

# Chemical modulation of mechanical properties during the making of wood in a growing tree

*Bernard Thibaut*

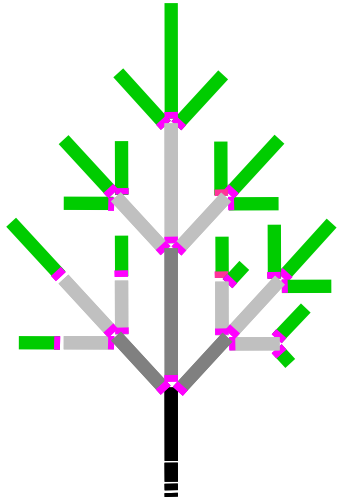
*CNRS*

## The physical chemistry of green chemistry

Montpellier Nov 26<sup>th</sup> 2015

# First step in building of a tree: external additive manufacturing

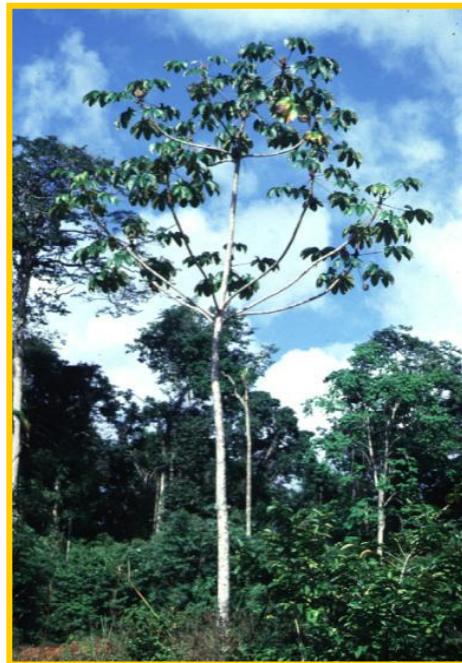
Growth in length give *long slender beams*  
whose section grows in diameter by adding  
successive new layers of woody material



Primary growth



Section of a trunk

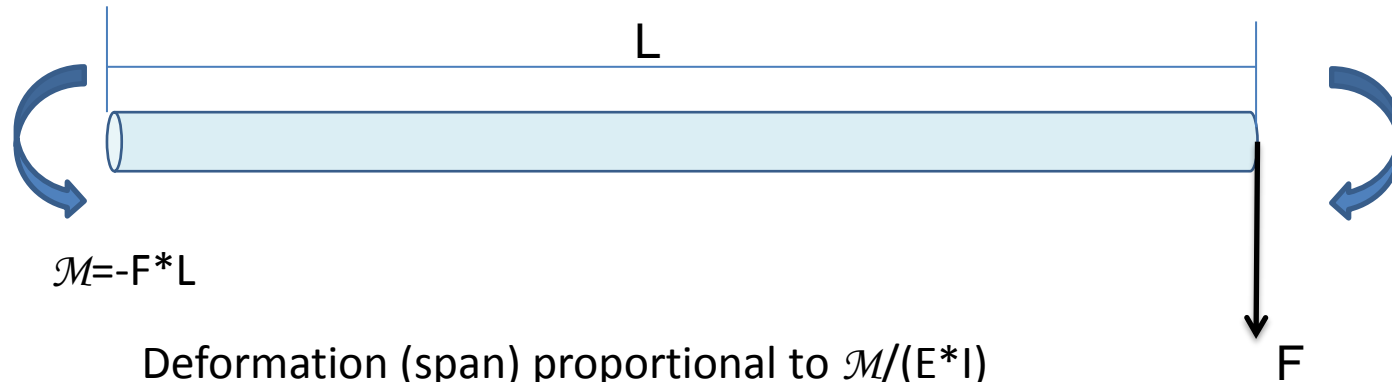


# Mechanical problems for a tree



Resistance to bending  
and  
posture control  
are the main problems

# Resistance of a beam to bending: a key for trees



Deformation (span) proportional to  $\mathcal{M}/(E \cdot I)$

$E \cdot I$ : stiffness of the beam

$I$ : second moment of inertia proportional to  $D^4$

$E$ : stiffness (modulus of elasticity) of the material

The maximum stress is proportional to  $\mathcal{M} / D^3$



*Importance of **geometry**:  $L$ ,  $D$ ,  $L/D$  for structural stiffness and force distribution*

