Advances in the Biomimicry of Wood for the Development of Novel Additively Manufactured Materials

Professor Philip D. Evans

British Columbia Leadership Chair in Advanced Forest Products Manufacturing Technologies

The International Academy of Wood Science

is a non-profit assembly of wood scientists, recognizing all fields of wood science with their associated technological domains, and securing a worldwide representation.

1963 Idea and Constitution

Kollmann, Univ of Munich | Discussions with colleagues especially in USA

1965 Decision to Establish the Academy & Journal

Mörath, Austrian Wood Research Inst | Wood Sci & Technol, Springer-Verlag

1966 Permanent Secretariat Established in Austria

Core advisory group of Kisser (Vienna), Collardet (Paris), Dadswell (Melbourne), Narayanamurti (Bangalore) and Ylinen (Helsinki)

- Promote high level wood research and technology
- Present wood research and science at conferences
- Focus attention on the importance of wood research and science to all stakeholders

IAWS Fellows by Country

Fellows elected in 2022

Pavlo BEKHTA, Ukraine

Rowland BURDON, New Zealand

Laurent MATUANA, USA

Nicole STARK, USA

Yan XIAO, China

Fellows deceased in 2023

Walter LIESE Germany

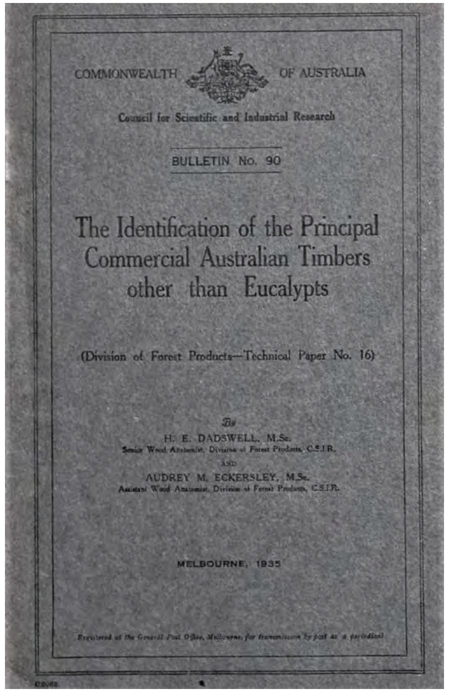
Fellows deceased in 2022

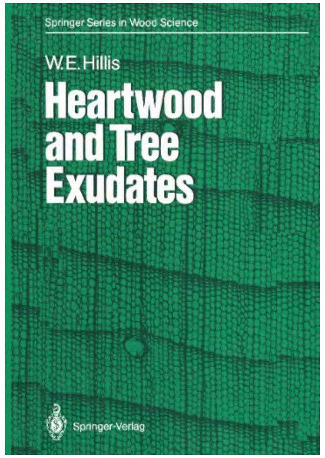
Frank BEALL, USA

Günter SCHULTZE-DEWITZ, Germany

Australian Wood Scientists

Eric Dadswell (1903–1964)



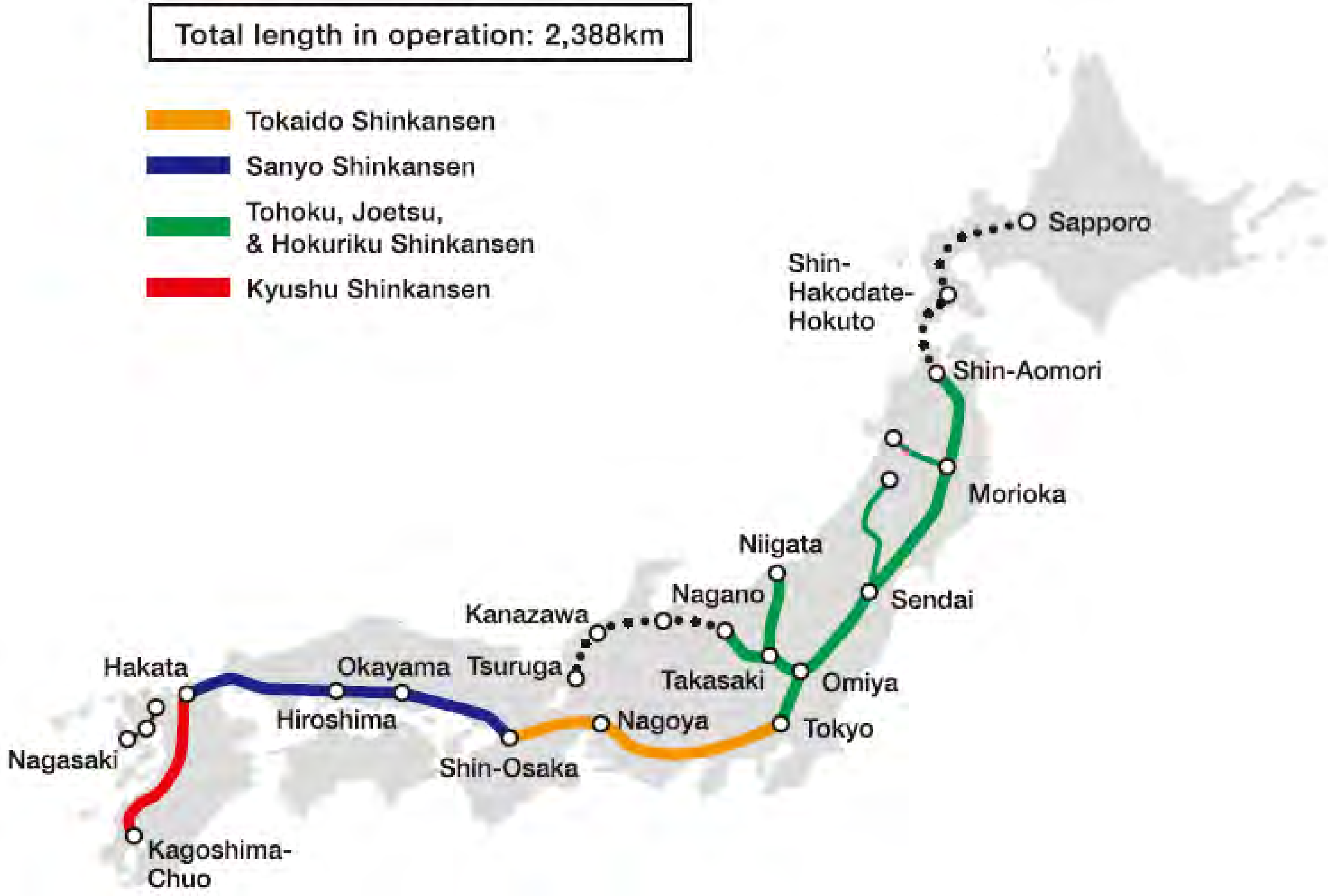


Ted Hillis (1921-2008) President (1978–1982) of IAWS

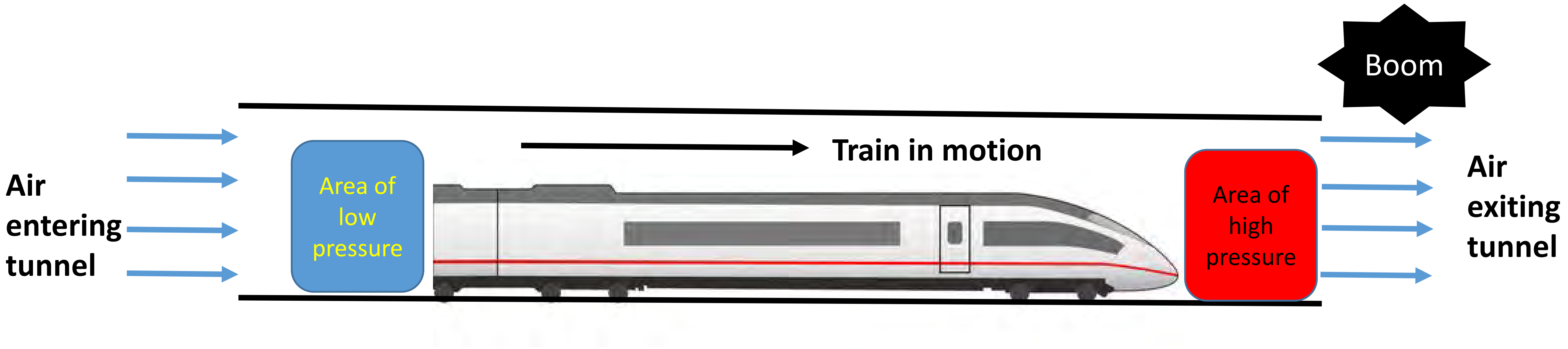
Biomimicry is the transfer of ideas from biology to solve problems and develop new materials, products, structures and sustainable systems

Successful Biomimicry

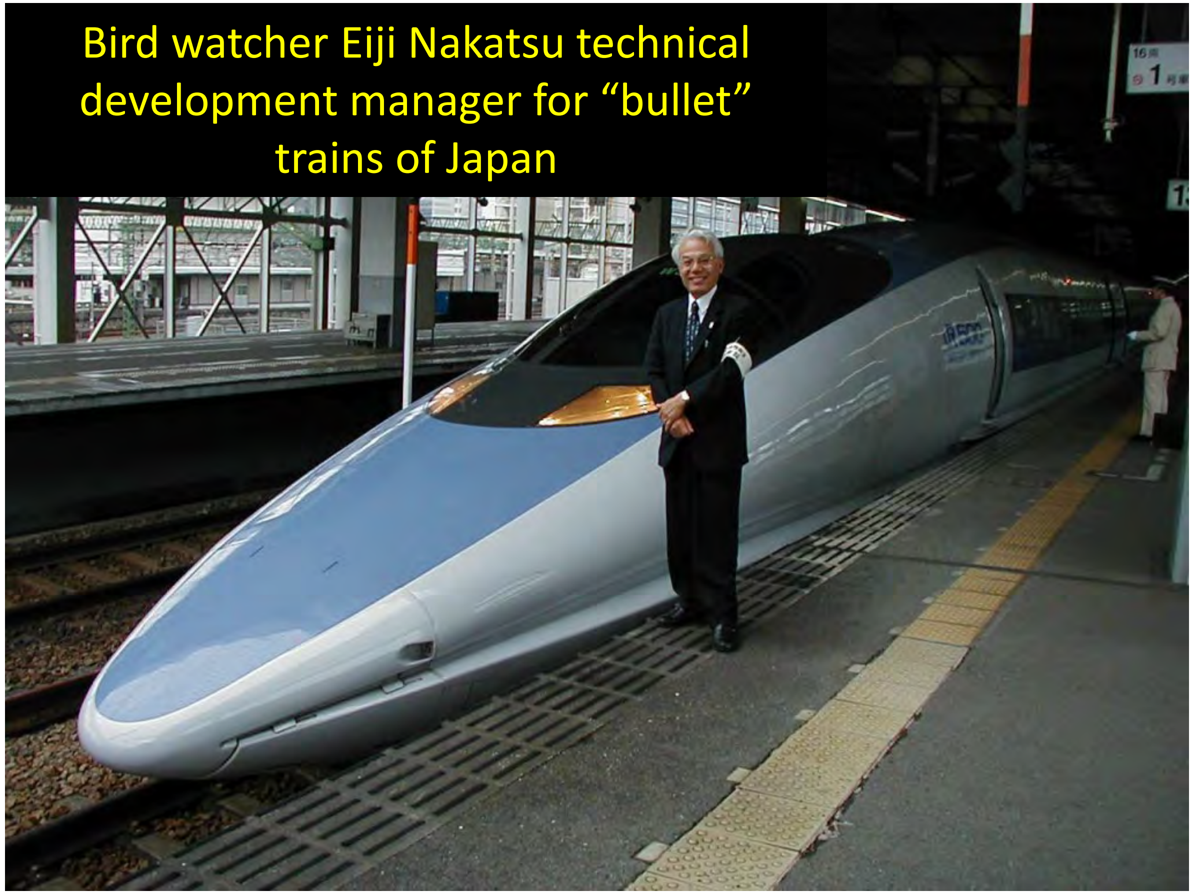
Early model Japanese Shinkansen bullet trains exiting a tunnel caused a sonic boom



When a train enters a tunnel, it generates atmospheric pressure waves that exit at the speed of sound producing a large boom



Pressure wave is proportional to the ratio of the cross-section of the train to that of the tunnel, and to the third power of train speed



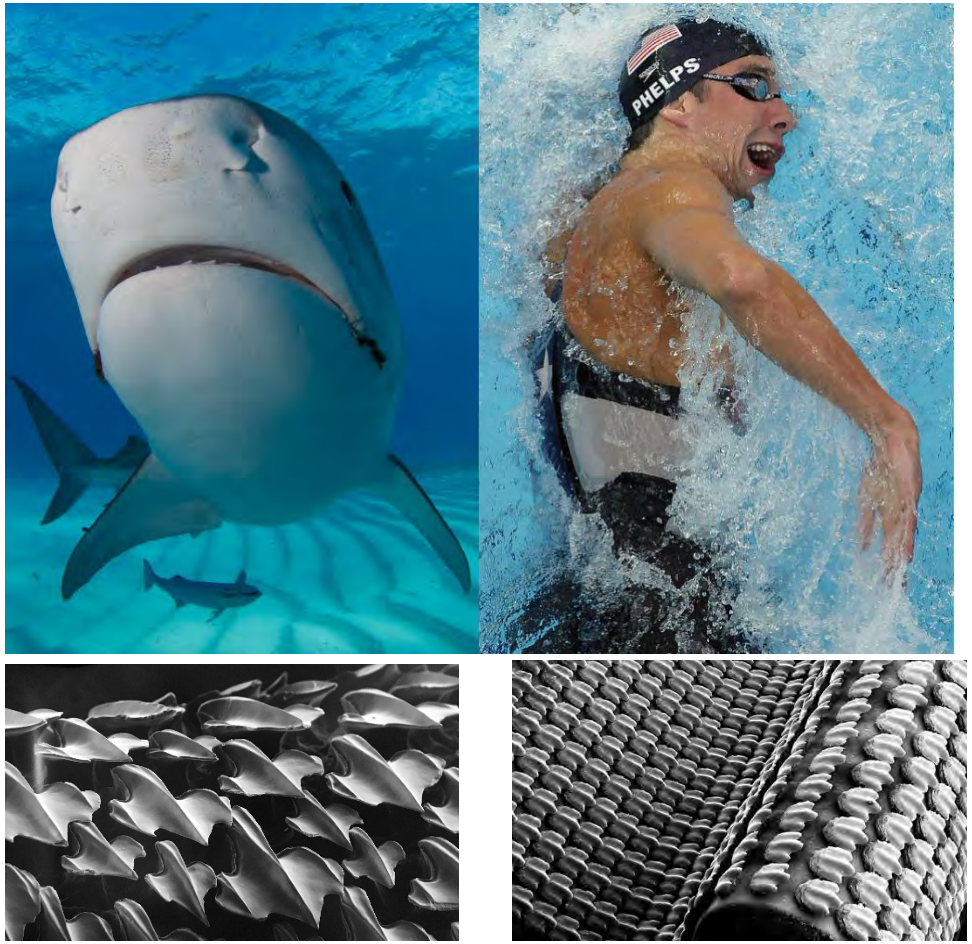
Bird watcher Eiji Nakatsu technical development manager for “bullet” trains of Japan

Pressure wave build up was reduced by redesigning the trains nose to mimic the beak of a kingfisher, a bird that dives at high speed from one fluid (air) to another that is 800 times denser (water) with barely a splash

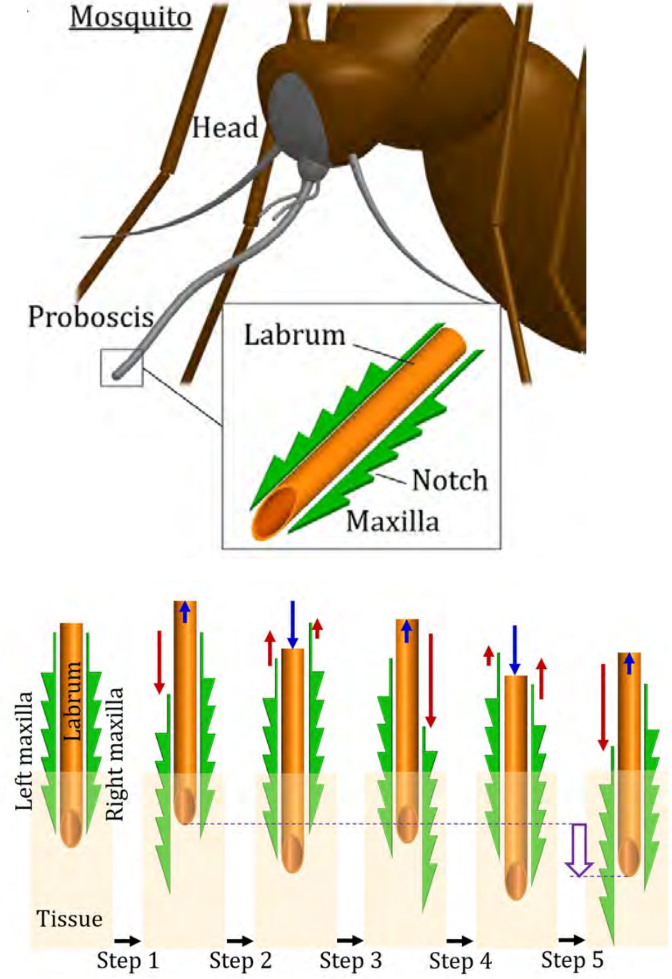
End result of biomimicry was 30 percent less air resistance, maximum speed of 300 km/h (world record) and ability to meet stringent noise standard

