CHEM-E2200: Polymer blends and composites

Introduction

Mark Hughes & Jon Trifol Guzman

7th September 2020

Today

- Course outline
- Passing the course!
- Composites: examples, manufacture, applications
- Fundamental concepts: reinforcement, matrix and interface; volume fraction

Why this course?

- To underpin the development of new fibre (reinforced) materials an excellent understanding of composite materials is essential
- The science and technology of these synthetic materials is well understood and continues to develop. Notable developments in transportation and aerospace
- Much can be learnt from these sectors and applied to composite reinforced with other fibre types, such as natural bio-based fibres and their derivatives
- This course provides a grounding for further study and developments

Learning outcomes

- Is familiar with the potential of synthetic polymers in composite technology
- Knows the role of reinforcement, matrix and interface in a composite system
- Knows the principles of load sharing and reinforcement processes in short and long fibre reinforced composites and the influence of fibre architecture on composite properties
- Can use simple micromechanical models to predict selected composite properties
- Can evaluate the compatibility between polymer and reinforcement/filler systems and is familiar with the main methods of controlling compatibility
- Knows the methods to process thermosetting and thermoplastic polymer composites into various products
- Can make a literature study and present his/her study orally

Perspective

- Principally we will consider ***micro-scale*** reinforcement, though we will discuss the utilisation of nanoscale reinforcement and fillers
- We will generally consider composites as ***engineering materials*** and so the main emphasis will be on mechanical properties and the factors that govern these. In particular strategies that might enable us to improve the performance of low environmental impact composites

Content

- Composites theory
  - Reinforcement, matrix and interface
  - Load sharing and stress-transfer
  - Fibre architecture
  - Elastic deformation in long and short fibre composites
  - Deformation and fracture behaviour
- Raw materials (fibres and matrices)
  - Types, sources and properties
  - Polymers, virgin, recycled, fossil-based, biopolymers
- Processes
  - Composites processing for thermoplastics and thermosetting resins
  - Fibre processing, including modification
- Applications

Passing the course!

- 6 weeks in period I of the Autumn term 2020
- 5 credit course
- 1 x 2 hour session per week (+ additional lecture on Tuesday 22nd September)
- Assessment:
  - Project: 60% (45% report; 15% presentation)
  - Examination*: 40%

*This will be in the form of a "home" exam. Please see following slide for details

Special arrangements for 2020

- This year <u>all classes</u> and sessions will be online! We will use Zoom for the "live" lecture sessions that will be given at the specified time. As in previous years, the slides will be put in MyCourses beforehand.
- <u>**Please try to attend the lectures**</u> as we use these to convey ideas and concepts, rather the regurgitate facts that you can easily find online! We plan to make them as interactive as possible, given the limitations of the online environment.
- For privacy reasons, we cannot share recordings of the interactive parts of the lecture, so will <u>**not**</u> record the "live" lectures. If you have questions just ask!!
- This will be a relatively new experience for all of us, so let's keep an open mind to ways of improving things!
- You will be assessed by a "home" exam to replace the usual formal written exam. In this, the format will differ in that you will be able to use materials (your notes, books, scientific articles etc.) when completing your exam paper in your home environment. More details will be given later….

Schedule

Date	Topic	Content	Teacher(s)
7.9	Introduction	Course intro and administrative matters. Composites; material property envelope; fibres; matrices; interface; manufacturing; applications; basic concepts	Mark Hughes Jon Trifol Guzman
14.9	Fibre 'architecture'	Reinforcement geometry and scale; fibre volume fraction and voids; packing arrangement; orientation of reinforcement	Mark Hughes
21.9	Reinforcement processes	Load sharing; elastic stress transfer (Cox shear-lag theory); stress transfer by slip; effect of aspect ratio; deformation in long fibre composites (axial and transverse)	Mark Hughes
22.9	Interfacial effects	Enhancing the compatibility between fibre and matrix interface; measuring interfacial properties	Jon Trifol Guzman
28.9	Elastic deformation of laminates	Axial and transverse stiffness of unidirectional laminae; off-axis loading and interaction effects; multi-ply laminates	Mark Hughes
5.10	Manufacturing	Manufacturing methods for thermoset and thermoplastic matrix composites	Jon Trifol Guzman
12.10	Strength and failure	Inelastic processes; predicting the strength of composites; toughness	Mark Hughes