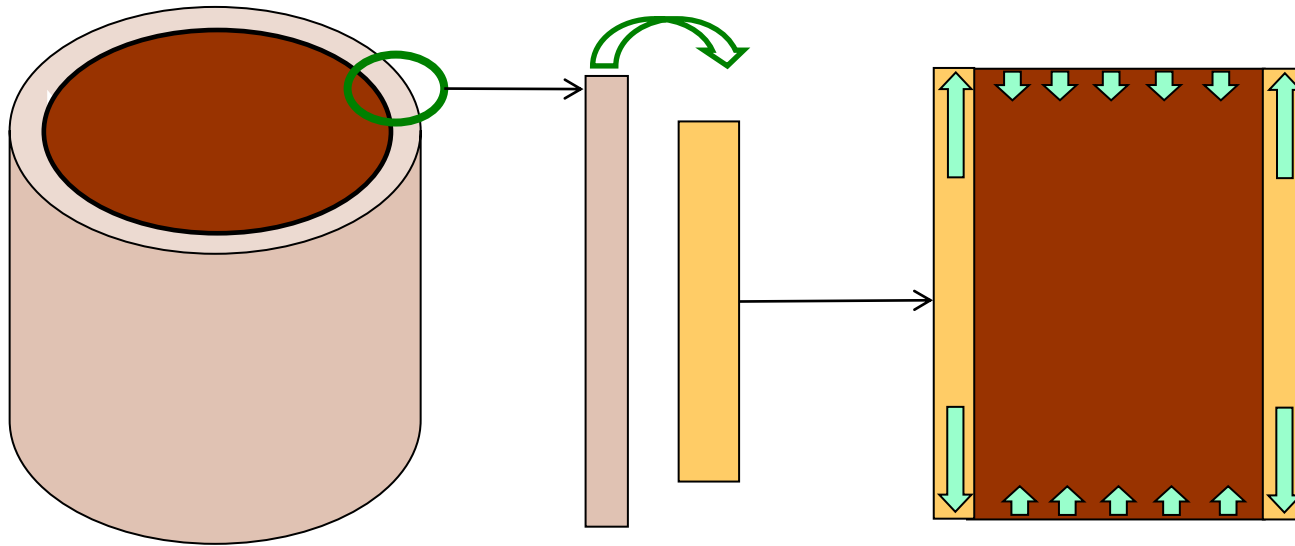
*Importance of **material properties** as modulus of elasticity and rupture strength (should be  $>$  maximum stress)*

# Additive manufacturing and branch posture control



*Increasing mass and bending momentum will lead to more and more deflexion of the beam unless there is an **active action (forces)** in the last produced layer in order to counteract the increase in bending momentum*

# Producing forces in polymer additive manufacturing



Step 1 adding a new layer, made of a mixing of monomers, on a solid core

Step 2  
In situ  
Polymerisation of the layer glued on the solid core

Step 3 at the end of the process the new layer is pre-stressed

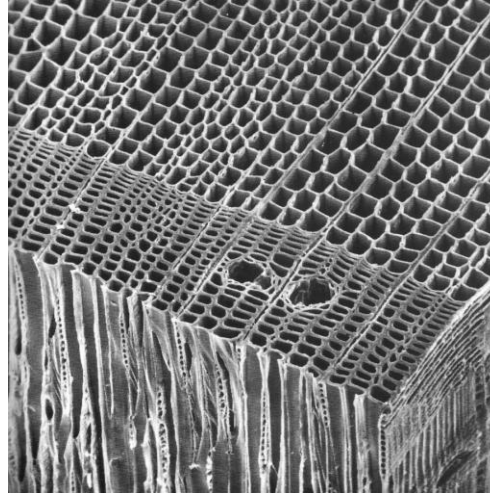
In this case, during the free polymerisation of the polymer, there should be a small shrinkage  $\varepsilon_p$ , from  $100 \mu\text{def}$  to some  $1000 \mu\text{def}$  ( $\mu\text{def} = 1/1000000$ ). Layer strain is blocked by the solid core, inducing a stress (necessary to produce an opposite strain in the layer)  $\sigma_p = E * \varepsilon_p$  ( $E$ : modulus of elasticity of the polymerised layer). The total force acting on the core is  $F = \sigma_p * \Delta S$  ( $\Delta S$ : area of the new layer section)

# Efficient material for beam manufacturing

*Low weight*  
*Good stiffness/weight ratio*  
*High anisotropy*



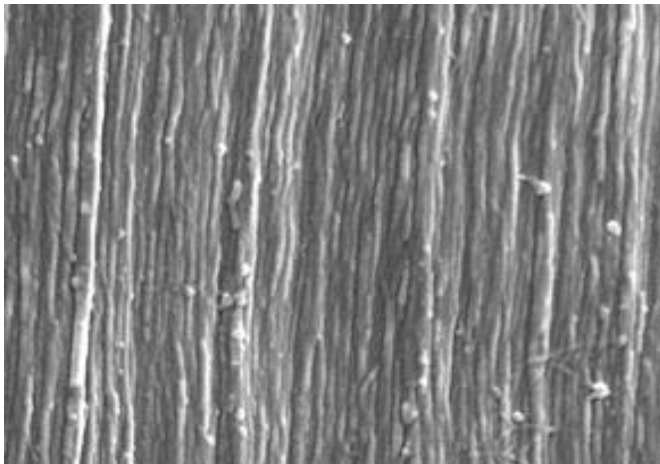
*Polymers*  
*Cellular materials*  
*Fibre composites*