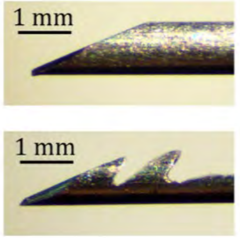
More Examples of Successful Biomimicry

Shape of B2 bomber modelled on that of a falcon



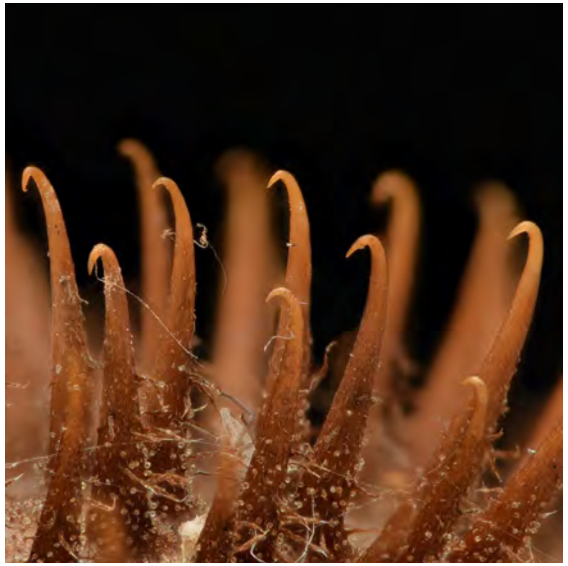
Low drag 3D swim suit fabric modelled on shark skin



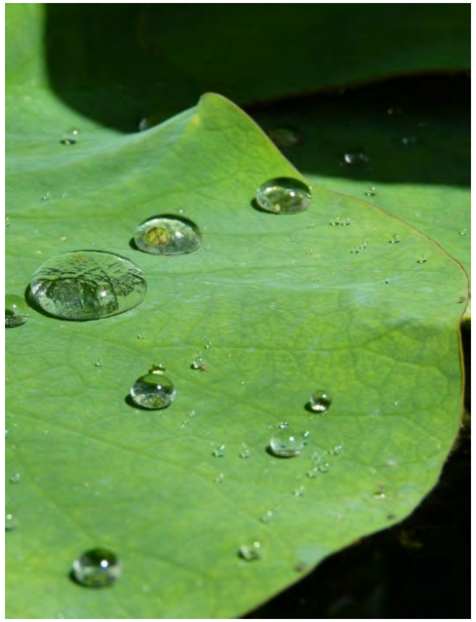


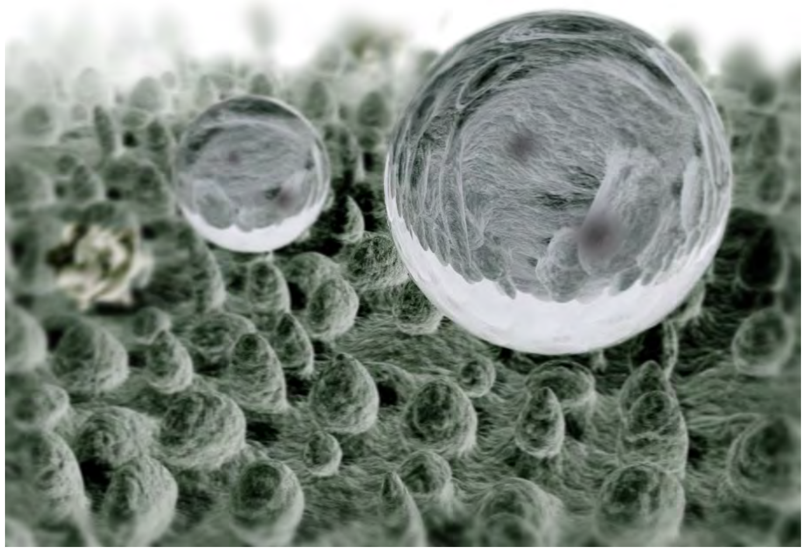
Less damaging hypodermic syringe needle modelled on proboscis of mosquito

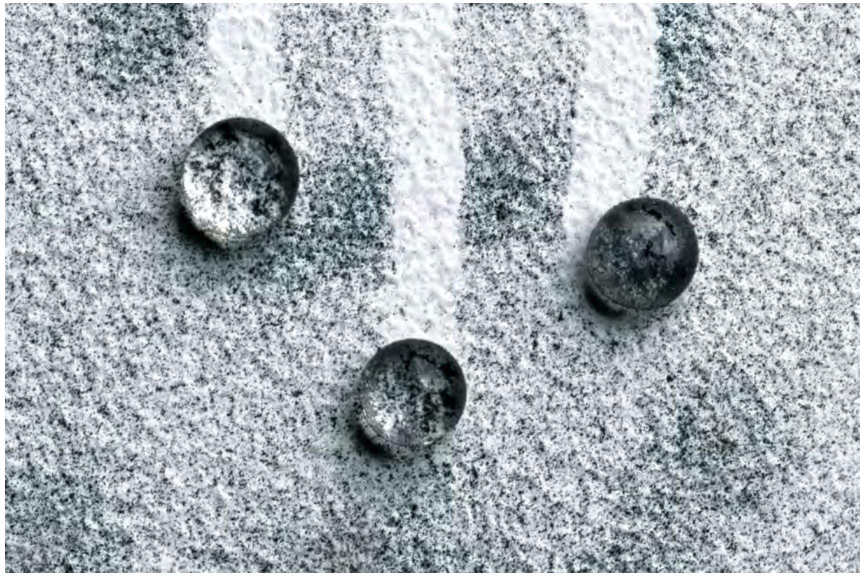
More Examples of Successful Biomimicry



Velcro and burdock burrs







Lotus leaf and hydrophobic self cleaning surfaces

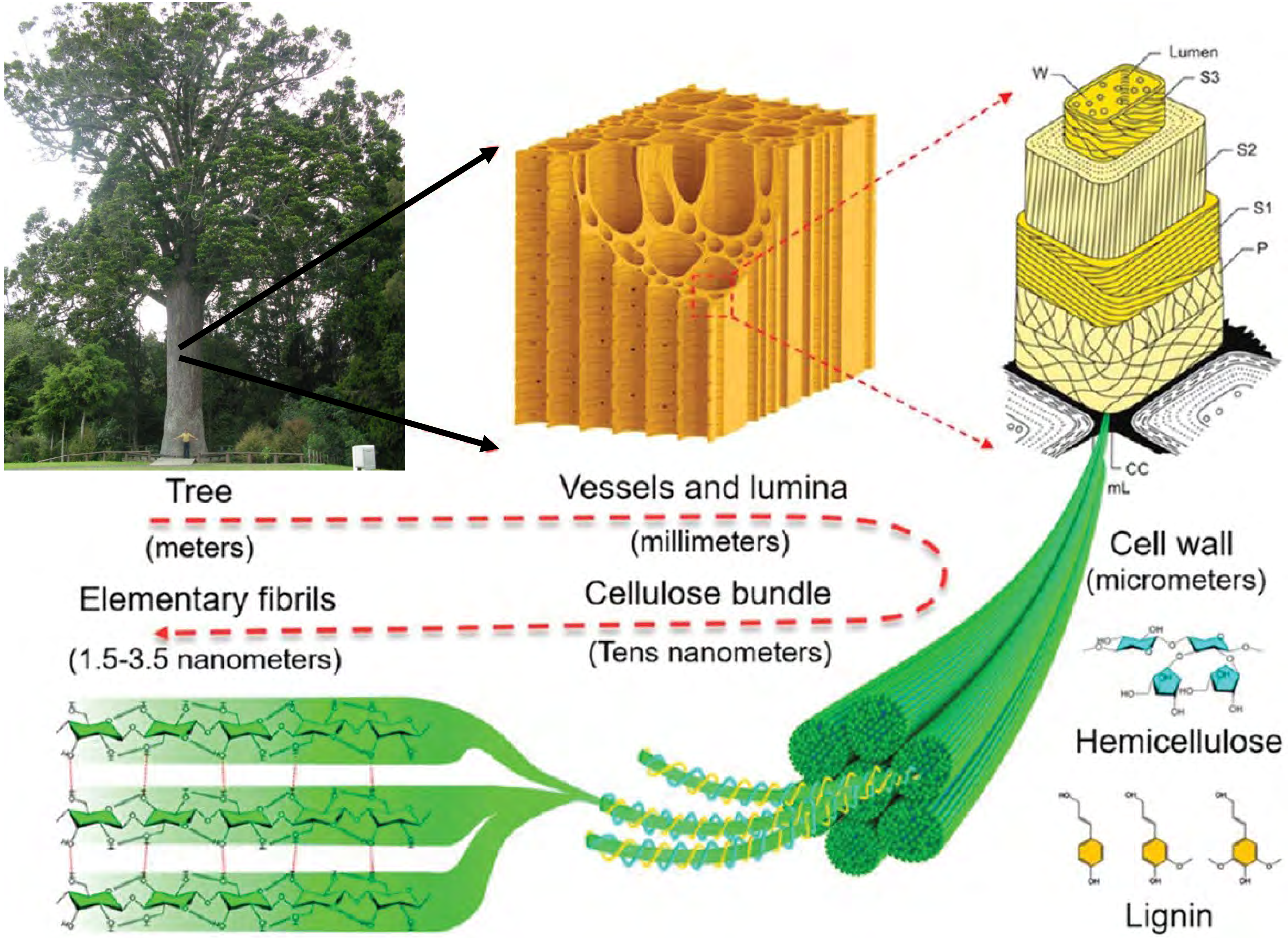
Structural Materials

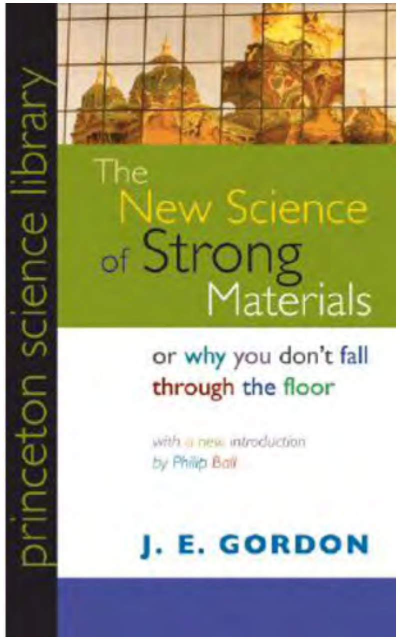
- Pressing need for new materials that are both strong, tough and light weight for transportation, buildings and energy applications (wind turbines)

- Natural materials such as nacre, bone and wood offer a solution to the engineers conundrum of designing materials that are strong, tough and light?

Wood is nature's structural material par excellence and an obvious target for biomimicry

It is strong, tough and lightweight employing ingenious toughening and strengthening mechanisms





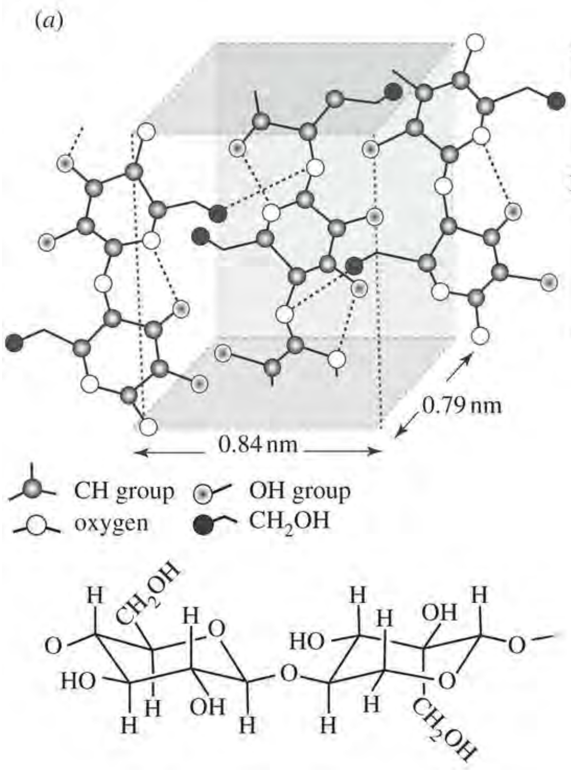
https://www.gatesnotes.com/The-New-Science-of-Strong-Materials

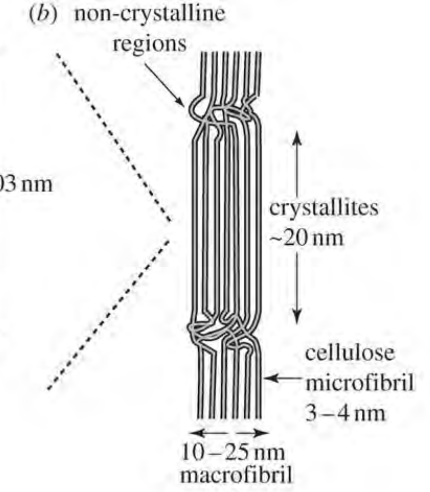
Wood Biomimetics (seeking materials with high strength and toughness)

Wood’s Strength and Toughness

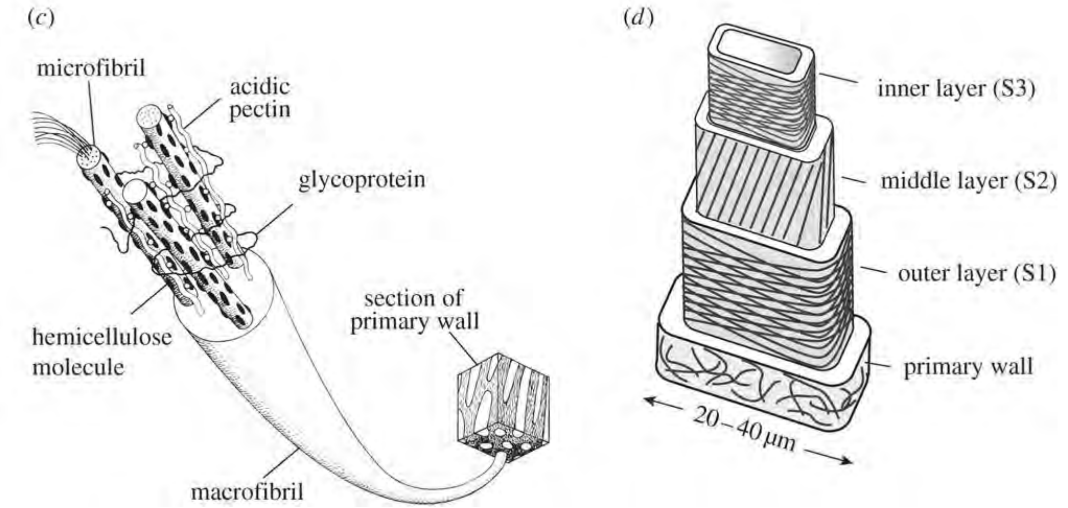
- High strength in fibre direction due to structural organization at molecular level
- Good toughness due to microstructure
  - Helical winding of microfibrils
  - Weak interfaces
  - Presence of holes (pores and lumens)
  - Presence of rays

Fibre & microfibril direction (covalent bonds = 50 kcal mol^{-1})



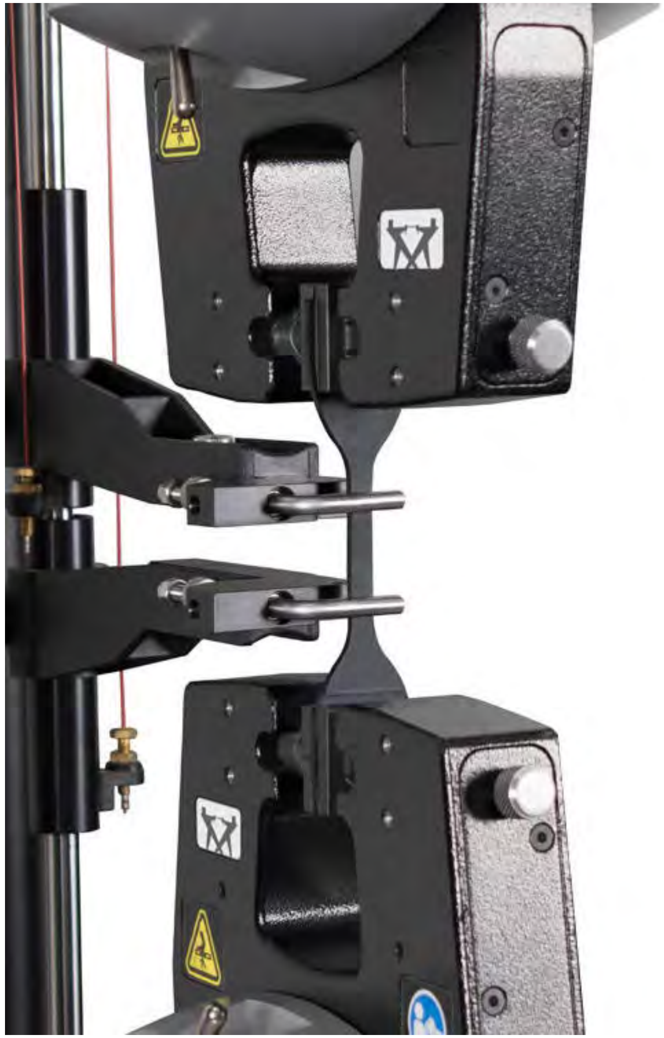


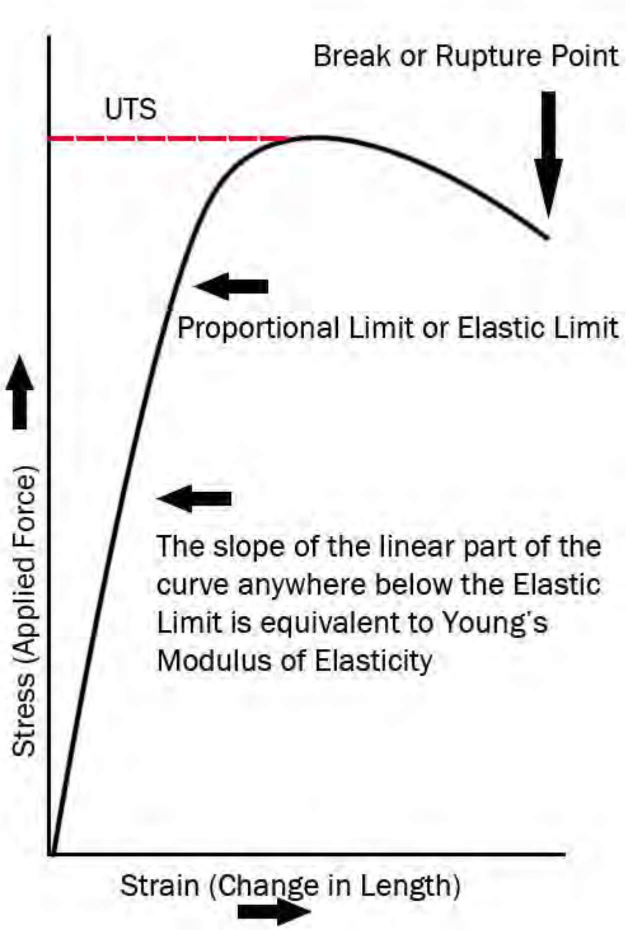
Between fibre & microfibril direction (hydrogen bonds = 15 kcal mol^{-1}