Project

- Completed in pairs
- Based on approximately 15-20 peer-review literature sources + others as appropriate (will depend upon chosen topic)
- This is a ‘desk-based’ research project. The information that you use will come form e.g.
  - Scientific literature (principally)
  - Internet (be critical about the information that you obtain)
  - Direct contact with companies (if appropriate)
- Assessment:
  - Report of around 15 pages of written text (please refer to guidelines)
  - Presentation and discussion. Sessions will be arranged in week 42 (e.g. 13th, 14th or 15th October)

Project assessment

- Introduction (5 points)
  - E.g. What is the rationale of the project. Provide the context (bigger picture). What are your hypotheses and objectives?
- Scope and relevance (5 points)
  - E.g. Is your project in the focus of the topic? Is it relevant to the topic?
- Content and depth (15 points)
  - E.g. How deeply do you go in to the topic. Better to have a narrower focus and more depth than very broad and superficial coverage.
- Use of literature (10 points)
  - E.g. Not just the sources you use, but also how you discuss these in the context of your report.
- Conclusions (5 points)
  - E.g. What can you conclude from your study. Concise and to the point.
- Presentation and style (5 points)
  - E.g. Does your report follow normal scientific reporting style? Do you use references in the correct way and are they listed correctly?

Project

- Select a topic and confirm by e-mail to Mark and Jon
  - Either Mark or Jon will mentor your project, depending upon the topic
- Send an outline of your first thoughts to Mark / Jon by 16.9
  - This should be no more than a short document to outline your first thoughts about the project (i.e. some background and rationale + objectives) and a provisional list of contents. This need be no more than about 1 page, but sufficient to convey your idea!
  - We will give you written feedback on this and if you want to discuss with either of us, please don't hesitate to make contact!
- Submit a draft of your report (approx. 50% complete) by Monday 28th September and arrange a Teams meeting with Mark / Jon to obtain further feedback/comments about the project on one of the following dates: 1st or 2nd October or 5th – 7th October
- Present your findings in one of two sessions organised at the end of week 42 (13th, 14th or 15th October)
- Report deadline: Friday 30th October

Topics

You are **free to propose** your own topic so long as it is in line with the aims of the course and supports the learning objectives! It is your chance to delve deeper into a topic that is of interest to you! Here are some suggested topics, however:

- Measuring fibre-matrix bond strength in polymer matrix composites
- A critical review of manufacturing processes for thermosetting PMCs
- Processes for the manufacture of thermoplastic polymer matrix composites
- The potential of bio-based fibres as reinforcement for composites
- Carbon fibres from non-traditional precursors
- Application of FRPs in ground transportation applications
- Polymer matrix composites in construction
- Recycling of polymer composites
- Textile reinforcement for composites
- Techniques in the micromechanical evaluation of composites
- Fracture and strength of composites
- Additives used in biocomposites
- Biopolymer composites in medicine
- Self-healing polymer composites
- Life Cycle Assessment (LCA) of biocomposites
- Damage analysis in polymer composites
- Biomimetic polymer composites

Other matters

- Will keep MyCourses up to date with any new information that becomes available
- Slides will be in MyCourses

Contact details:

- Mark Hughes (mark.hughes@aalto.fi; room 221, Vuorimiehentie 1)
- Jon Trifol Guzman (jon.trifol@aalto.fi; Chemistry building)