Honeycomb like structure  
for spruce



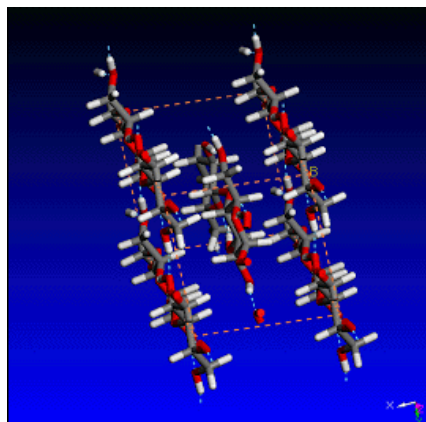
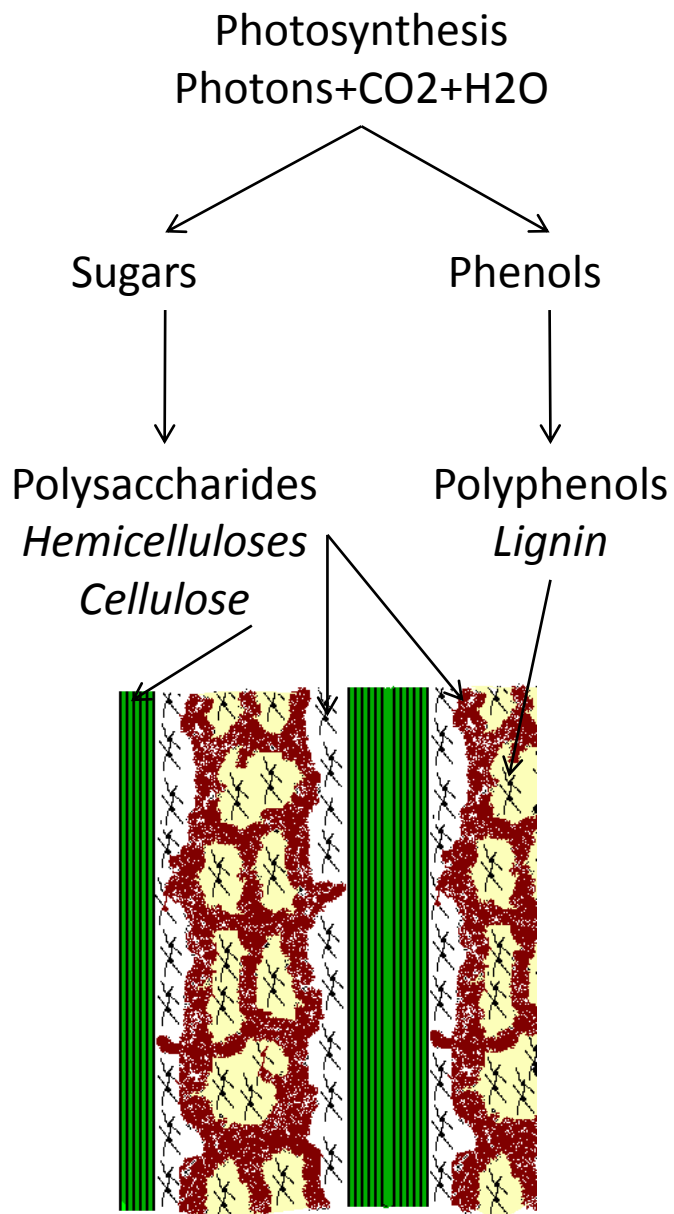
Irregular radial growth  
for a Guyanese tree



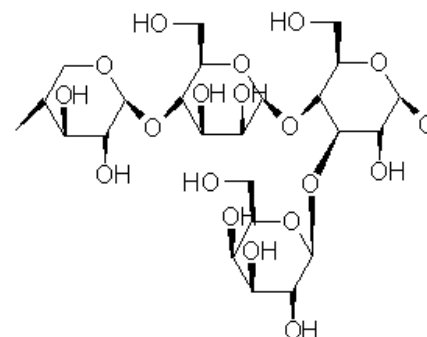
*Fibre composite is highly anisotropic  
and efficient in bending*

*Honeycomb materials are anisotropic.  
Playing on cell number and cell expansion is a  
way to modify geometry at constant weight*

# Green polymers as basic material

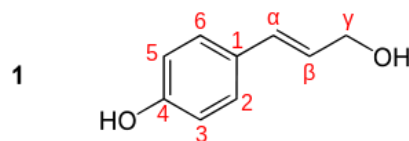


Cellulose

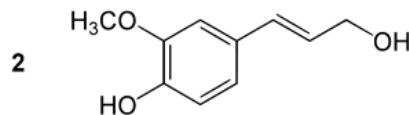


- Xylose -  $\beta$ (1,4) - Mannose -  $\beta$ (1,4) - Glucose -  
-  $\alpha$ (1,3) - Galactose