Examples of Wood Biomimicry

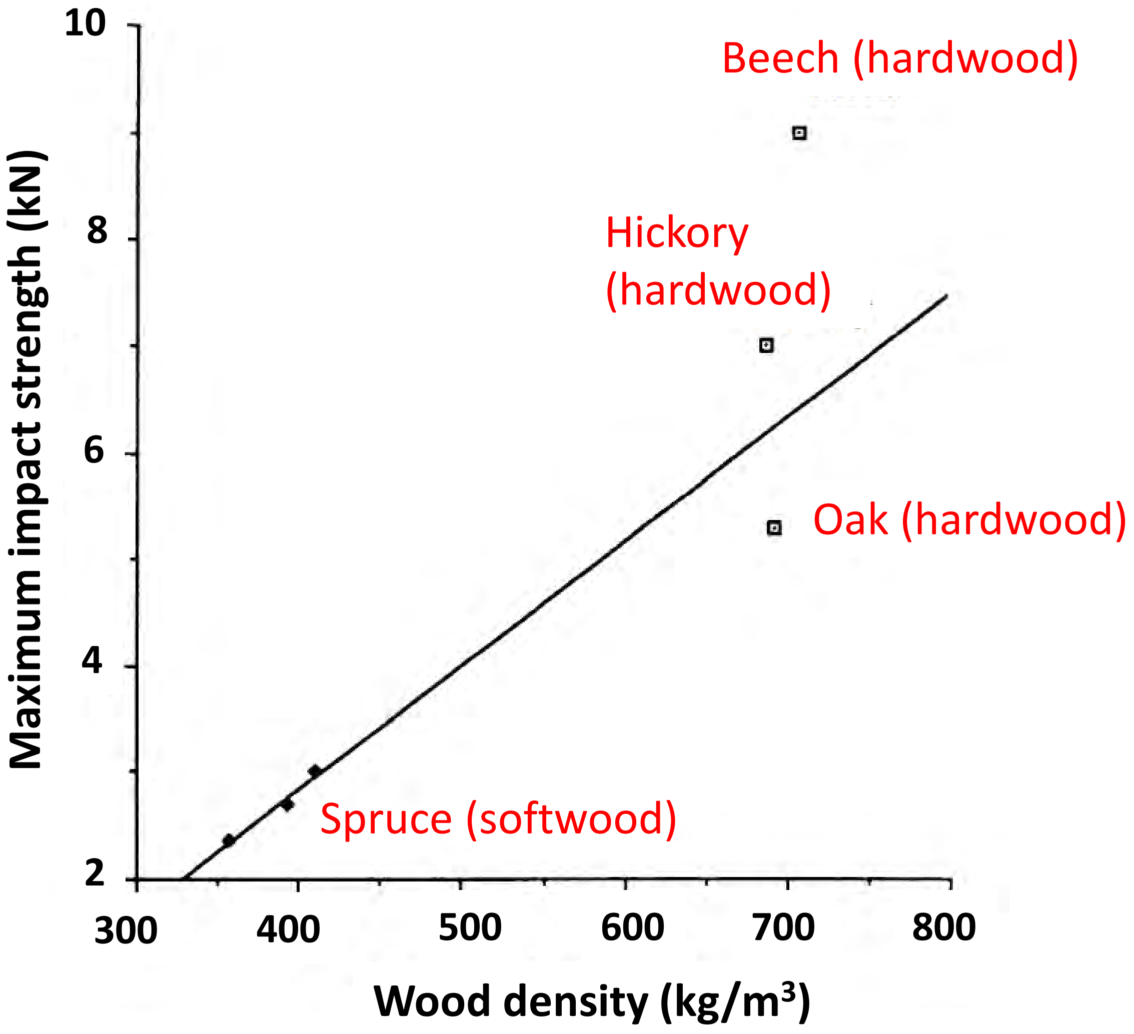
1. Biomimicry of hardwood vessels to make softwood tougher
2. Biomimicry of hardwood rays to make wood composites tougher
3. Biomimicry of wood to make new high performance synthetic materials

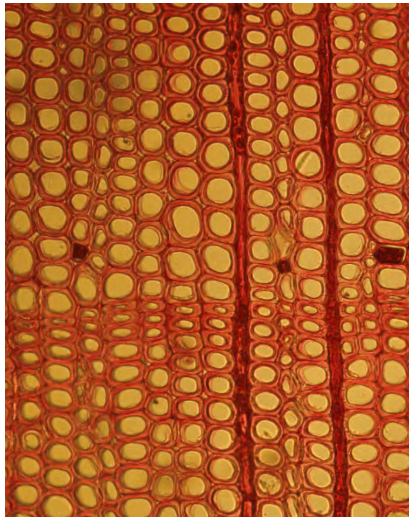




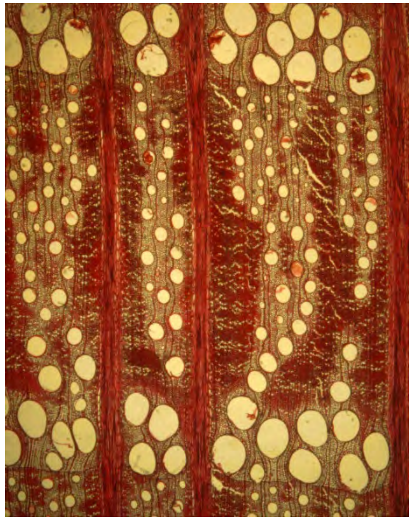
Example 1: Vessel Collapse- Mechanism Worthy of Mimicking to Make Softwoods Tougher

Toughness v Density

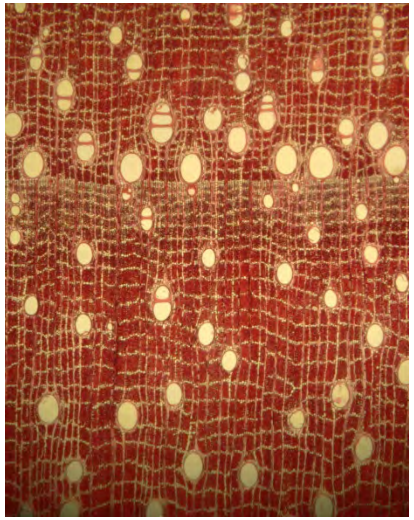




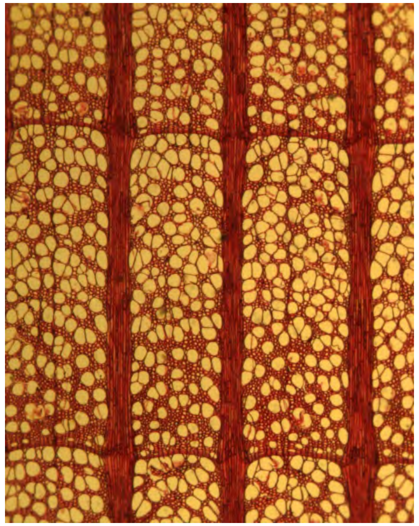
Softwood (*Callitris*)



Quercus rubra (red oak)



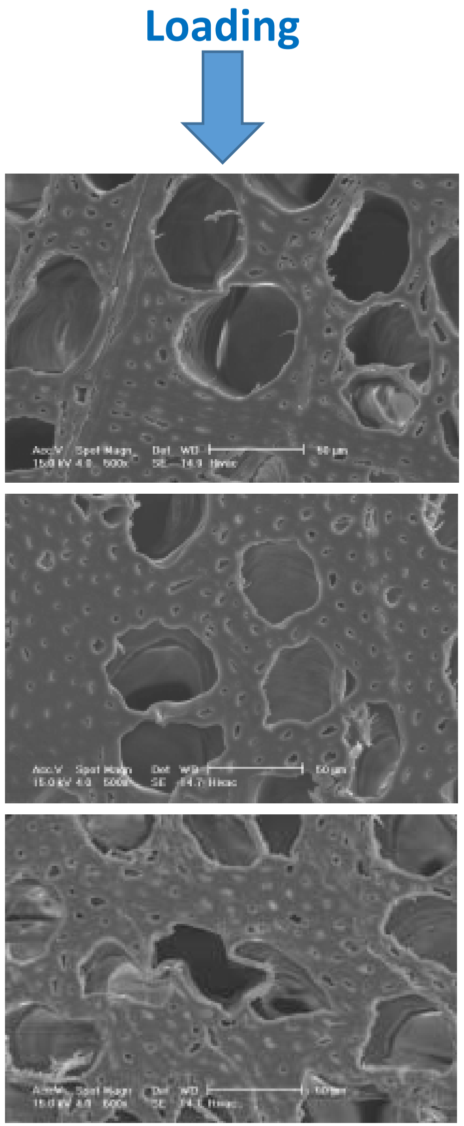
Carya sp. (hickory)



Platanus occidentalis
(sycamore)

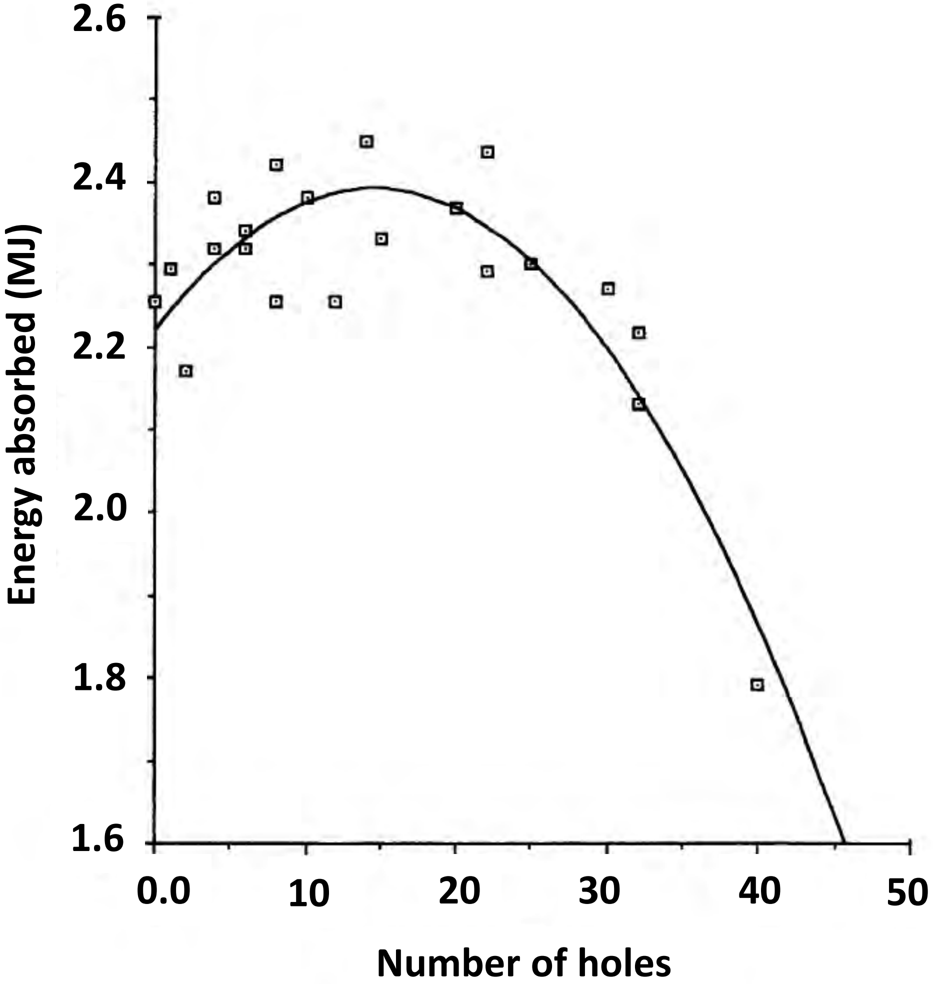
Vessel Mimicry

- Deformation of vessels during loading absorbs energy and toughens wood
- Drilling holes in softwoods can mimic the effect of vessels and increase the toughness of softwoods



Progressive plastic deformation and collapse of beech wood vessels during loading. Müller et al. IAWA J. 2003 24: 117-28.

Drilling 0.6 mm diam holes 0.6 mm into blocks of spruce, increases toughness by distributing the collapse of the wood more uniformly, (imitating hardwood failure)

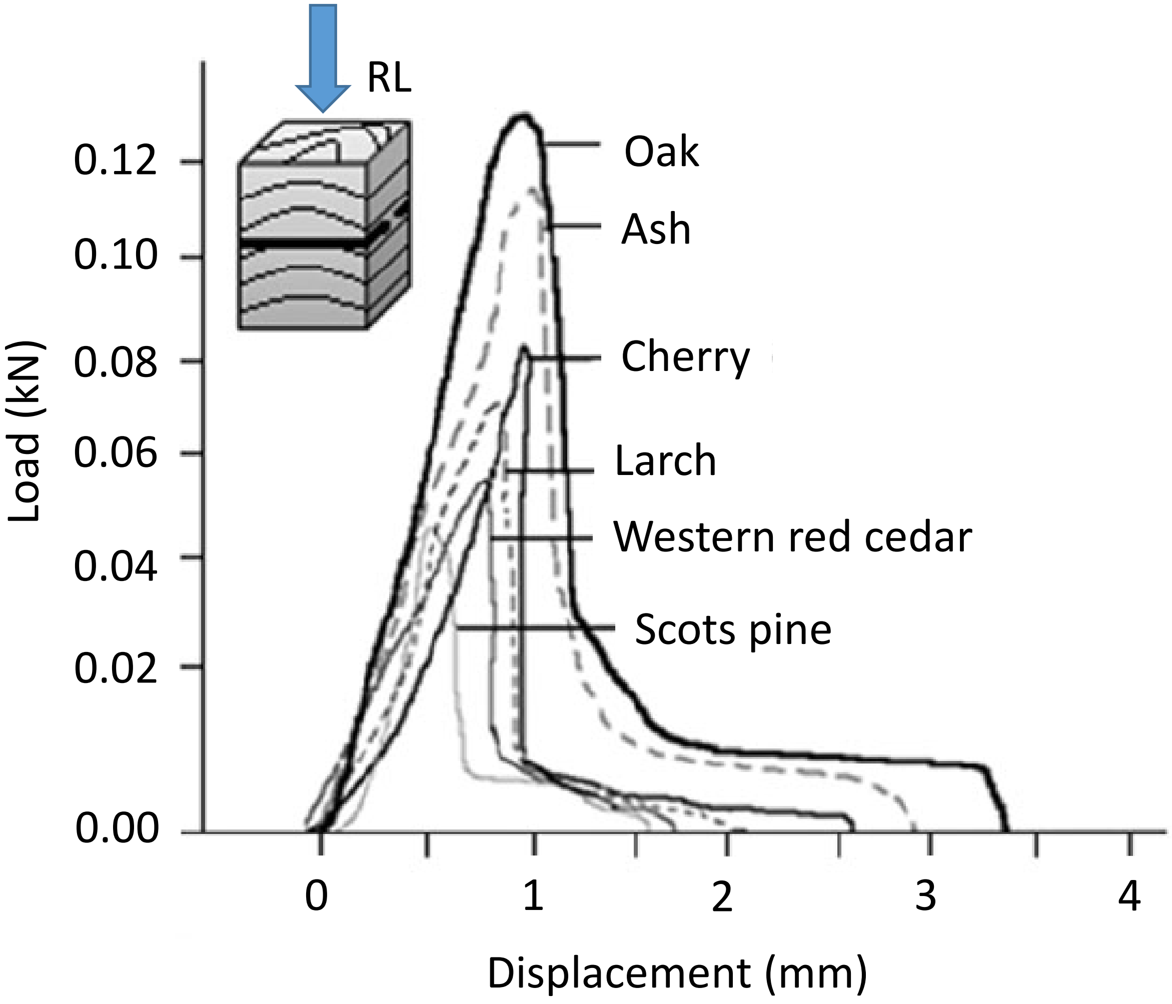


Vincent, J. Phil Trans Royal Soc. B: Biol Sci. 2003 358:1597-603

Example 2. Mimicking the Toughening Effects of Rays to Make Wood Composites Tougher