Reading material

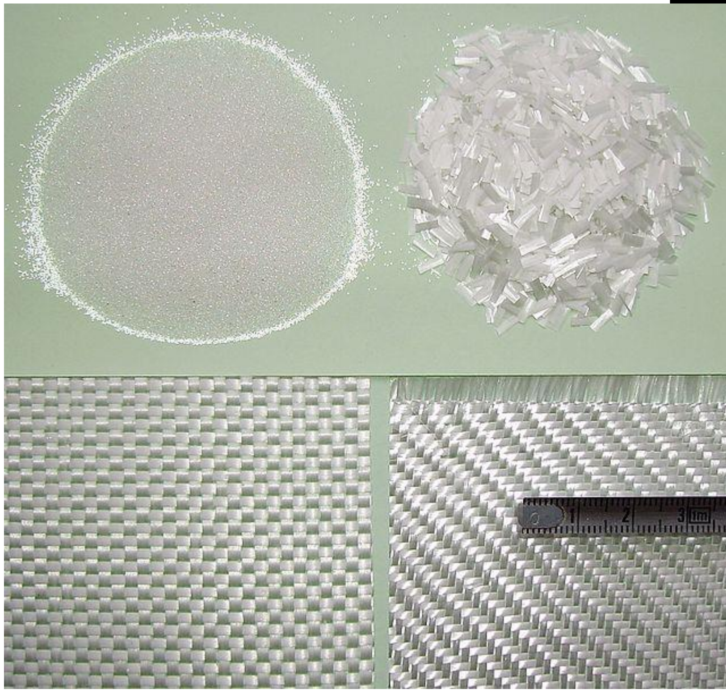
- General introduction to materials:
  - JE Gordon. "The New Science of Strong Materials or Why You Don't Fall Through the Floor" (Princeton Science Library). BUY IT!
- Many books covering composite materials science:
  - D. Hull, and T. W. Clyne. "An Introduction to Composite Materials" (Cambridge Solid State Science Series) – available from Amazon and copies are available in the library
  - M.R. Piggott. "Load bearing fibre composites"
- Green composites:
  - Caroline Baillie. "Green Composites" Woodhead Publishing Ltd
- Many others relating to composite materials

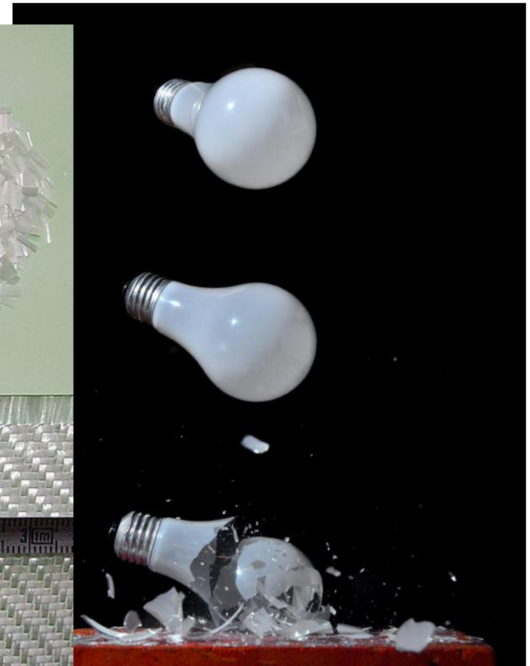
What is a composite?

“The whole is greater than the sum of its parts”

- Aristotle

- A composite is a material composed of **two** or **more** distinct constituents (or **phases**) separated by an identifiable **interface**
- Generally (but not always) the phases have different physical and/or chemical properties
- The properties of the resulting composite can be entirely different from those of the original components
- For example GRP (Glass-fibre Reinforced Plastic) is composed of (brittle) glass and (also brittle) thermosetting polymer, but the resulting composite is very ‘tough’ (the fracture energy is about 10^3 to 10^4 times greater)
- Why is this? **Structure** (and particularly microstructure)