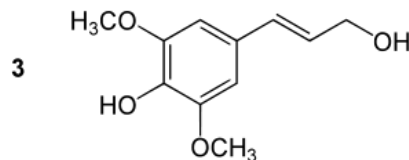
Hemicelluloses



*p*-coumaryl alcohol



coniferyl alcohol

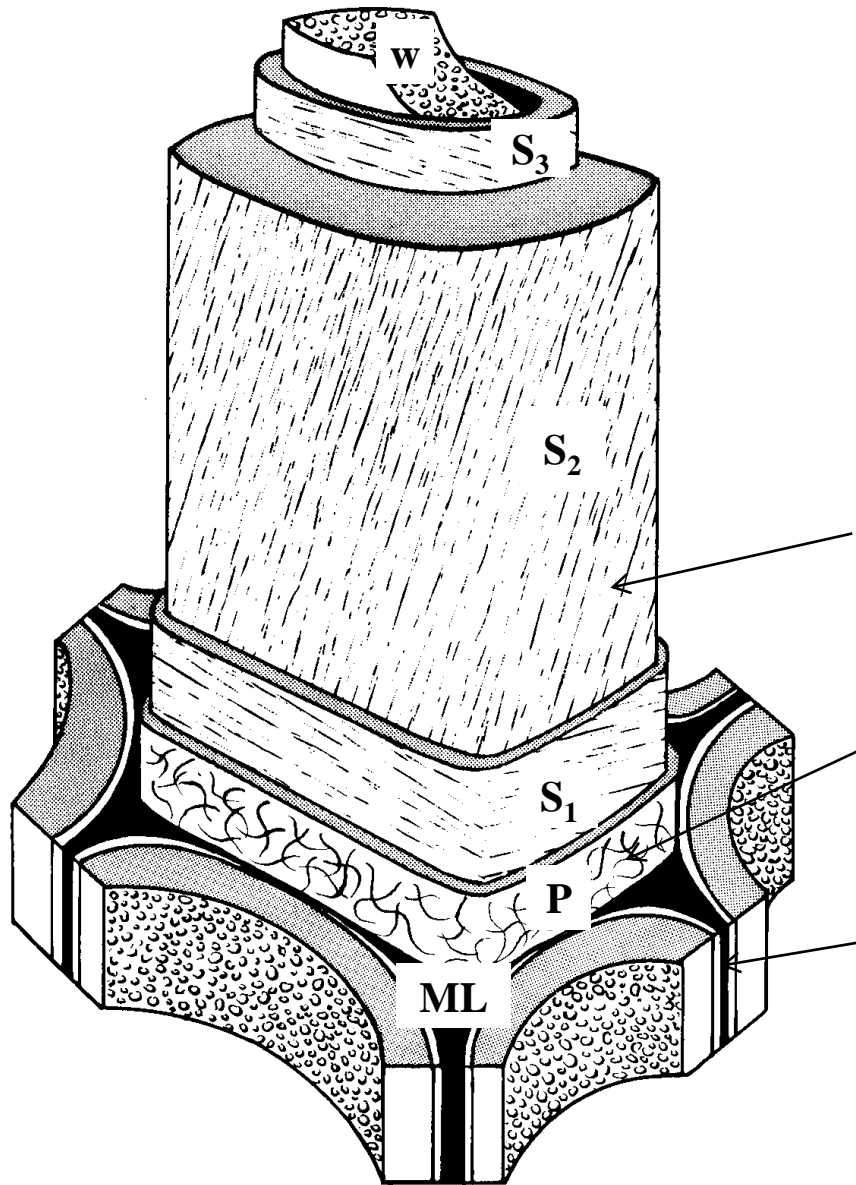


sinapyl alcohol

Lignin monomers



# Second step: internal additive manufacturing



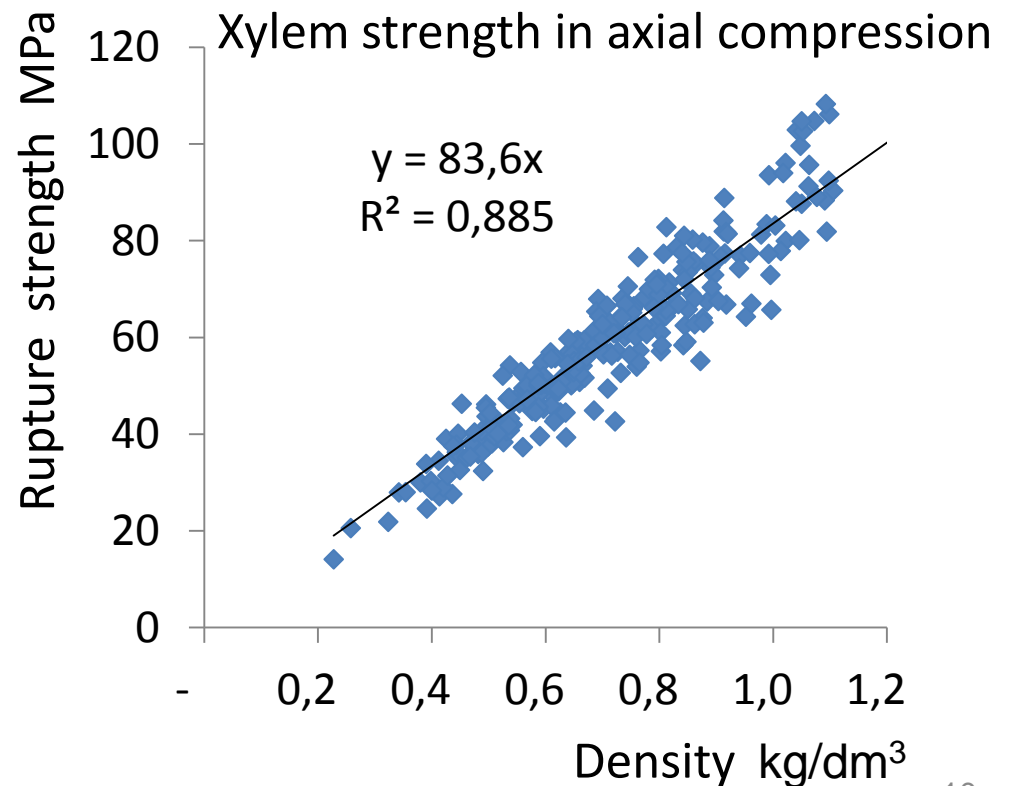
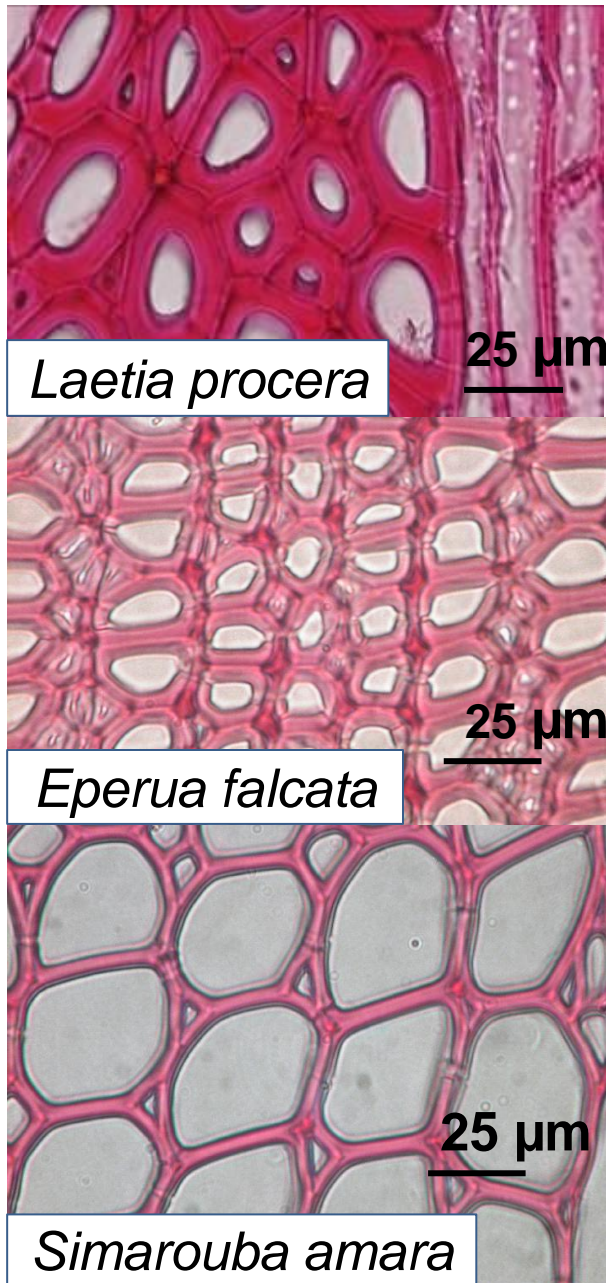