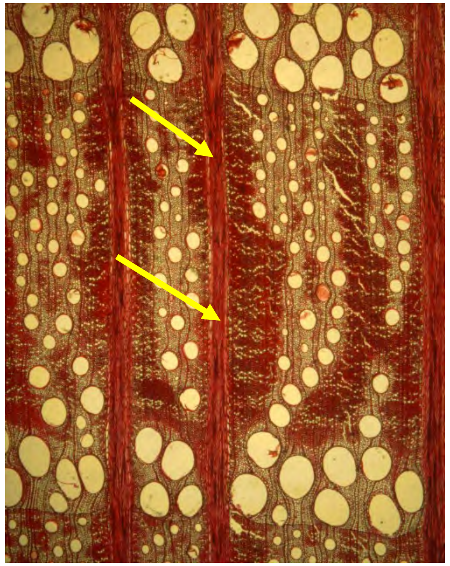
Ray Mimicry

Rays appear to toughen wood particularly when it is loaded in the radial direction

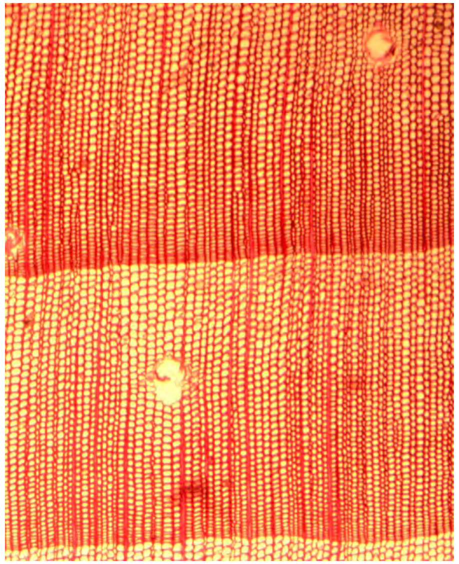


Load–displacement diagrams of different wood species during tensile tests in the radial direction

Özden, et al. 2017. Forestry: Int. J. For Res. 90:58-69

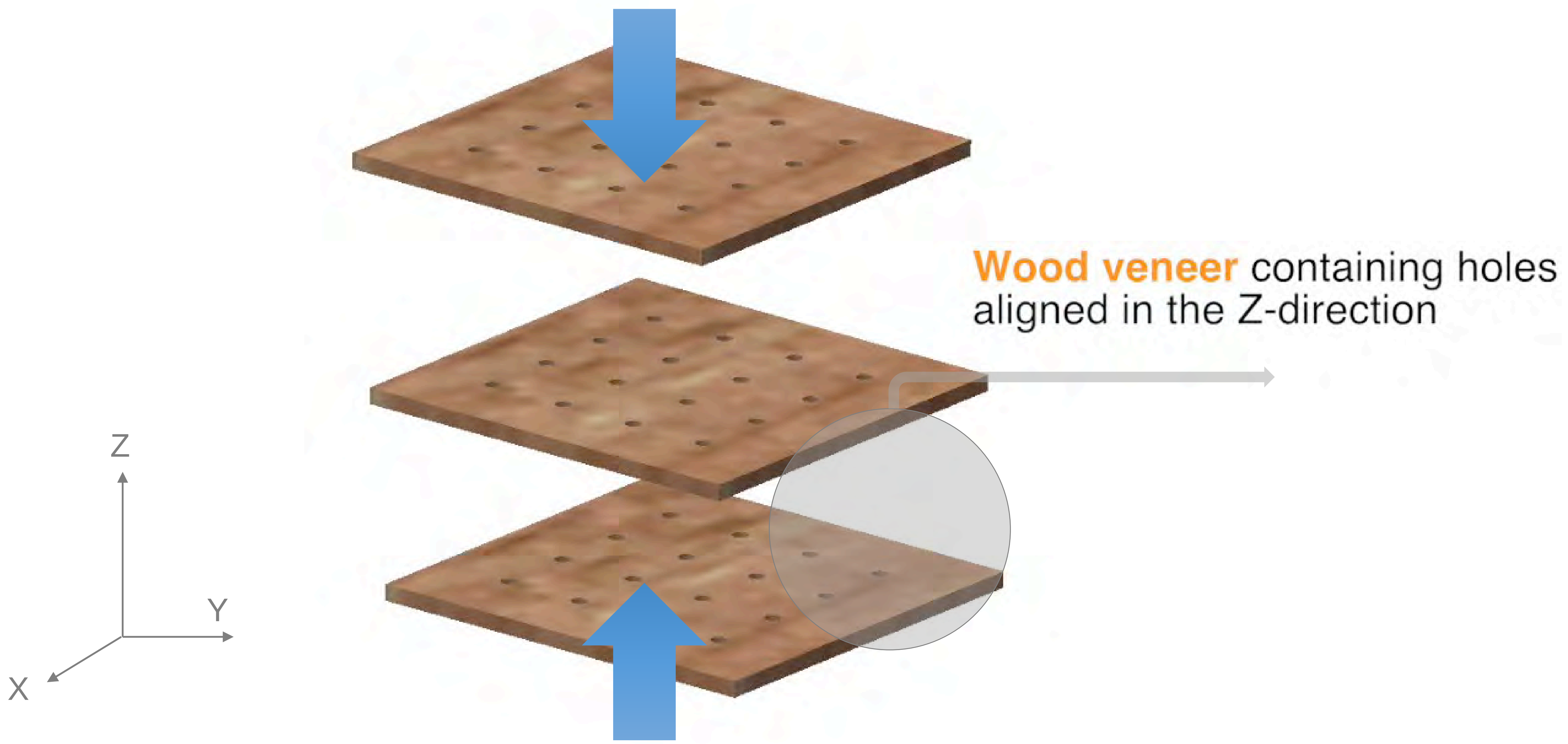


Red oak (wide rays)

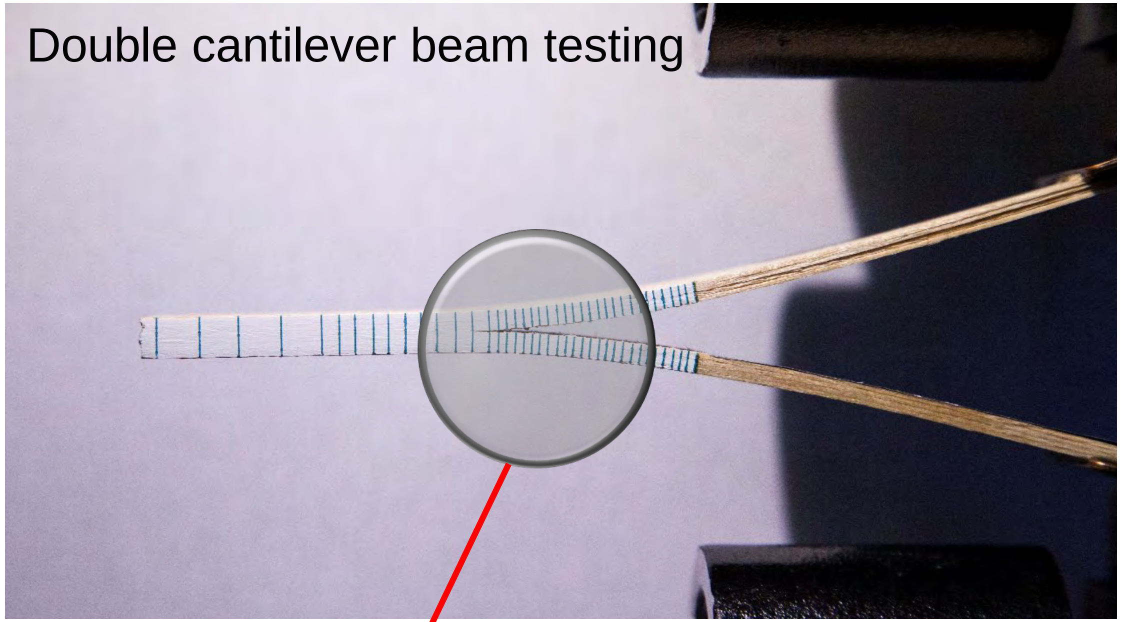


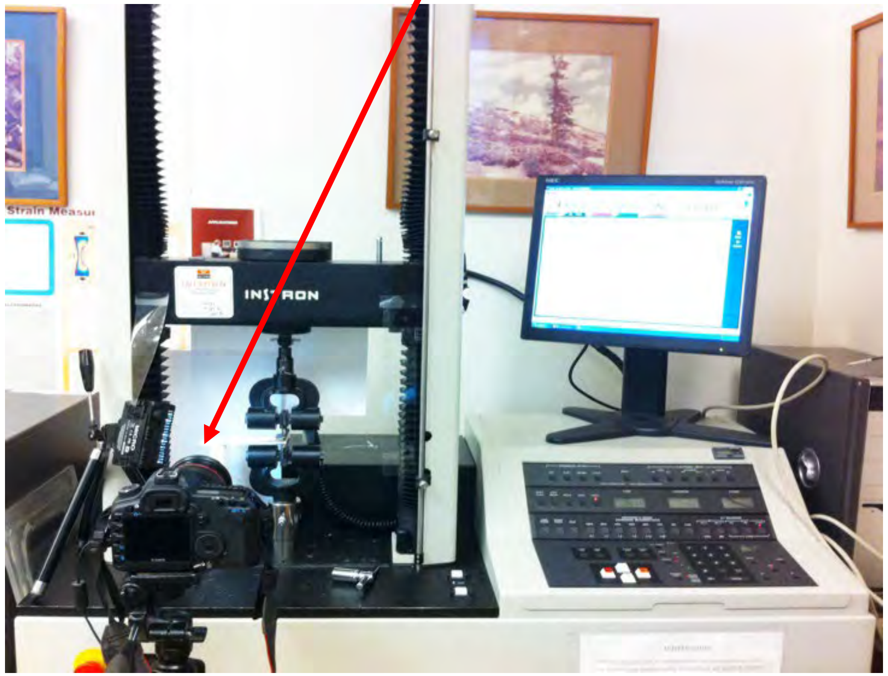
Pine (narrow rays)

Adhesive Penetration and Formation of Artificial Rays (Z-connections)

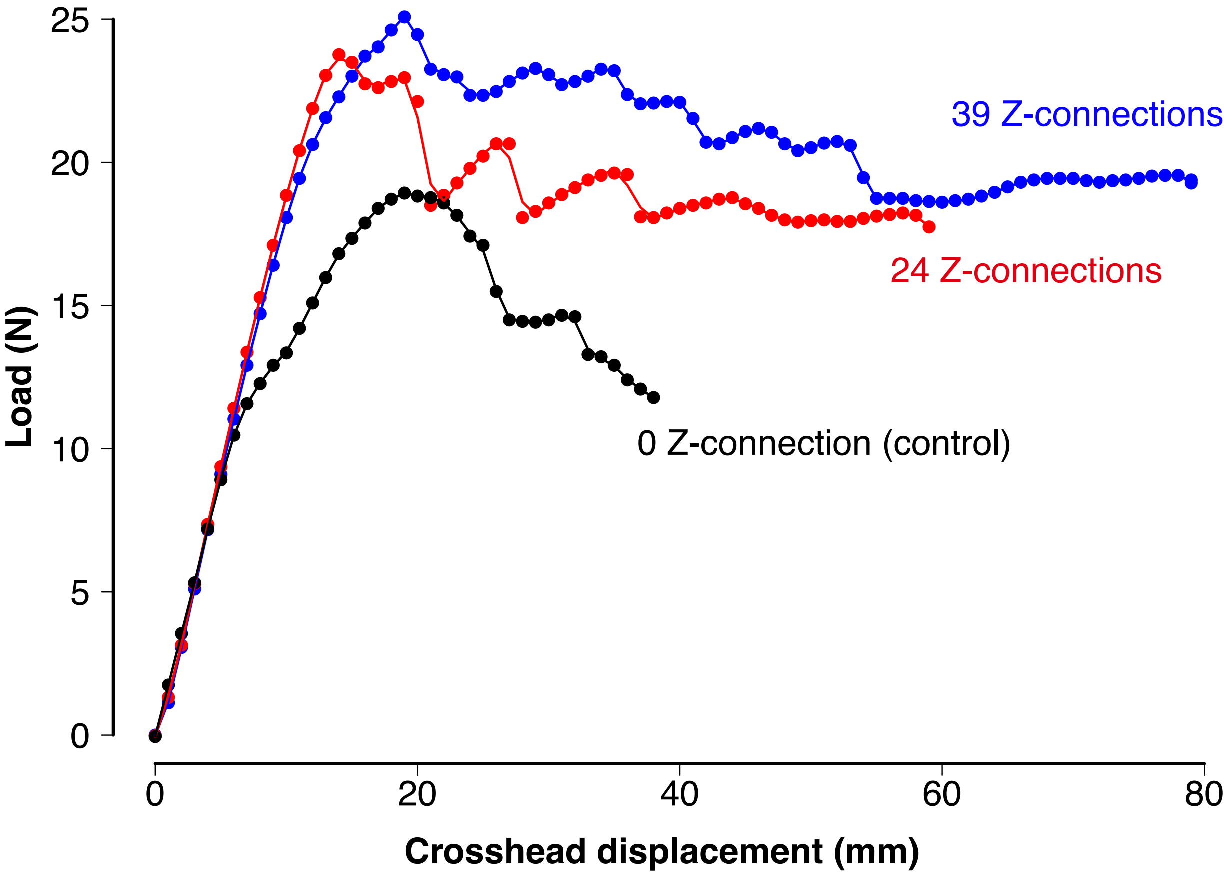


Effects of simulated rays (adhesive Z-connections) on toughness





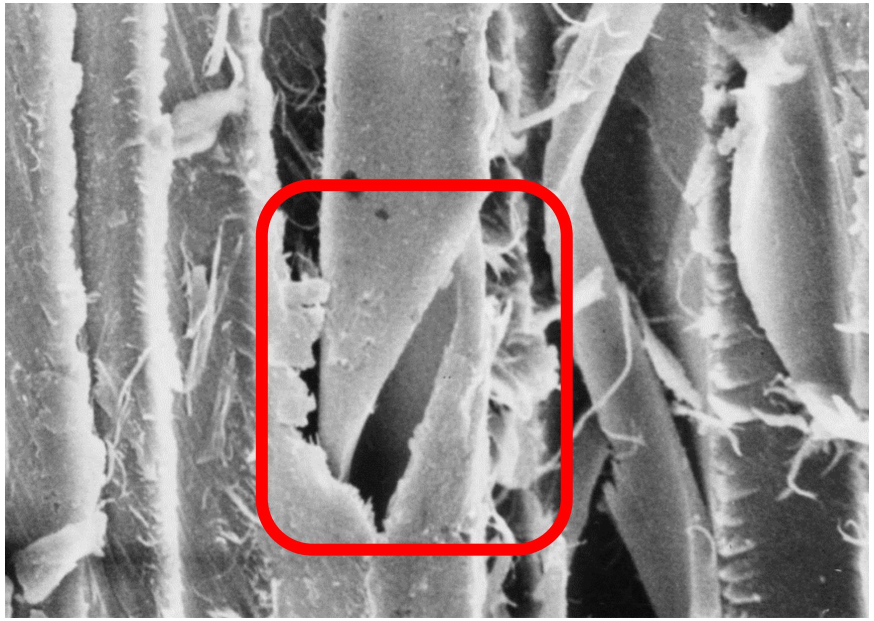
DSLR Camera to record crack propagation

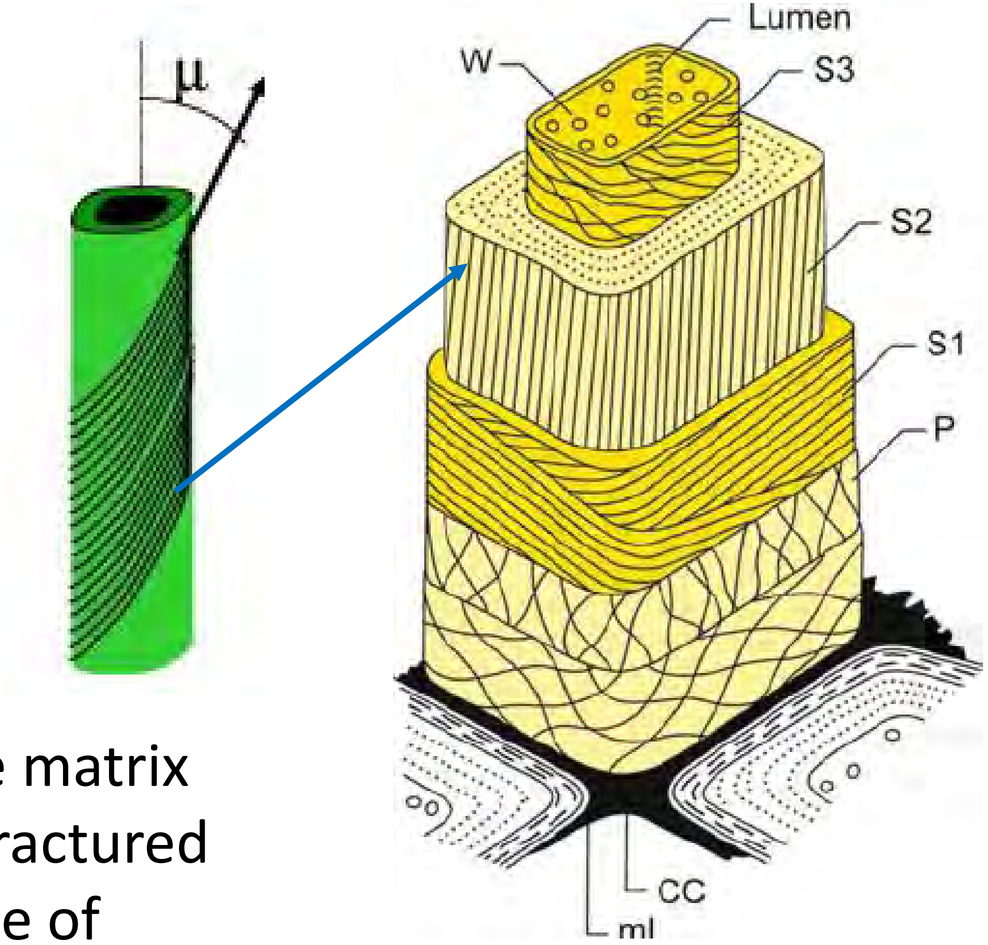


He, Evans. Advances Mat Sci Eng. 23, 2017

Example 3. Mimicking the Toughening Effects of Fibre Failure to Make Tough Synthetic Composites

