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

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The physical chemistry of green chemistry
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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.
Mechanical problems for a tree

- Weight
- Wind

Resistance to bending and posture control are the main problems.
Resistance of a beam to bending: a key for trees

Deformation (span) proportional to $\frac{M}{(E*I)}$
- $E*I$: 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 $\frac{M}{D^3}$

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)
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 $\mu$def to some 1000 $\mu$def ($\mu$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

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

Fibre composite is highly anisotropic and efficient in bending
Green polymers as basic material

Photosynthesis
Photons + CO₂ + H₂O

Sugars
Phenols

Polysaccharides
Hemicelluloses
Cellulose

Polyphenols
Lignin

Cellulose

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 $S_1, S_2$ and $S_3$

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.

Laetia procera

Eperua falcata

Simarouba amara

Xylem strength in axial compression

\[ y = 83.6x \]

\[ R^2 = 0.885 \]
Secondary wall layers: fibre composite material
(second level of anisotropy)

Specific MOE = MOE / Density

MFA: cellulose microfibril angle in S2 layer
Managing polymerisation to control posture: active reaction against bending in a branch

Direction of the branch

Shrinkage

Tensile stress

Same layer glued on a rigid beam

Compression stress

Expansion

Creation of a bending momentum

maturation
Maturation strain is depending on chemical composition

Higher lignin content and different composition in lignin monomers in CW
Maturation strain is also depending on MFA

Maturation strain $\mu_{def}$

- Normal wood
- Tension wood
- Compression wood

$MFA^\circ$

$-3000$ to $+3000$
Conclusion: bio-inspiration in additive manufacturing?

• Chemistry of the monomers using CO2 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

- Veneering
- Fragmenting

Solid wood

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