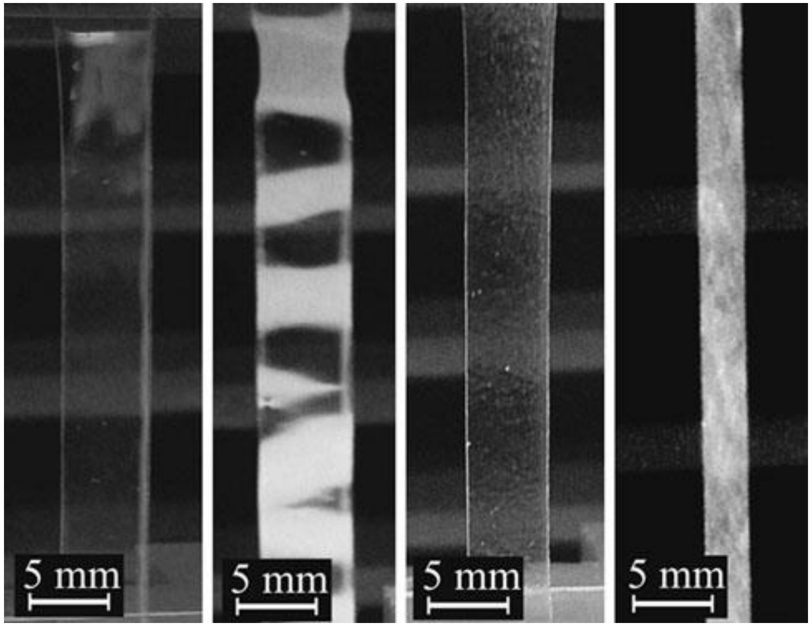
+

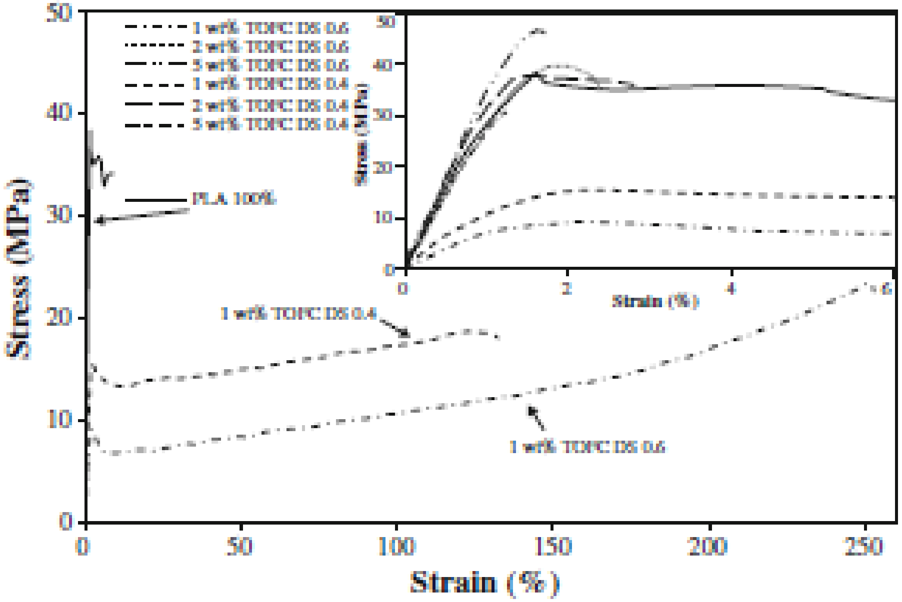

Reliable solution
for your composite
Resin

=


Cerbera

Toughening polymers with nanocellulose





PLA + 1% nanocellulose ➔

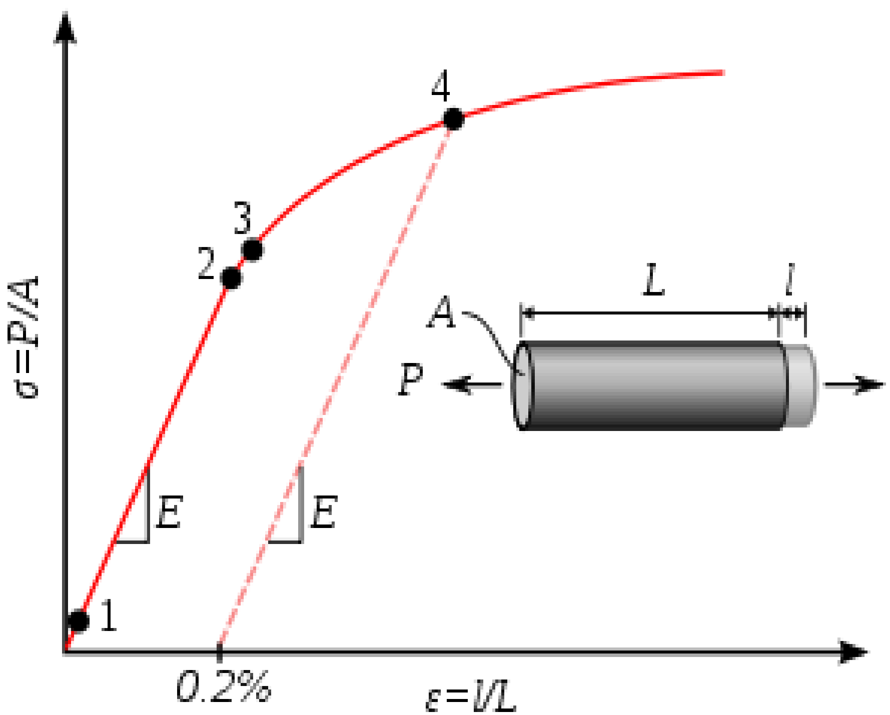
x10 work of fracture

Mechanical properties

For many real-life engineering applications it is often desirable to have a blend of properties:

- Good **stiffness**:
  - *resistance to deflection under short-term loading*
- Adequate **strength**:
  - *how much force can be sustained before it breaks*
- **Toughness**:
  - *the ability to resist the propagation of cracks (arguably the most important property of an engineering material)*

Stress, strain, stiffness, strength



(Source: Wikipedia)

- **Stress**: load/cross-sectional area
- **Strain**: extension/original length
- **Poisson's ratio**: ratio of transverse to axial strain
- **Stiffness**: Young's modulus, *E*, stress/strain (in linear elastic region – Hooke's law)
- **Strength**: stress at ultimate load (tension or compression)