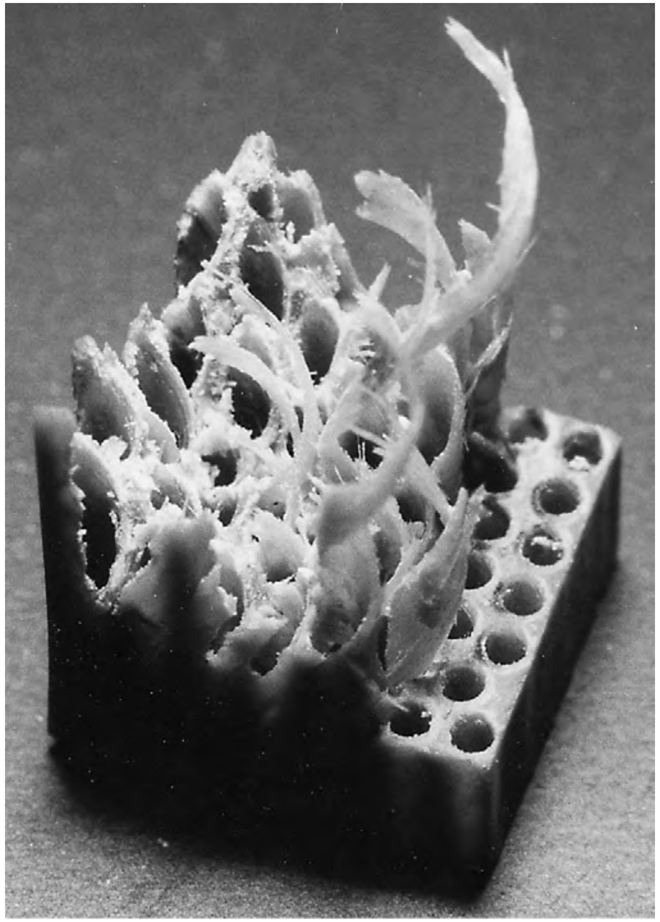
A Toughening Mechanism Worthy of Mimicking



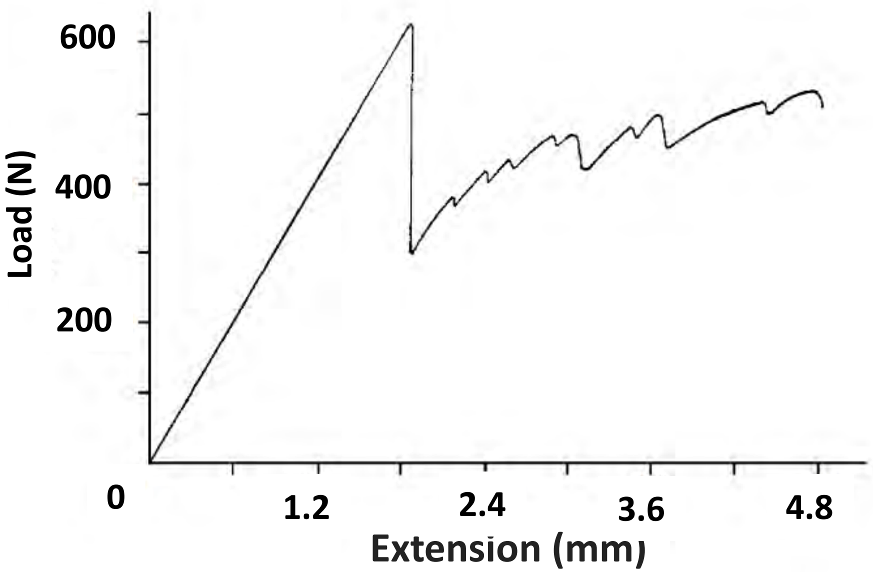


Spruce wood broken in tension (vertical direction). The matrix between the cellulose microfibrils in the cell wall has fractured in a helical fashion leaving the fibres (tracheids) capable of carrying a load

Jeronimidis Synthetic Wood Model

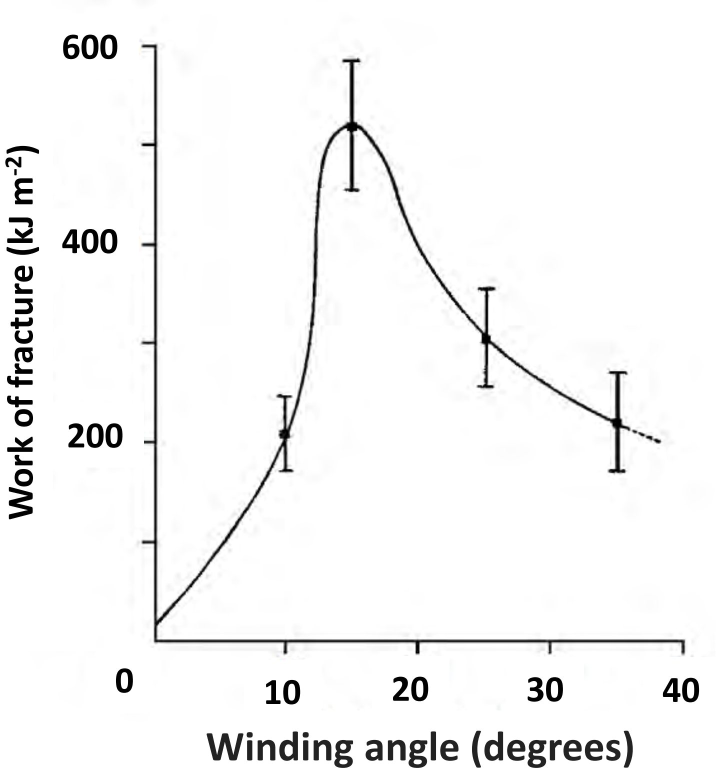


A wood model made of several wound GFRP tubes; the fracture surface is very similar to splintered wood



Failure curve of a tube of GFRP wound at 15°. After the initial failure, many small ones follow extending the strain to failure and absorbing large amounts of energy (proportional to the area beneath the curve)

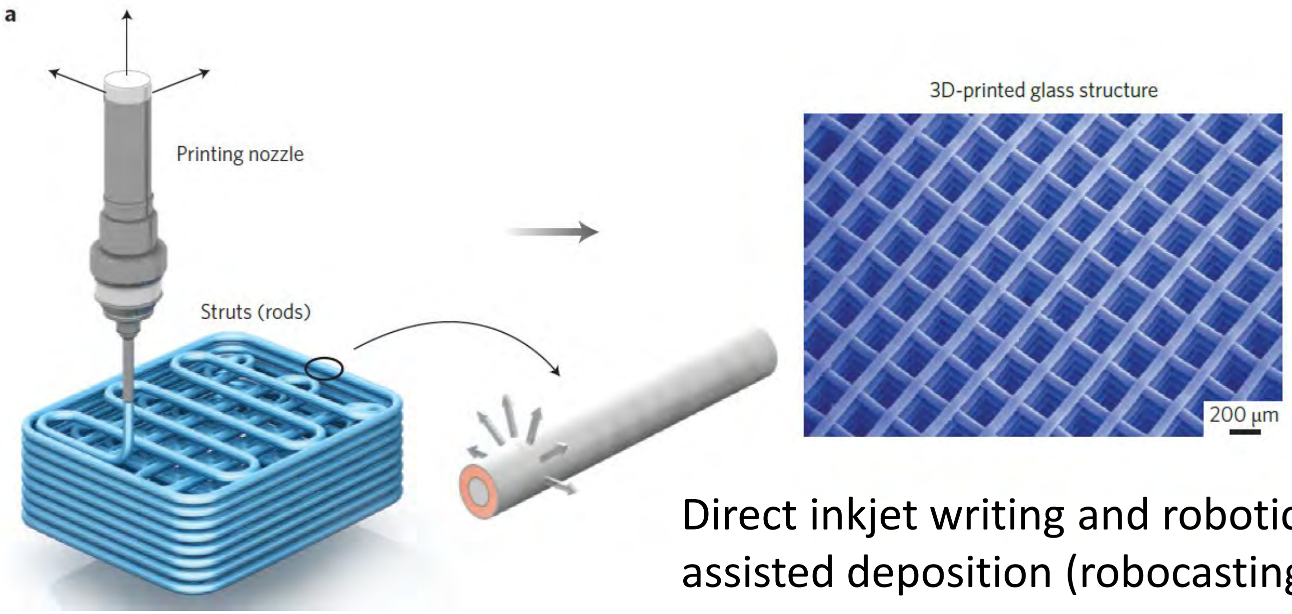
Work of fracture varies with the winding angle in the GFRP tubes



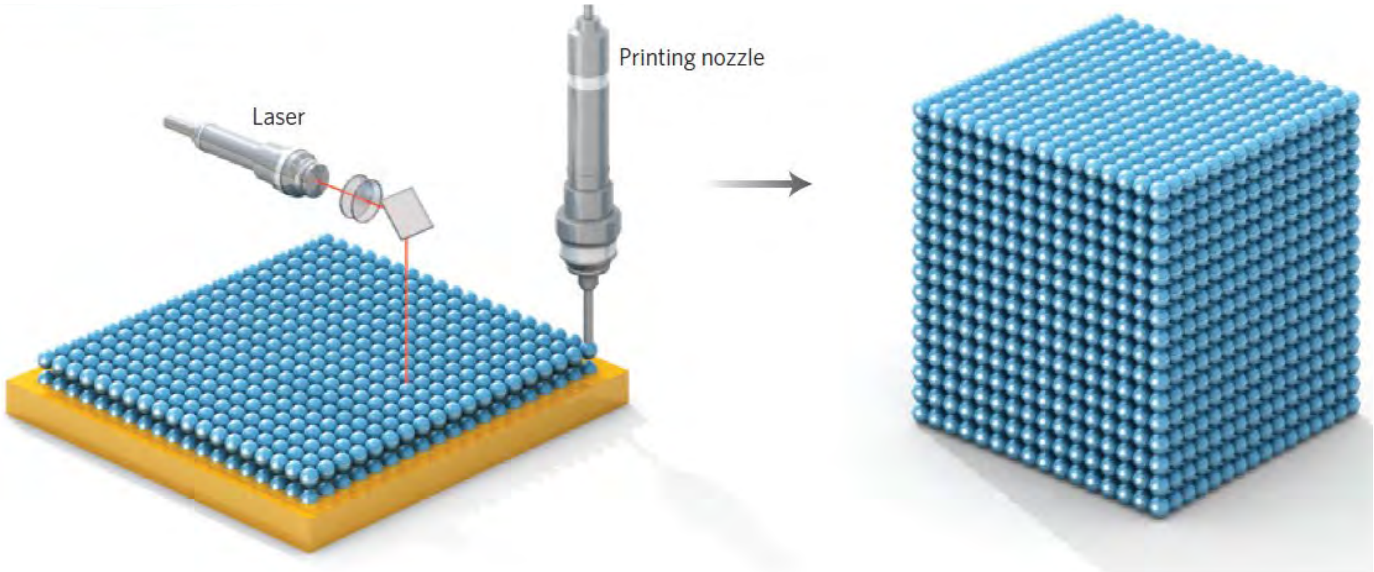
Jeronimidis Proc Royal Soc London. B. Biol Sci. 1980 208:447-60

Translating Key Design Parameters From Wood into New Materials

- All of the aforementioned examples took structural (meso-scale) features from wood to create new materials with improved strength/toughness parameter
- But the approaches have not been adopted
- Could the development of 3D printing technologies change this?

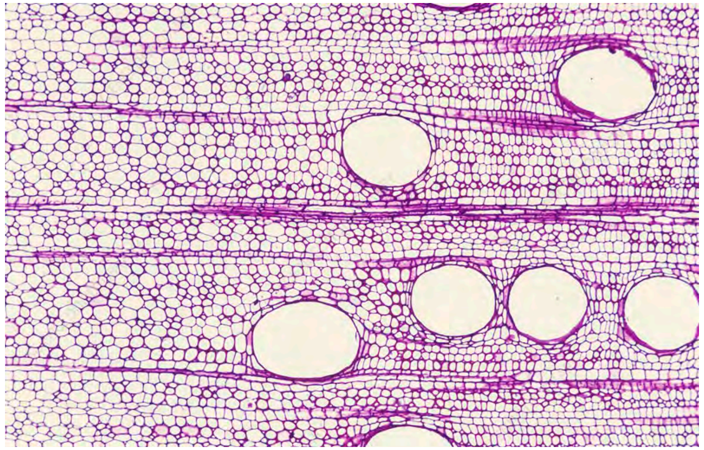


Direct inkjet writing and robotic-assisted deposition (robocasting)

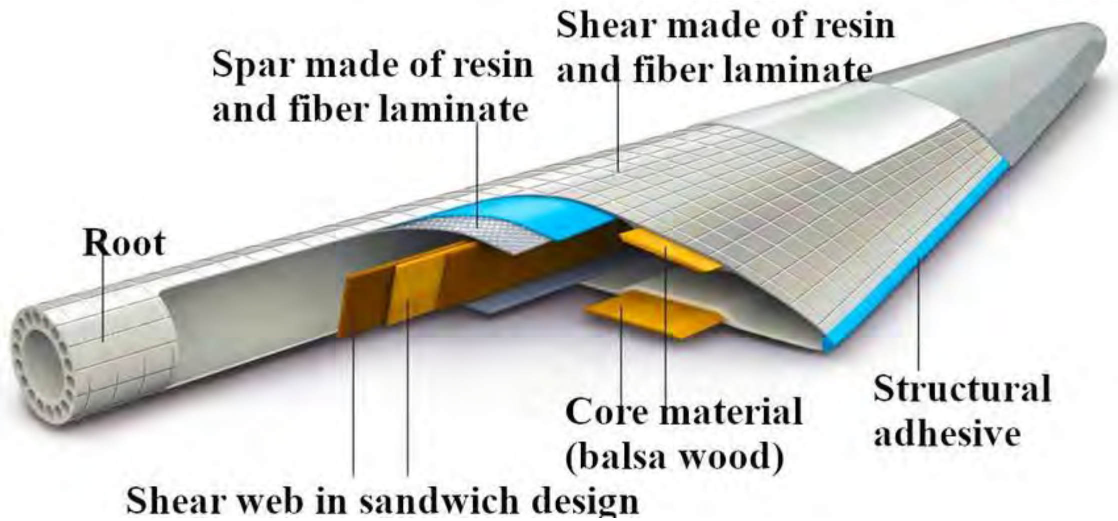


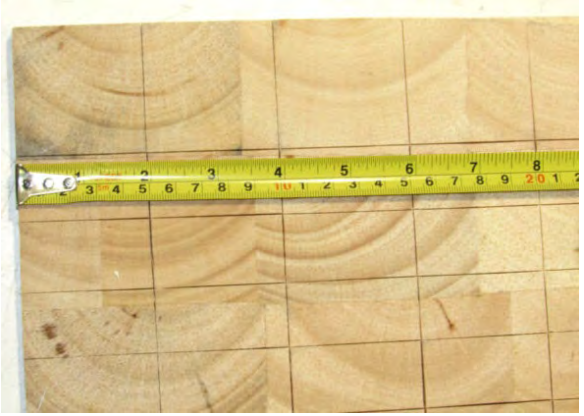
Droplet-deposition (jetting), to form printed droplet networks

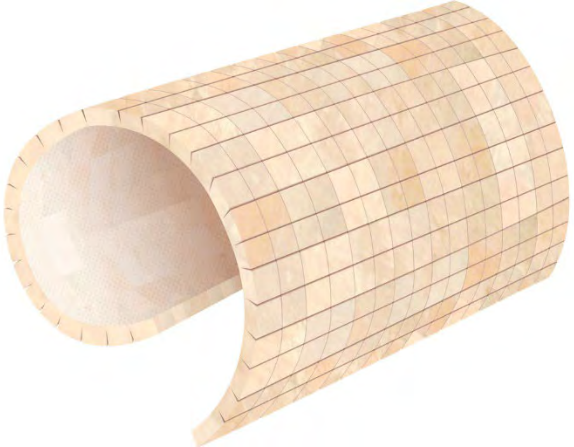
Biomimetic Balsa for Wind Turbine Blades