*Cell wall thickening by deposit of polymer layers inside the cavities*

S: secondary wall deposited inside the cell, on the primary wall, during maturation  
With 3 layers S<sub>1</sub>, S<sub>2</sub> and S<sub>3</sub>

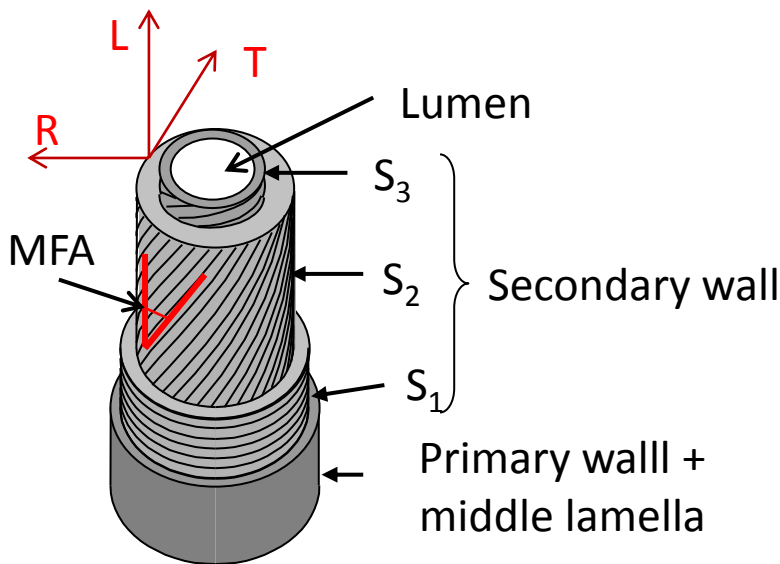
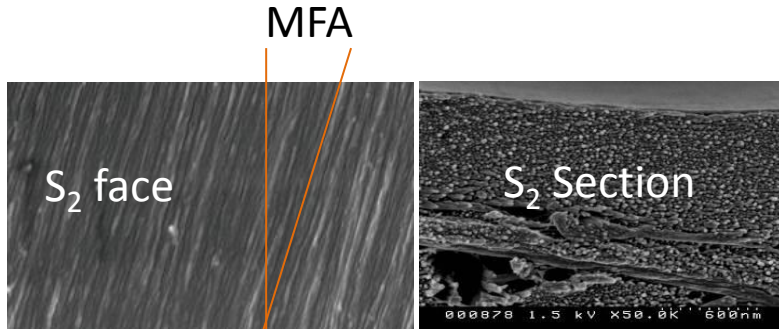
P: primary wall produced during cell expansion