The range of properties that Nature can achieve

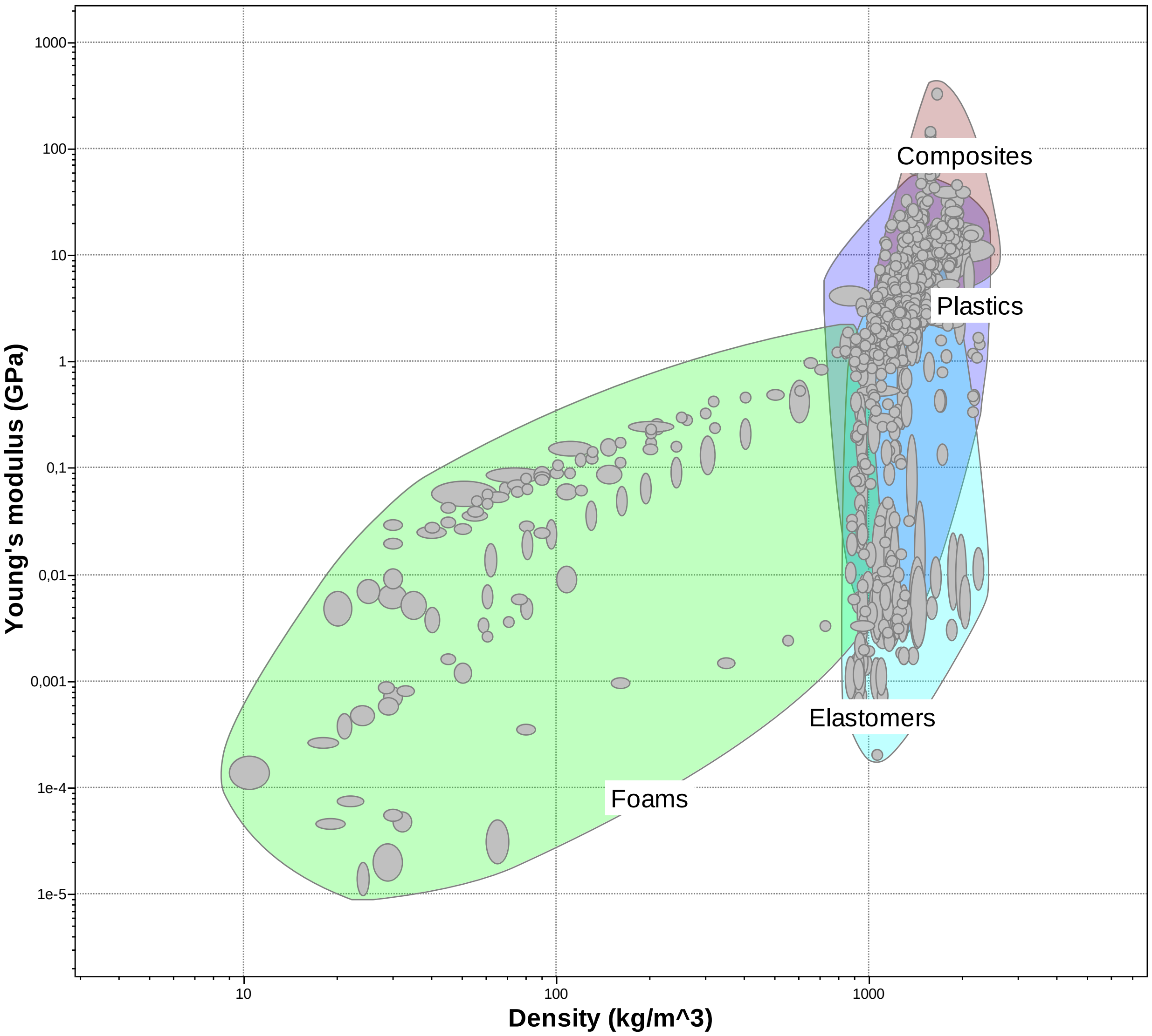
TABLE 1

Approximate Young's moduli of various solids

Material	Young's modulus (E) p.s.i.	Young's modulus (E) MN/m²
Soft cuticle of pregnant locust*	30	0.2
Rubber	1,000	7
Shell membrane of egg	1,100	8
Human cartilage	3,500	24
Human tendon	80,000	600
Wallboard	200,000	1,400
Unreinforced plastics, polythene, nylon	200,000	1,400
Plywood	1,000,000	7,000
Wood (along grain)	2,000,000	14,000
Fresh bone	3,000,000	21,000
Magnesium metal	6,000,000	42,000
Ordinary glasses	10,000,000	70,000
Aluminium alloys	10,000,000	70,000
Brasses and bronzes	17,000,000	120,000
Iron and steel	30,000,000	210,000
Aluminium oxide (sapphire)	60,000,000	420,000
Diamond	170,000,000	1,200,000

