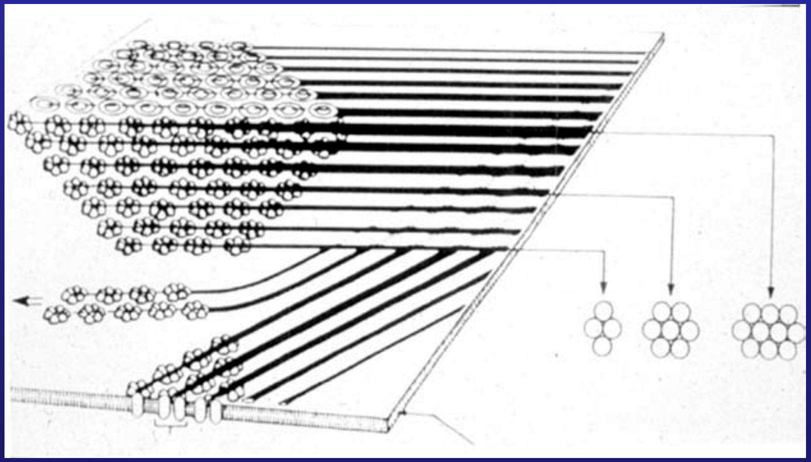
(c)

(a), (b) J.R. Barnett (pers. comm.); (c) J.M. Dinwoodie, 1979

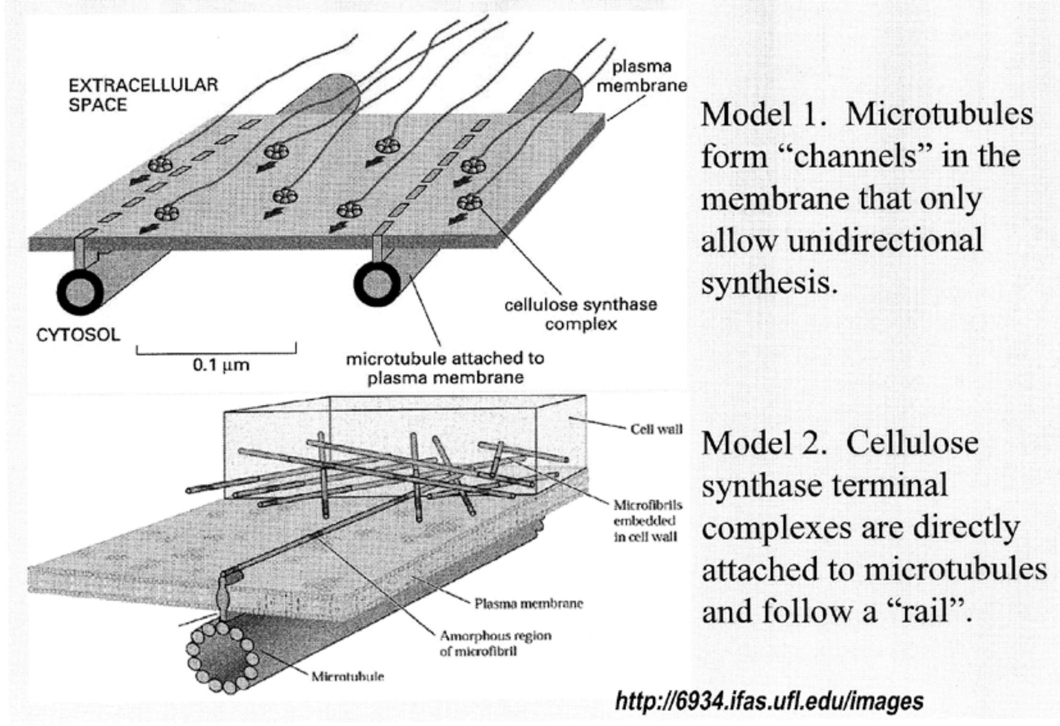








Giddings et al., 1980



The role of microtubules for cellulose fibre organisation in cell walls

CONCLUSIONS

- We cannot replicate growth and all its associated control, sensing and modulation mechanisms which lead to successful biological hierarchical structures

- However, we can extract principles of good composite design from biological systems which are continuously adapting and compromising

- Introducing levels of hierarchy can provide better utilisation of fibres and achieve higher levels of functionality

"MATERIAL" LEVEL

Fibres, Matrices, Anisotropy, Heterogeneity

+

"STRUCTURE" LEVEL

Hierarchies, Dimensions, Geometry, Shape

↓

FUNCTIONAL INTEGRATION AT THE "SYSTEM" LEVEL

THANK YOU FOR YOUR ATTENTION