ML: middle lamella glue line between two cells produced by cell division

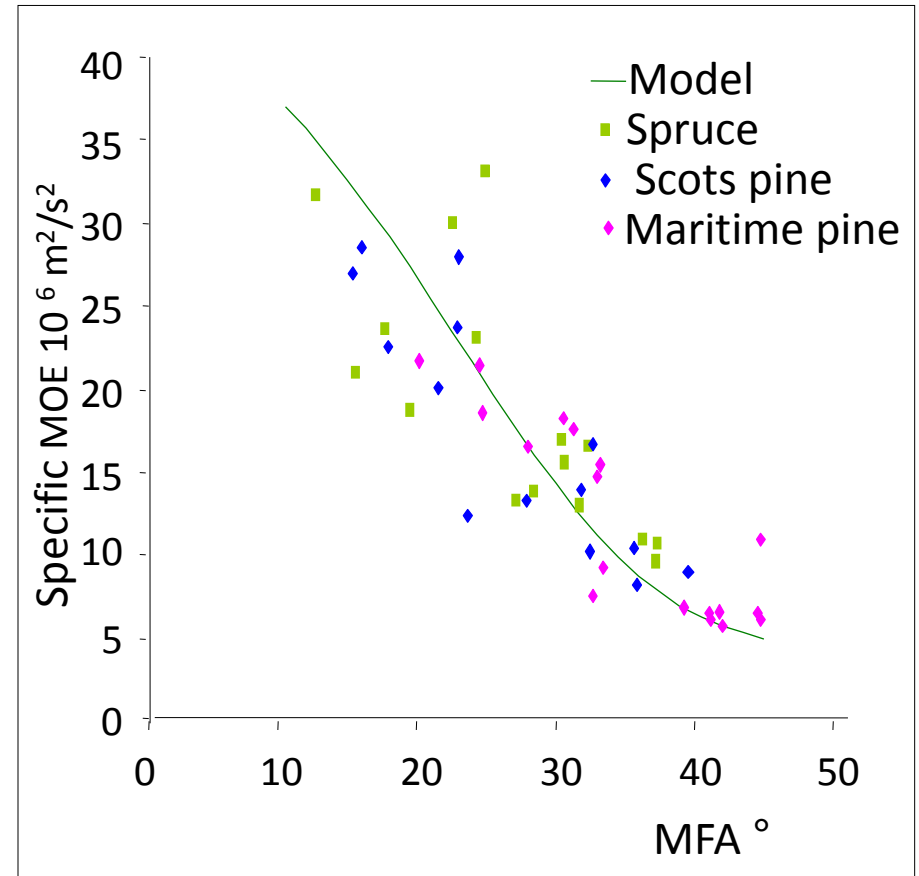
# Growing wall thickness means growing wood density and wood strength