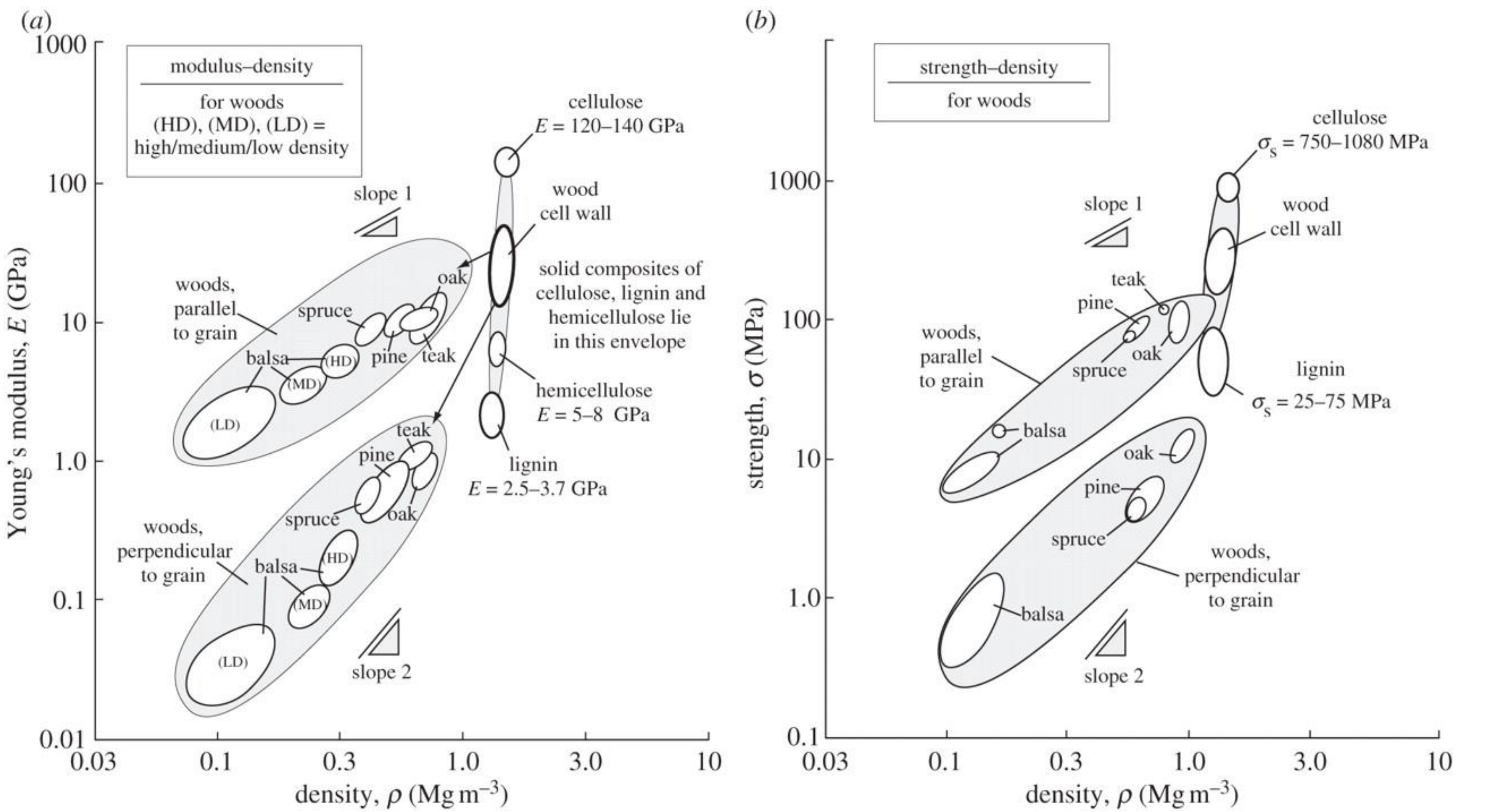
* By courtesy of Dr Julian Vincent, Department of Zoology, University of Reading.

(Source: J.E. Gordon: "Structures")