Transverse surface of balsa

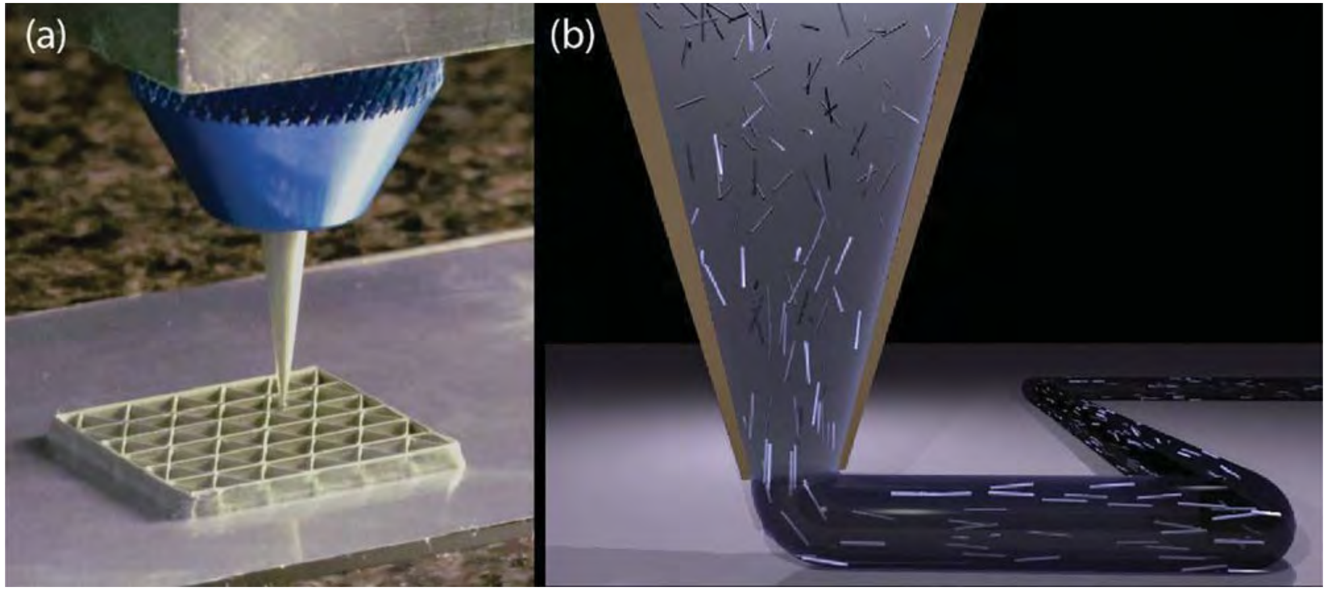


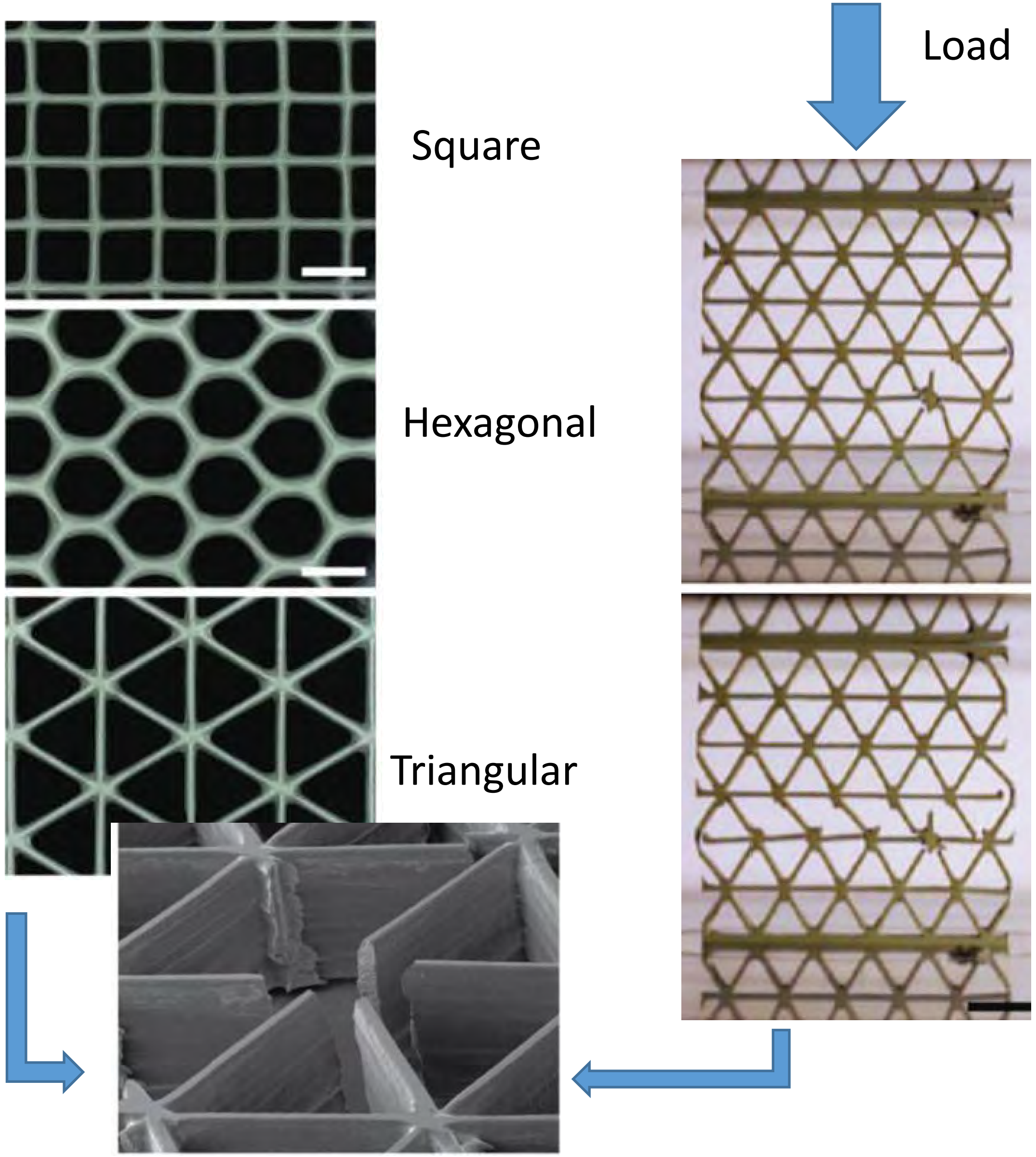




End grain balsa core

3D printed ‘balsa’ honeycomb epoxy composite containing SiC whiskers



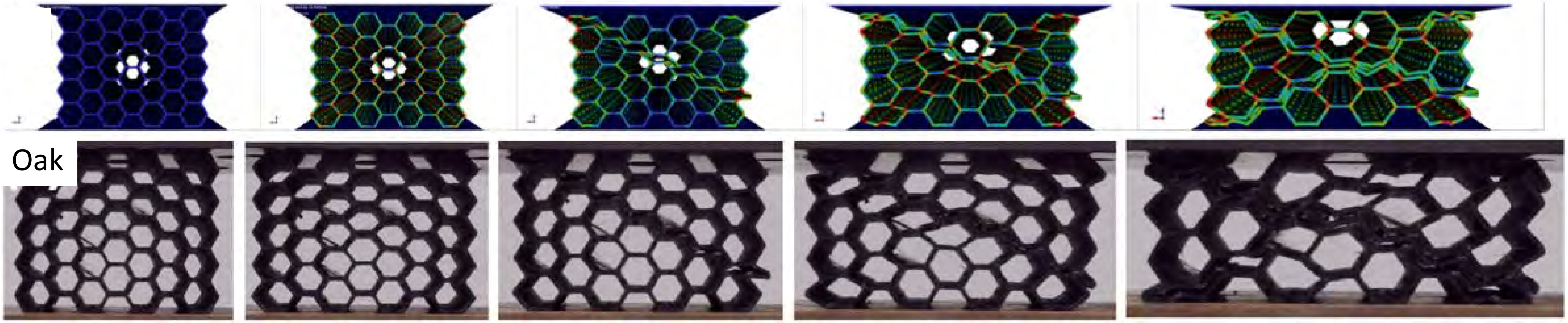


Compton & Lewis 2014 Advanced Mat. 26:5930

Honeycomb structures composed of SiC-filled epoxy. Scale bars are 2 mm

More realistic 3D printed models of wood and testing and modelling of mechanical properties

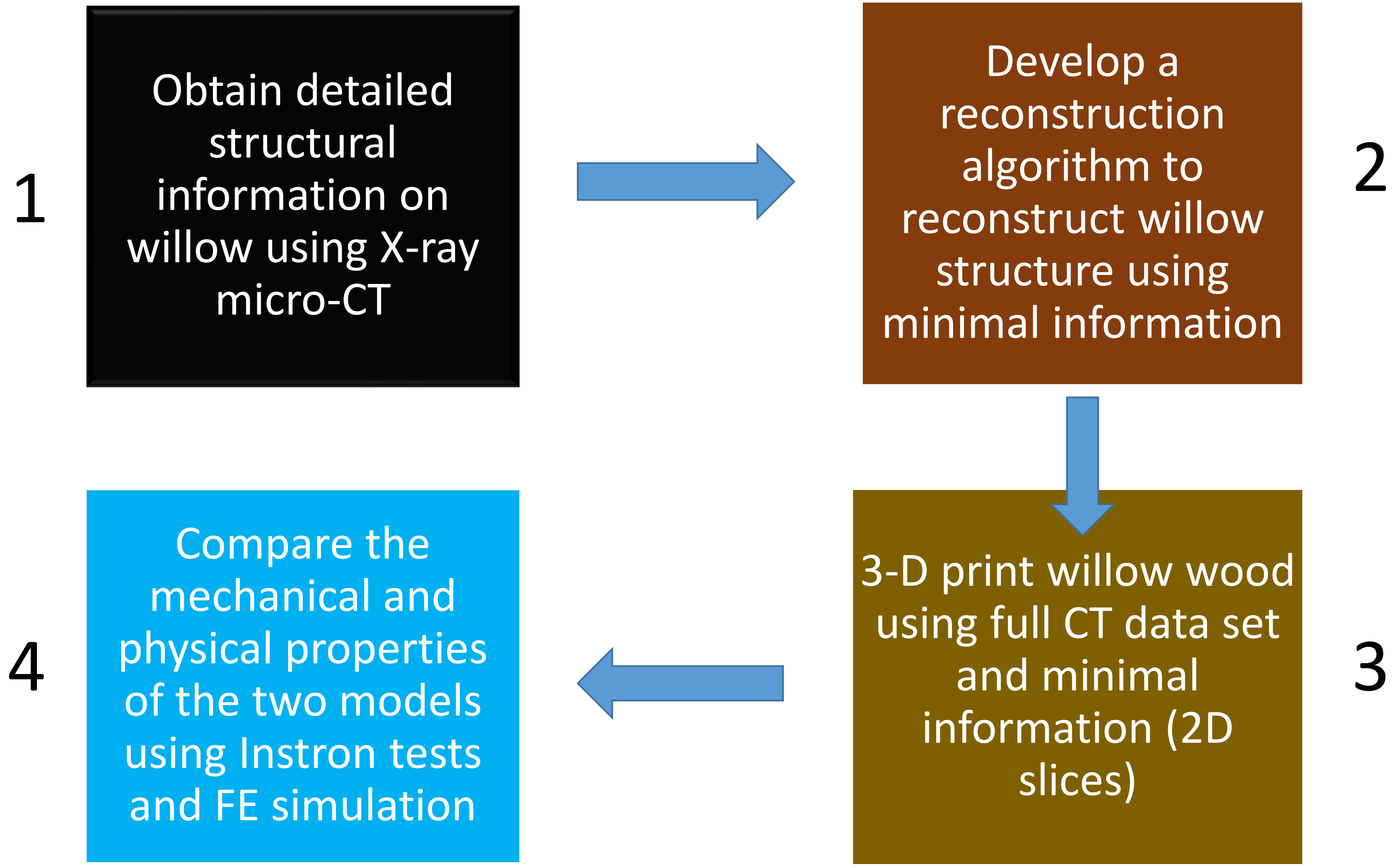
Cedar Oak Palm



Ufodike et al. 2021. J Mech Behavior Biomed Mat. 123:104729

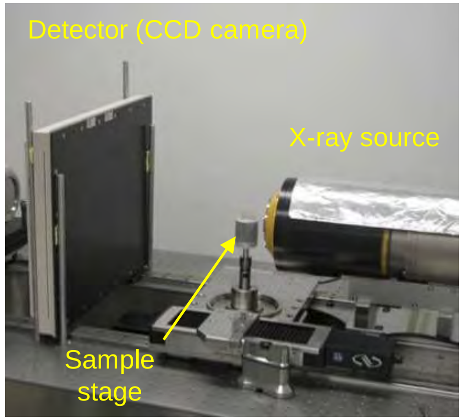
None of the studies carried out to date capture the complex meso-scale microstructure of wood. Therefore it has not possible to extract design feature from wood for potential biomimicry

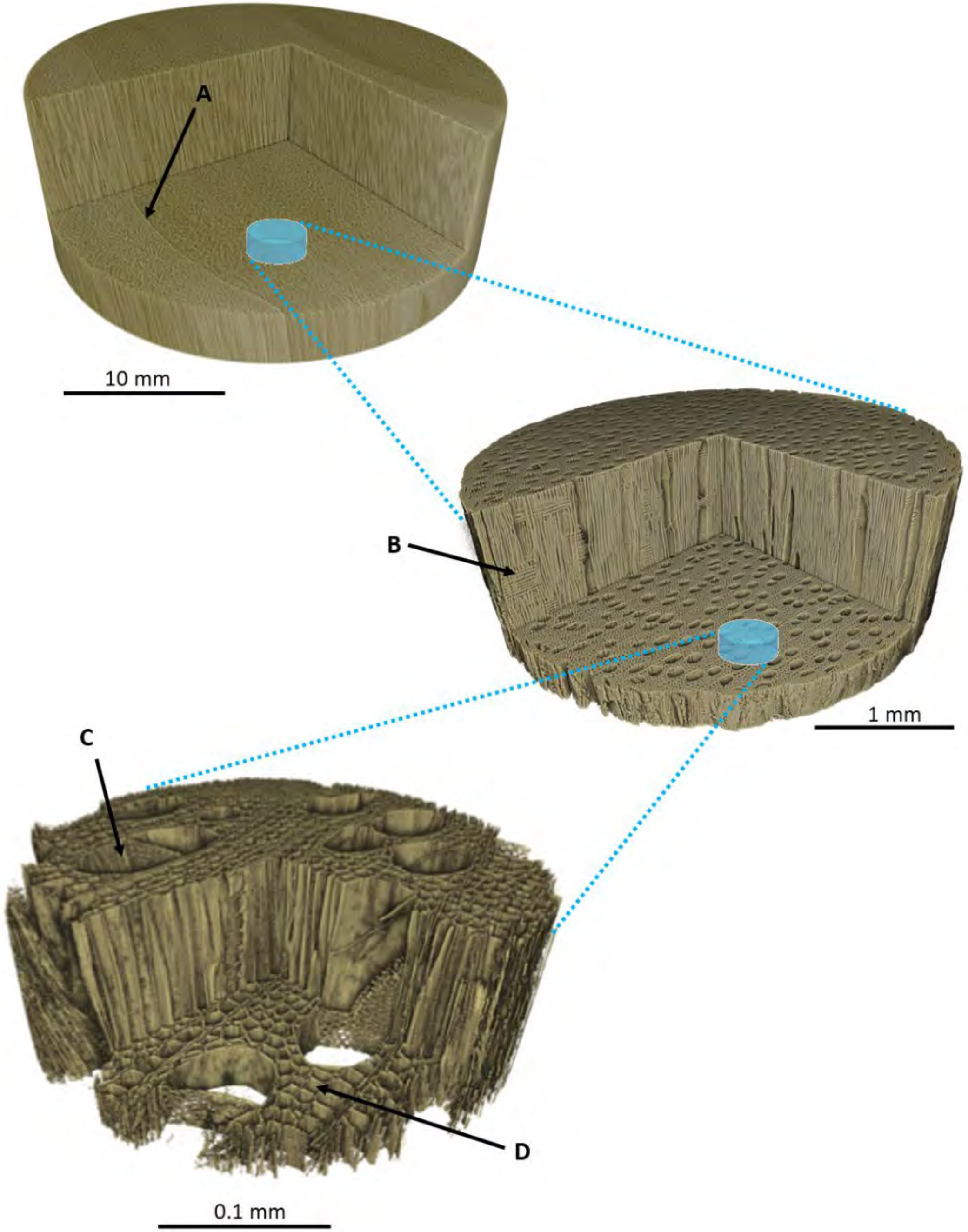
This is a Problem we have Addressed in our Latest Work