# Secondary wall layers: fibre composite material (second level of anisotropy)



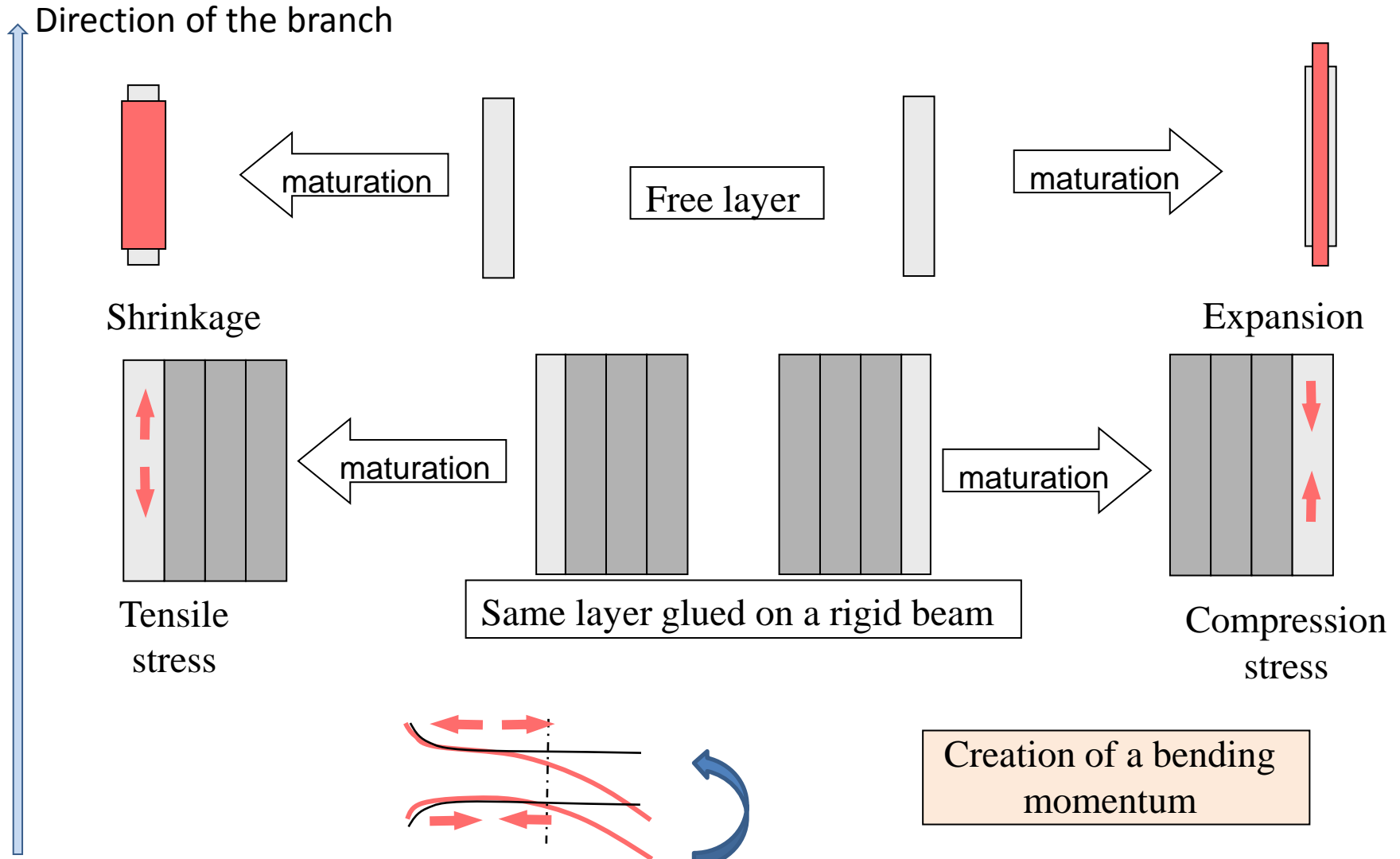
Fibre cell wall composition  
S<sub>2</sub> layer is the thickest one