Prepared using CES EduPack 2016

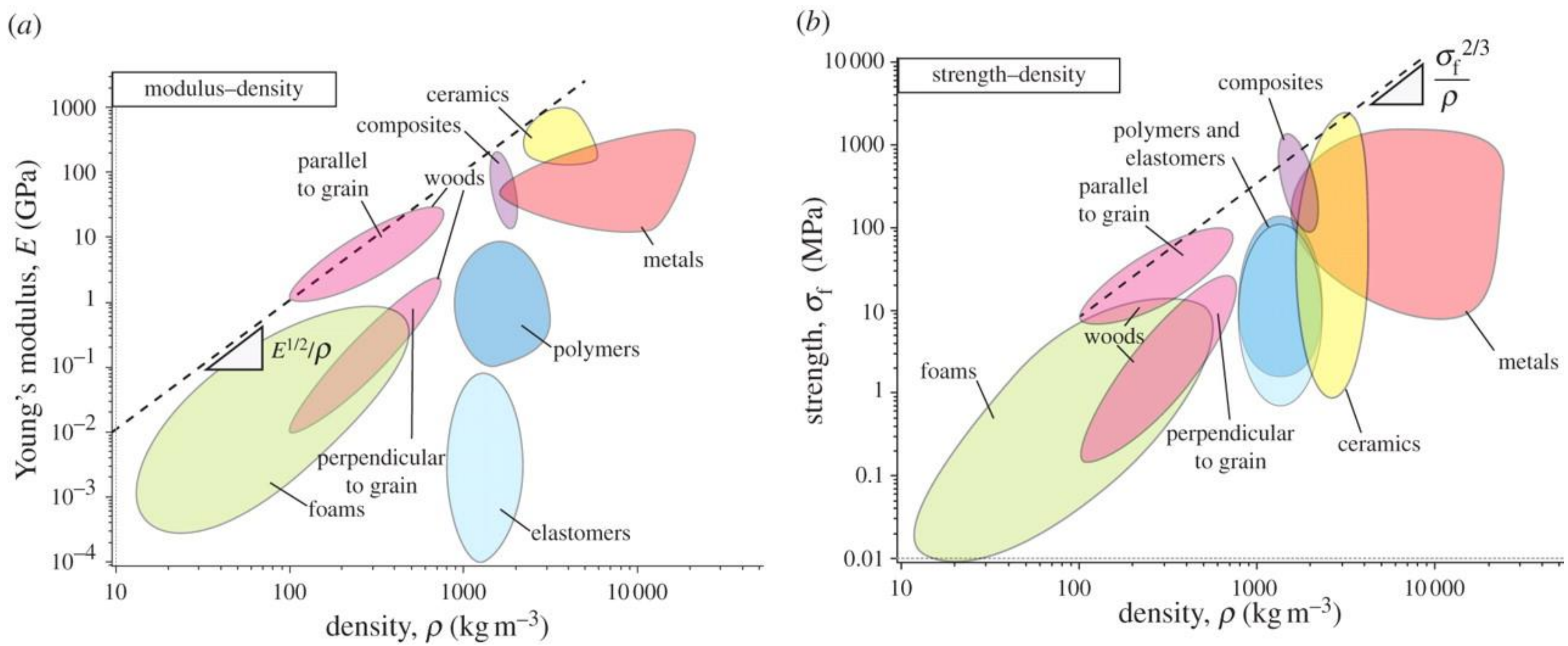
(a) Young's modulus and (b) strength plotted against density for woods and their constituents.