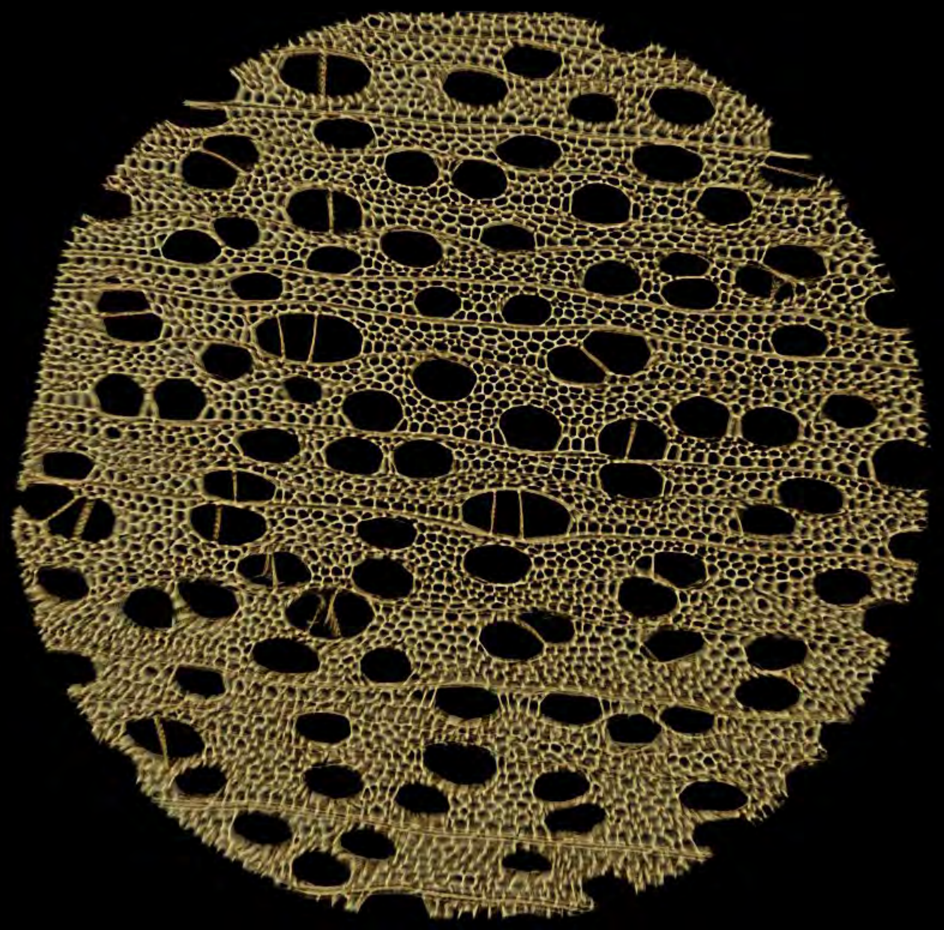

1
Obtain detailed structural information on willow using X-ray micro-CT
2
Develop a reconstruction algorithm to reconstruct willow structure using minimal information
3
3-D print willow wood using full CT data set and minimal information (2D slices)
4
Compare the mechanical and physical properties of the two models using Instron tests and FE simulation

Step 1. X-ray micro-CT

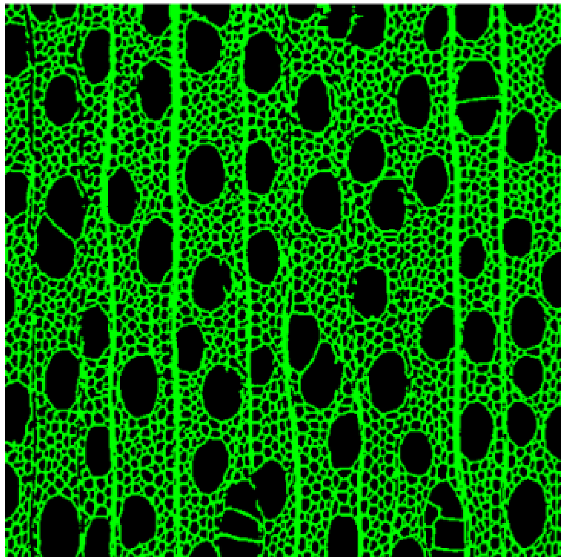
High resolution imaging (X-ray CT) coupled and the use of a super-computer to reconstruct the meso-scale structure of willow in exquisite detail



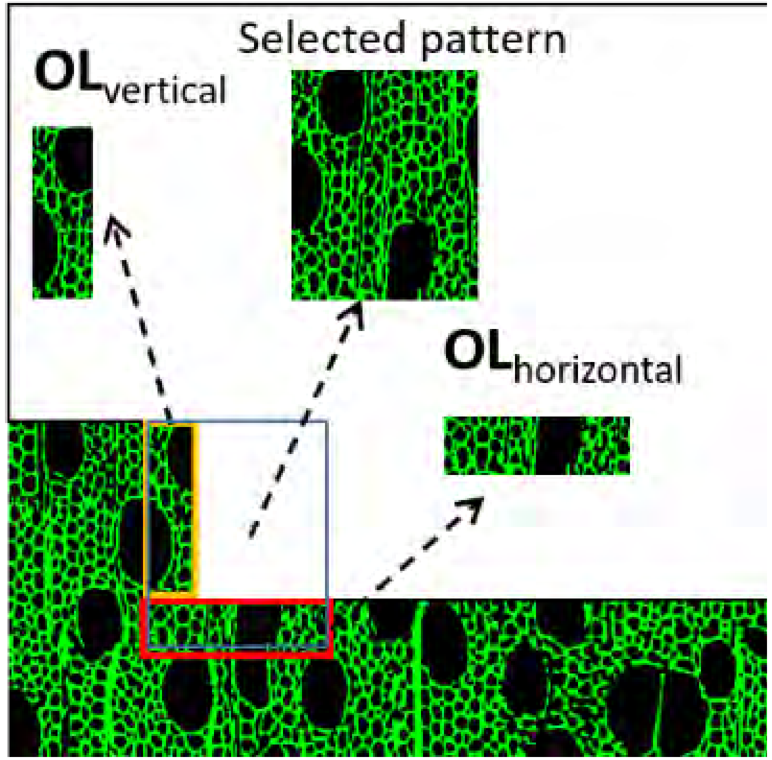




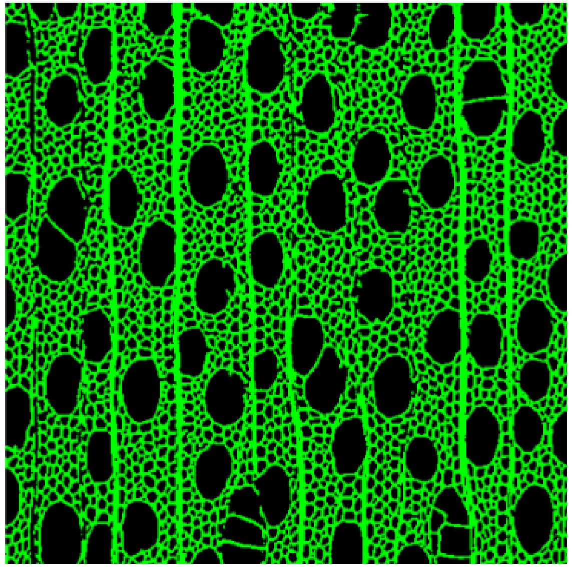
Step 2. CCSIM reconstruction method



A single slice of willow's (wood) microstructure from CT is used as input to the CCSIM algorithm



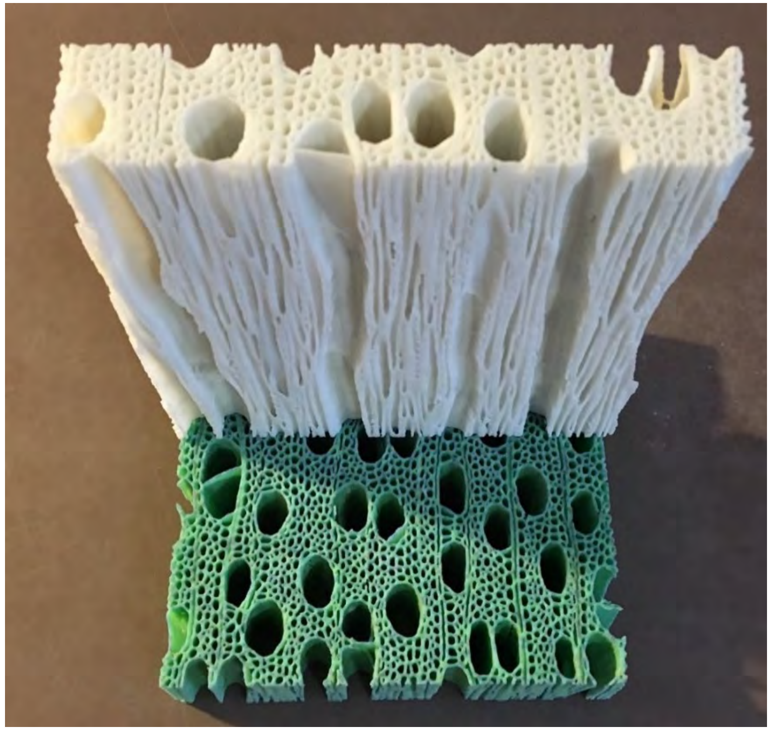
Two overlap (OL) regions are extracted from previously reconstructed locations and their cross correlations are calculated against the patterns in the input image. The patterns in the input image are then sorted and one of the most accurate patterns is selected



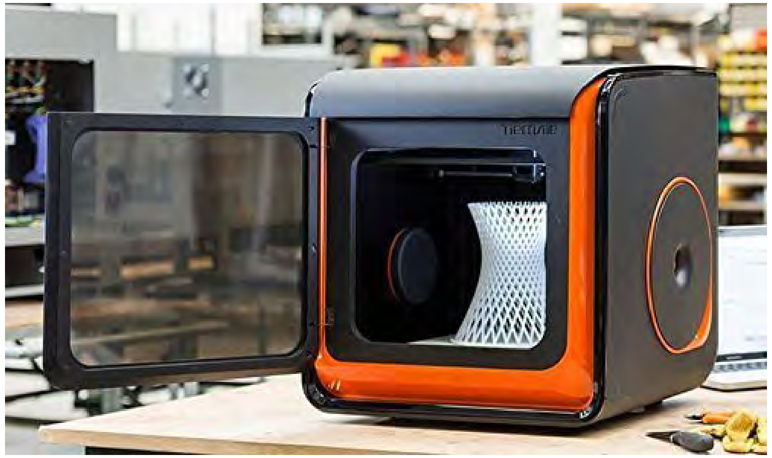
A 2D slice of the output 3D reconstruction by CCSIM

Step 3. 3D printing of willow: one model from full CT data set and another from smaller data set via CCSIM reconstruction

- 3D models made from 70% wood particles and 30% of polylactic acid
- Nozzle size (diameter) of 0.30 mm for printing
- Layer height (z) resolution) of 0.1 mm and horizontal (x-y) resolution of 0.4 mm. Nozzle temperature of 200°C and printing bed temperature of 50°C



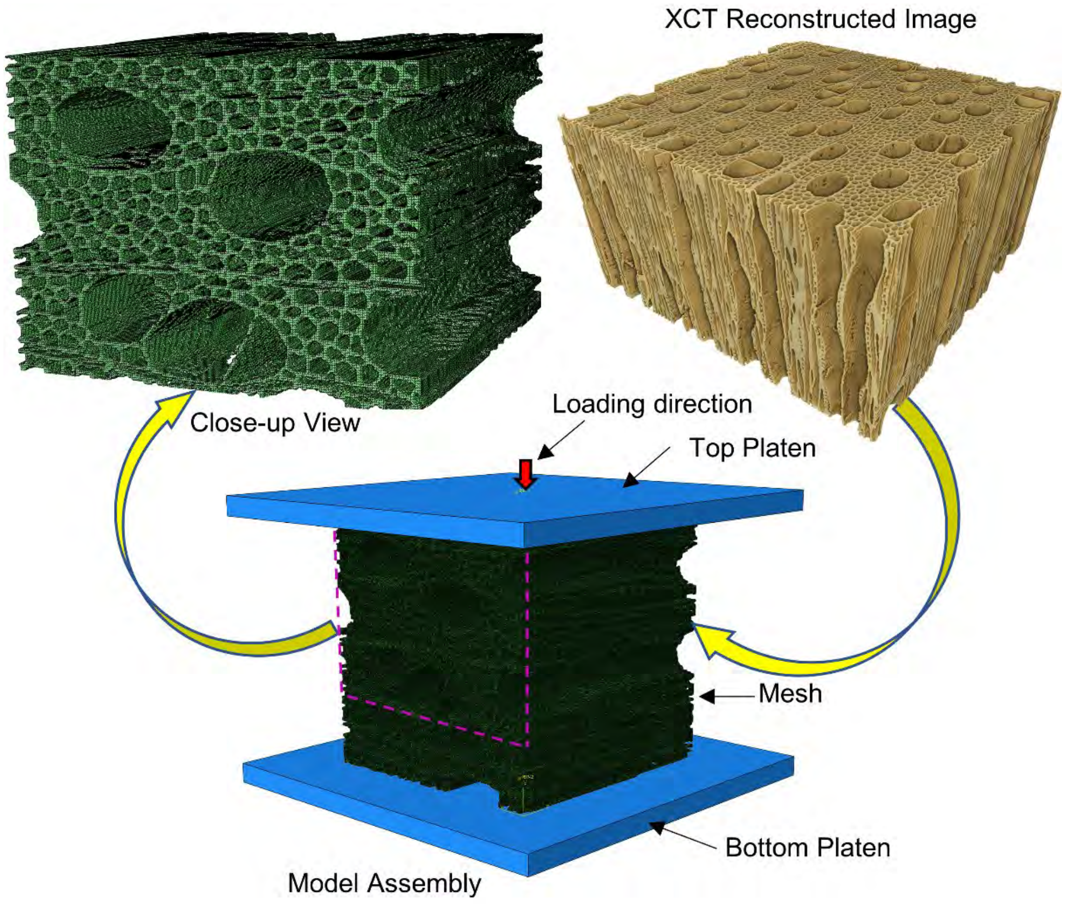
Examples of 3D printed willow models



3D printer (UP BOX + made by Tiertime)

Step 4. Compare the physical properties of the two models using mechanical tests and FE simulation

- Quasi-static compression tests including capture of deformation of (XCT and CCSIM-generated samples)
- Finite-element method (FEM) employing a fast conjugate-gradient method compared the elastic properties of CCSIM-reconstructed 3D models and 3D images of wood structures derived from XCT

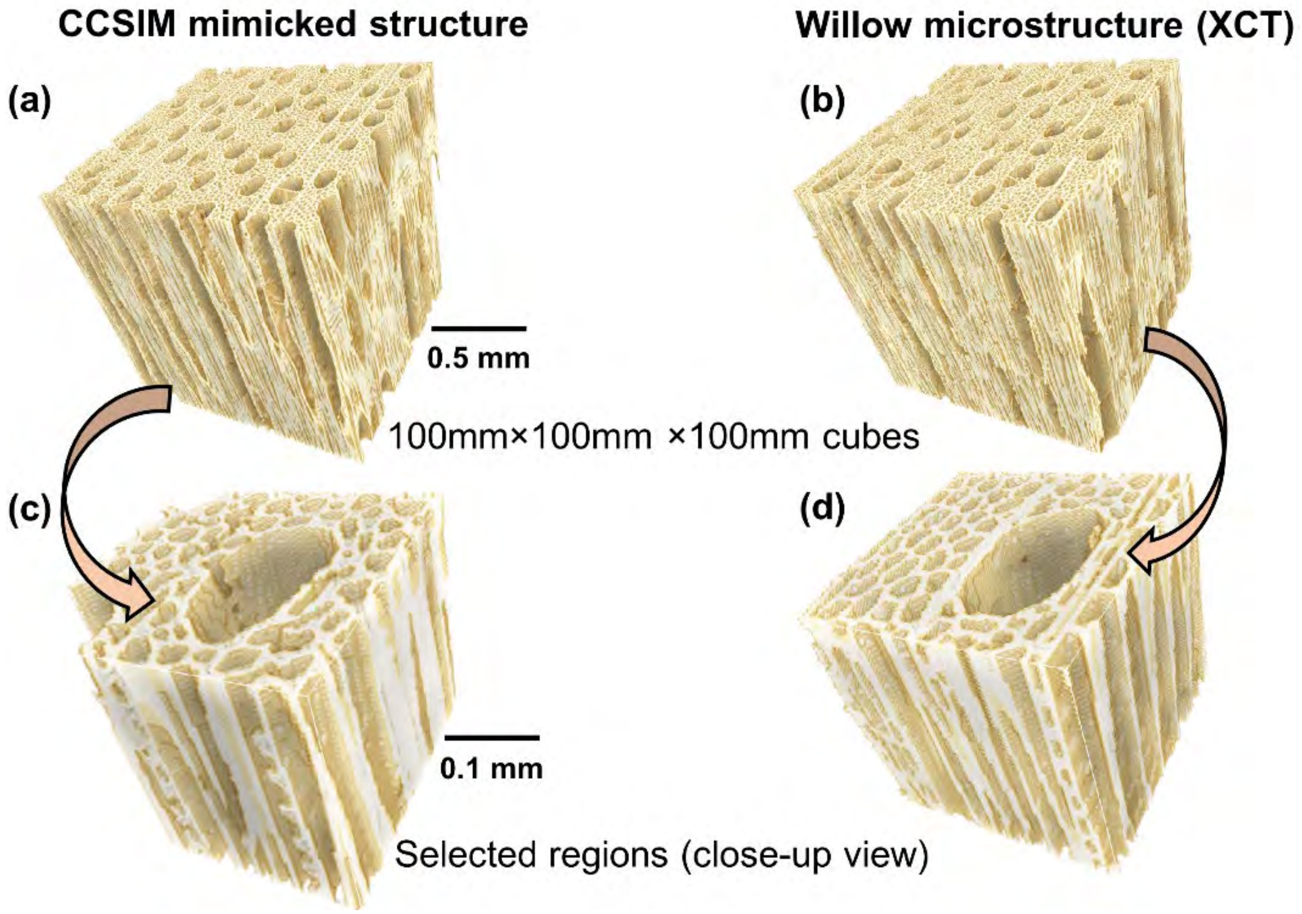


FE model assembly and the close-up view of the wood microstructure and the generated mesh