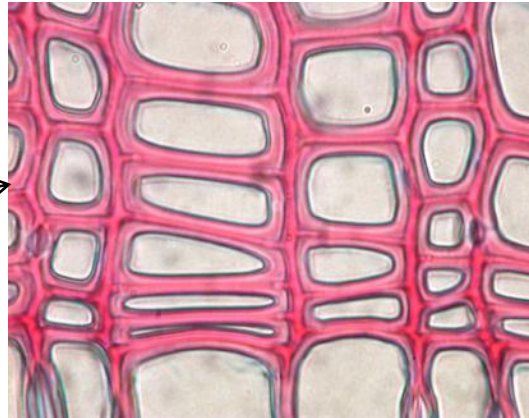
Specific MOE = MOE / Density

*MFA: cellulose microfibril angle in S<sub>2</sub> layer*

# Managing polymerisation to control posture: active reaction against bending in a branch

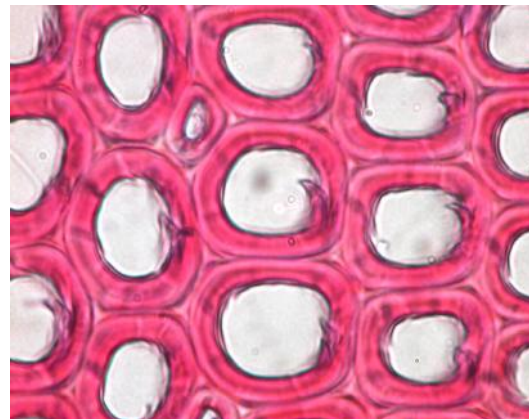


# Maturation strain is depending on chemical composition



Normal wood

Maturation strain  
-200/ 1200  $\mu\text{def}$

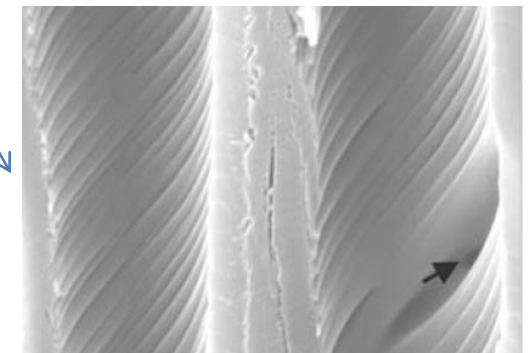
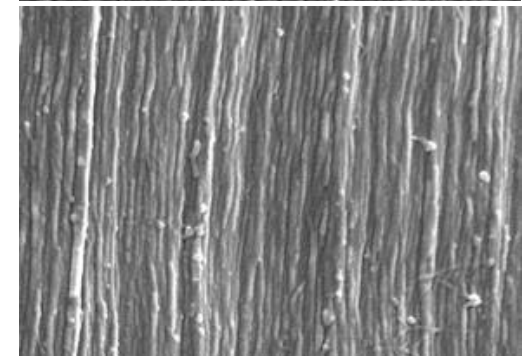
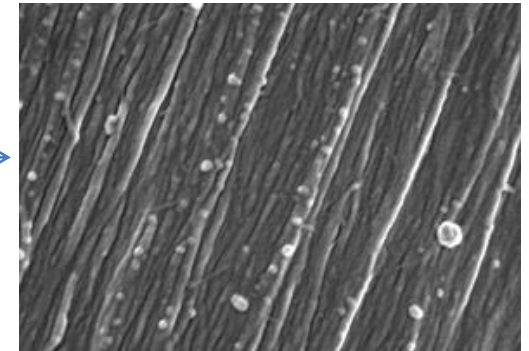
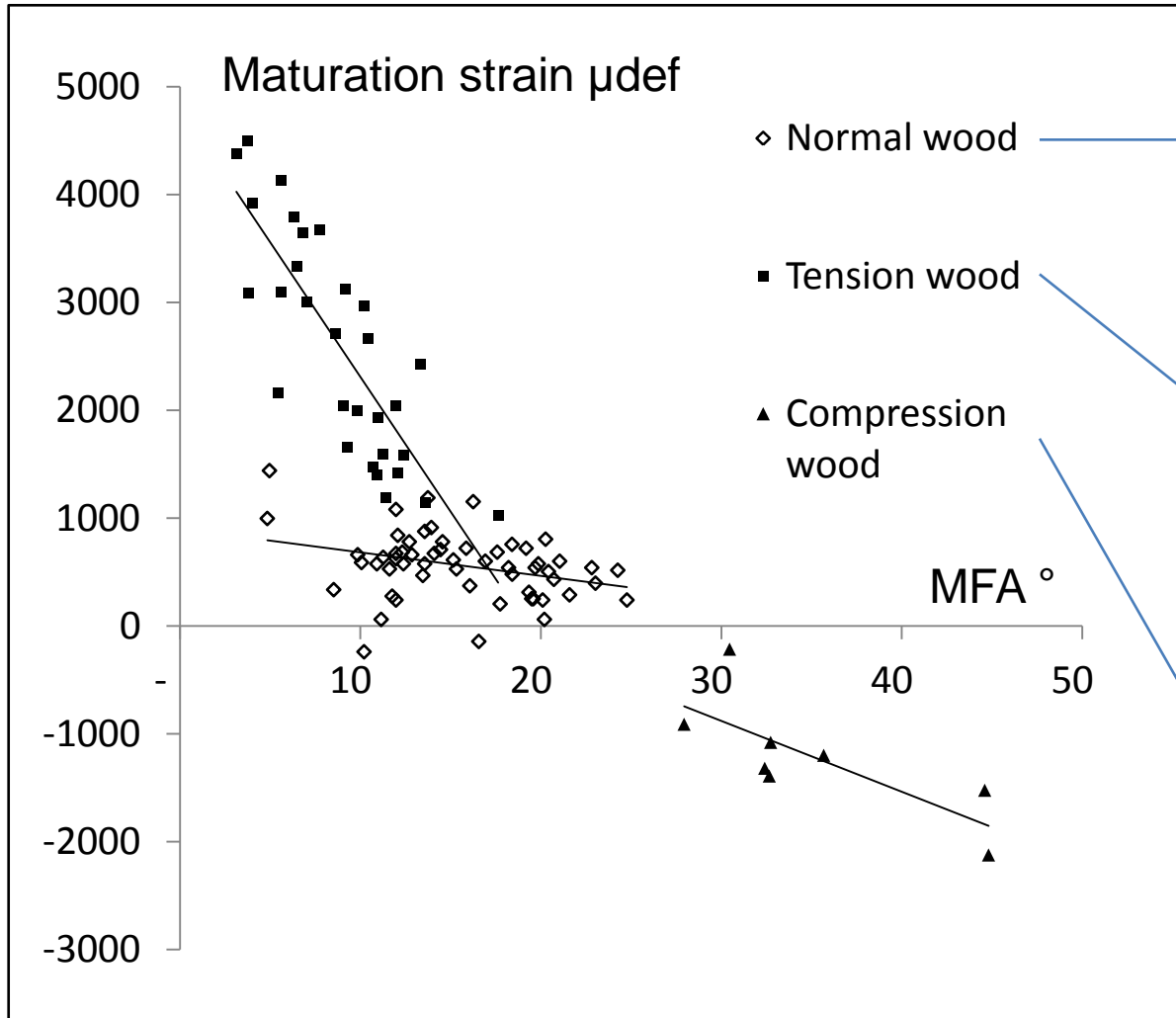


Compression wood

Maturation strain  
-2500/ -200  $\mu\text{def}$

Higher lignin content and different composition in lignin monomers in CW

# Maturation strain is also depending on MFA



# Conclusion: bio-inspiration in additive manufacturing?

- Chemistry of the monomers using CO<sub>2</sub> resource
- Combining honeycomb and fibre composite
- Combining *structural effect* by cell expansion and *material effect* by fibre organisation
- Using polymerisation residual stresses as tools for final form control

# And/or bio-sourcing by tree deconstruction?

- Cross-cutting
- Splitting
- Sawing



*Solid wood*



- Veneering
- Fragmenting



*Plywood and particle panels*



- Defibration → *Paper and fibre panels*
- Fibrillating → *Crystalline nano-cellulose*
- Molecule extraction → *Synthons*



*At the end energy is always available*



Thank you for your attention