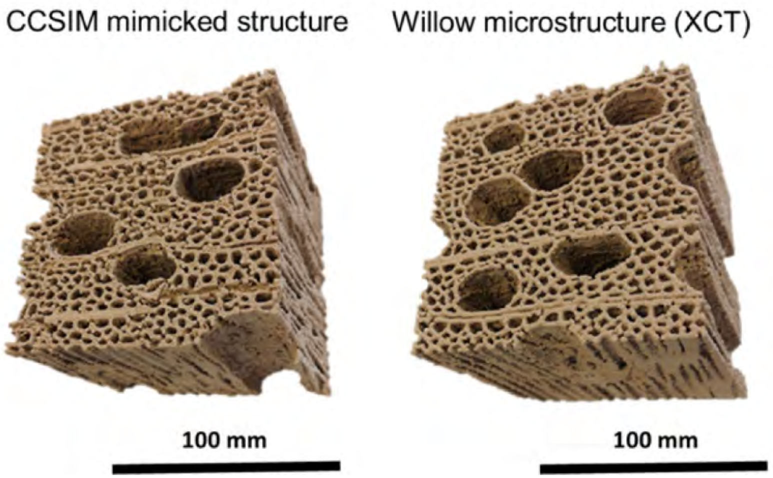
Results

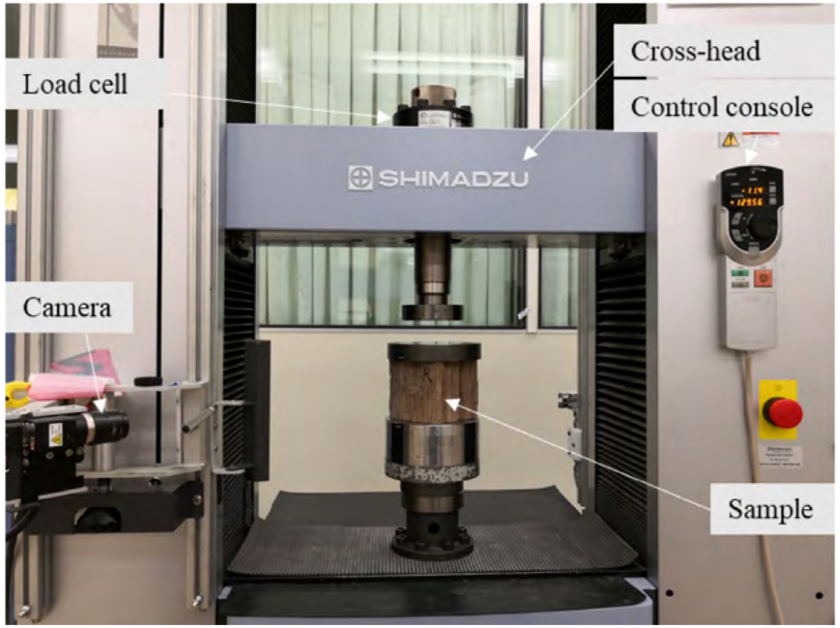
Comparison of the Structure of CCSIM and XCT Models

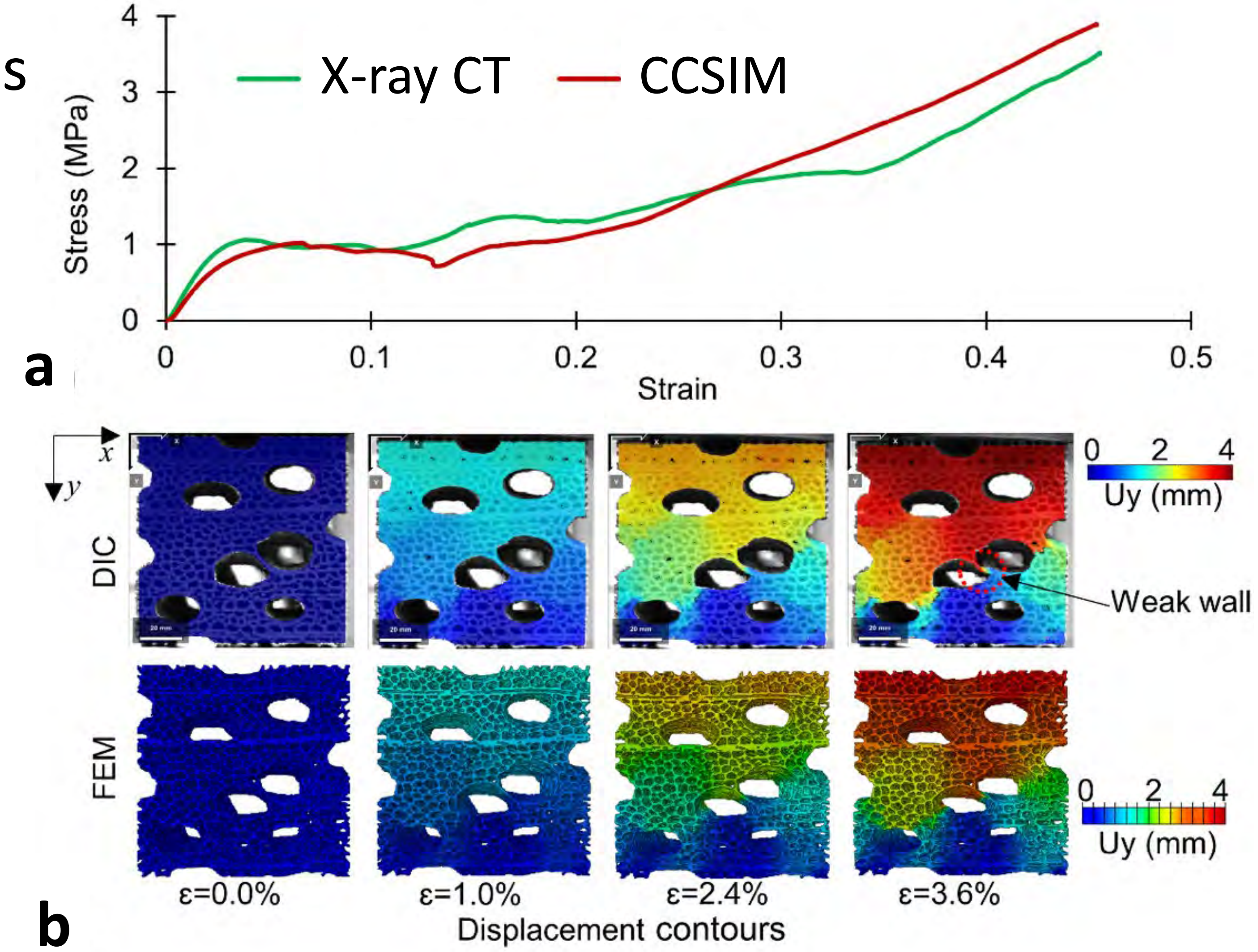
- At lower resolution the CCSIM and XCT images look remarkably similar. The diffuse porous distribution of vessels is evident, as is the presence of vessel multiples and rays
- At higher resolution some cellular elements in the CCSIM model are lacking part of their cell wall



Comparison of the Mechanical Properties of CCSIM and XCT Models





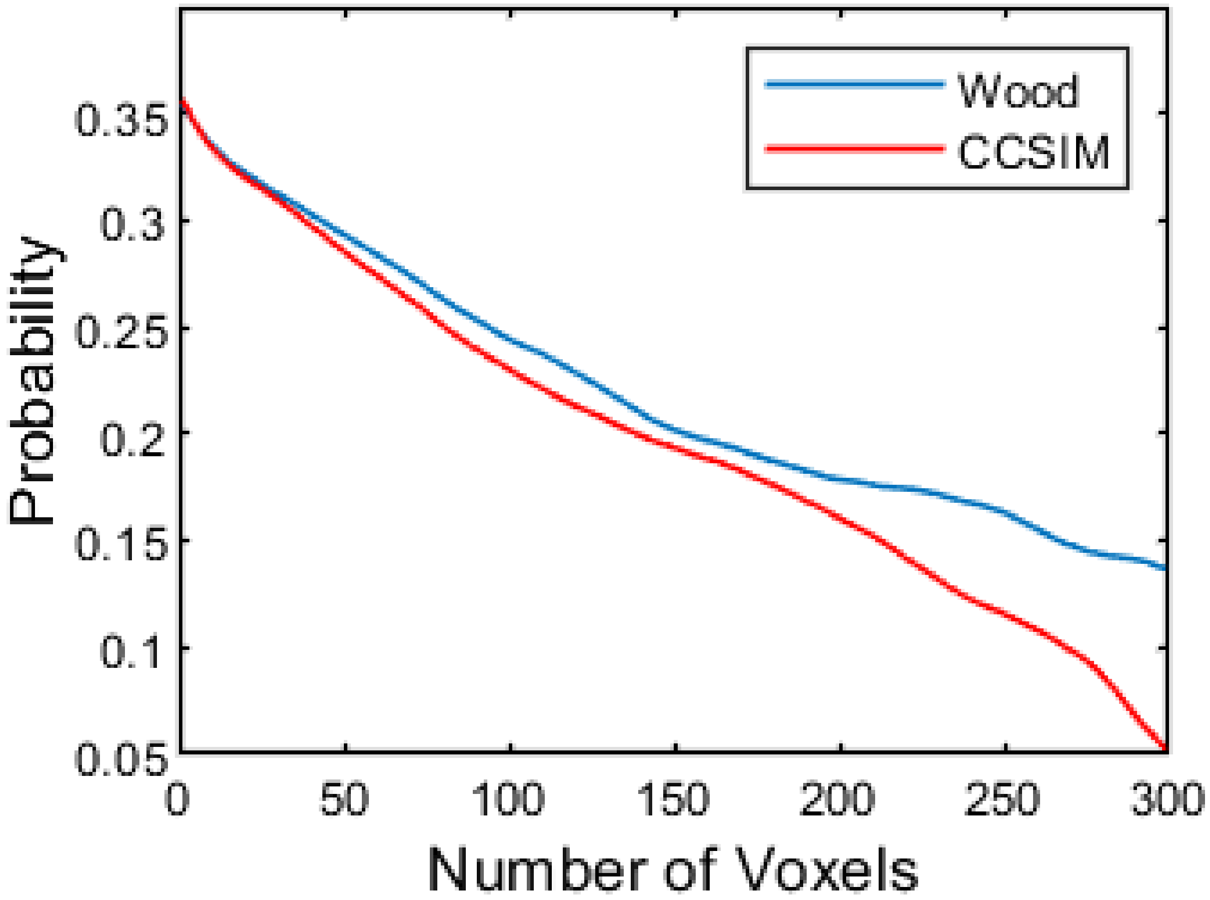


(a) Comparison of stress–strain responses of the X-ray CT and CCSIM samples (experimental). (b) The displacement contours obtained by the FEM and experiment (Digital Image Correlation) for the structures

Comparison of the Connectivity of Algorithmic and X-ray CT Models

- The lower probability of connectivity of the CCSIM model may be due to inaccuracies the stochastic reconstruction process
- The lower elastic and plastic strength of CCSIM structure shown accords with this assertion

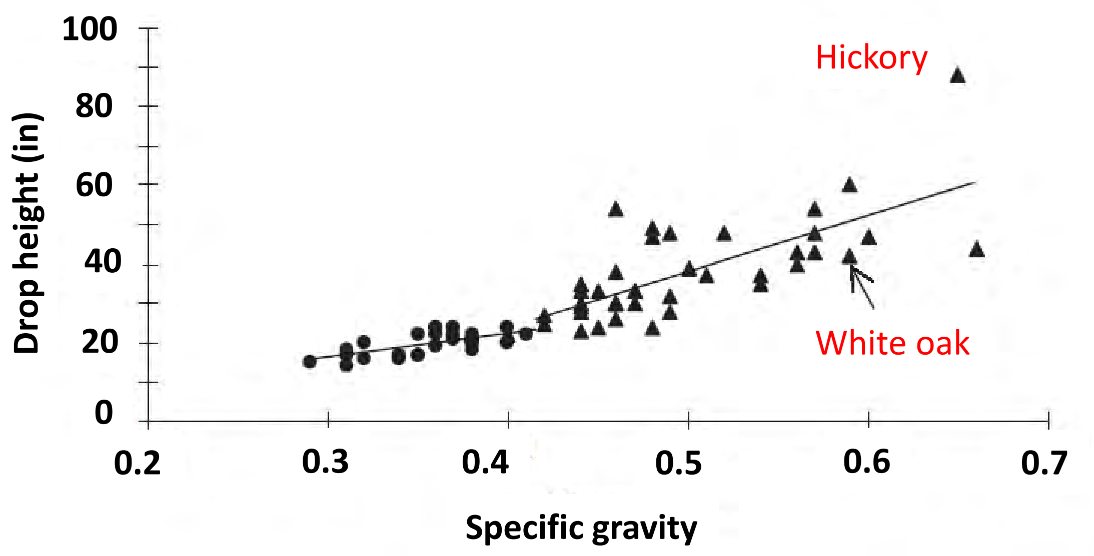
Probability of voxel connectivity provides a statistical measure of structural continuity



Summary

- Our algorithm used limited 2D data set to generate 3D microstructures for willow that were similar to that obtained using massive CT-data set
- We may be able to use our approach to understand why some woods are outliers in terms of their density-strength-toughness relationship
  - High shock resistance of hickory
  - Greater hardness of barriguda v balsa

Higher shock resistance of hickory v other wood species



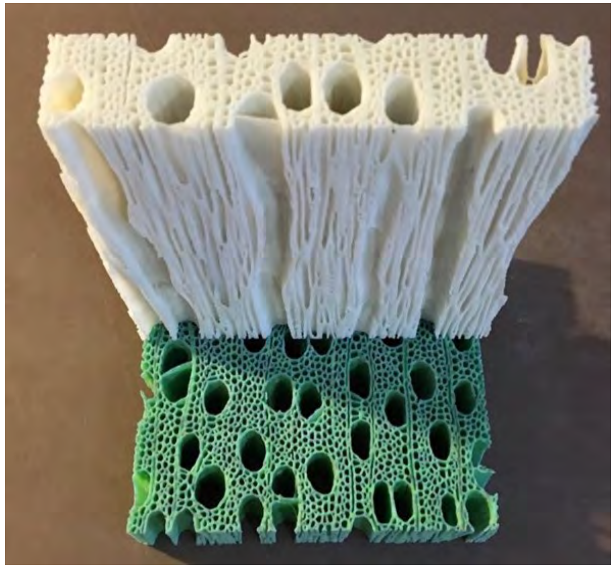
Barriguda (*Cavanillesia* spp.) wood and tree

The Future and Payoff

‘The possibility of combining structure control found in nature with modern synthetic materials would be a major technological achievement shattering limitations of current materials in terms of density, strength, toughness and environmental resistance’

Wegst et al. 2015. Bioinspired structural materials. Nature Materials. 14(1):23-36.

3D-printed Houses and Structures Made from Strong, Light Composites (70% Wood: 30% Bio-plastic)

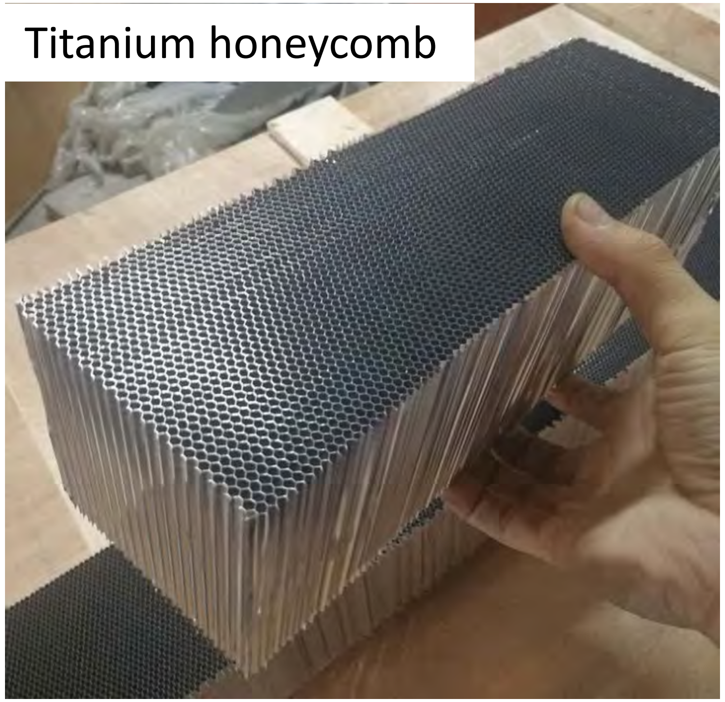


Our 3D printed willow

3D printed house, BioHome3D, made from wood and biobased polymer at University of Maine

Structural composites for bridges

High density polyethylene bridges replacing treated timber



Titanium honeycomb

Metal Honeycomb Materials Modelled on Wood?

Aerospace Space vehicles, missile fins.

Aviation Aircraft, thrust reversers, exhaust nozzles, hush kits and quiet wing systems, engine plugs. Hot section applications.

Boeing 777x exhaust system

World's largest 3D metal printer

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Wood biomimetics: Capturing and simulating the mesoscale complexity of willow using cross-correlation reconstruction algorithm and 3D printing

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HIGHLIGHTS

- We provide a platform for biomimicry of different wood species, which have technologically interesting properties.
- Critical structural and morphological elements of willow wood derived from X-ray micro-CT can be captured with a high degree of fidelity using a novel cross-correlation reconstruction algorithm.
- Orthotropic symmetry of willow wood and its structural anisotropy can be captured, reconstructed and 3D printed for applications of wood biomimicry.

GRAPHICAL ABSTRACT

Thanks & Qs


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