Lorna J. Gibson J. R. Soc. Interface 2012;rsif.2012.0341

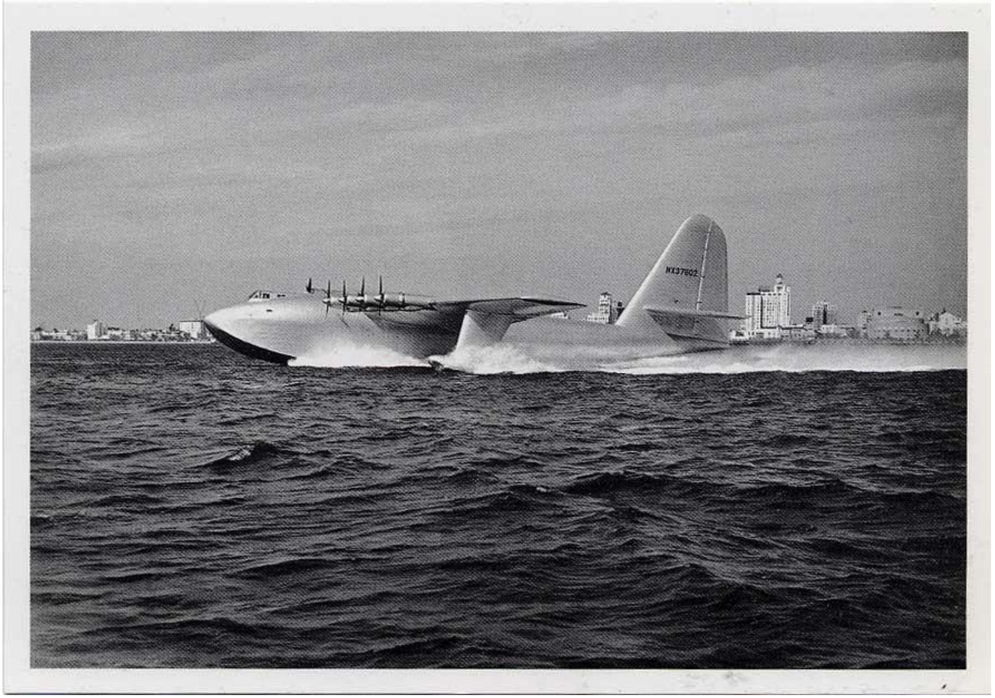
JOURNAL OF THE ROYAL SOCIETY Interface

(a) Young's modulus–density chart for engineering materials, including woods.



Lorna J. Gibson J. R. Soc. Interface 2012;rsif.2012.0341

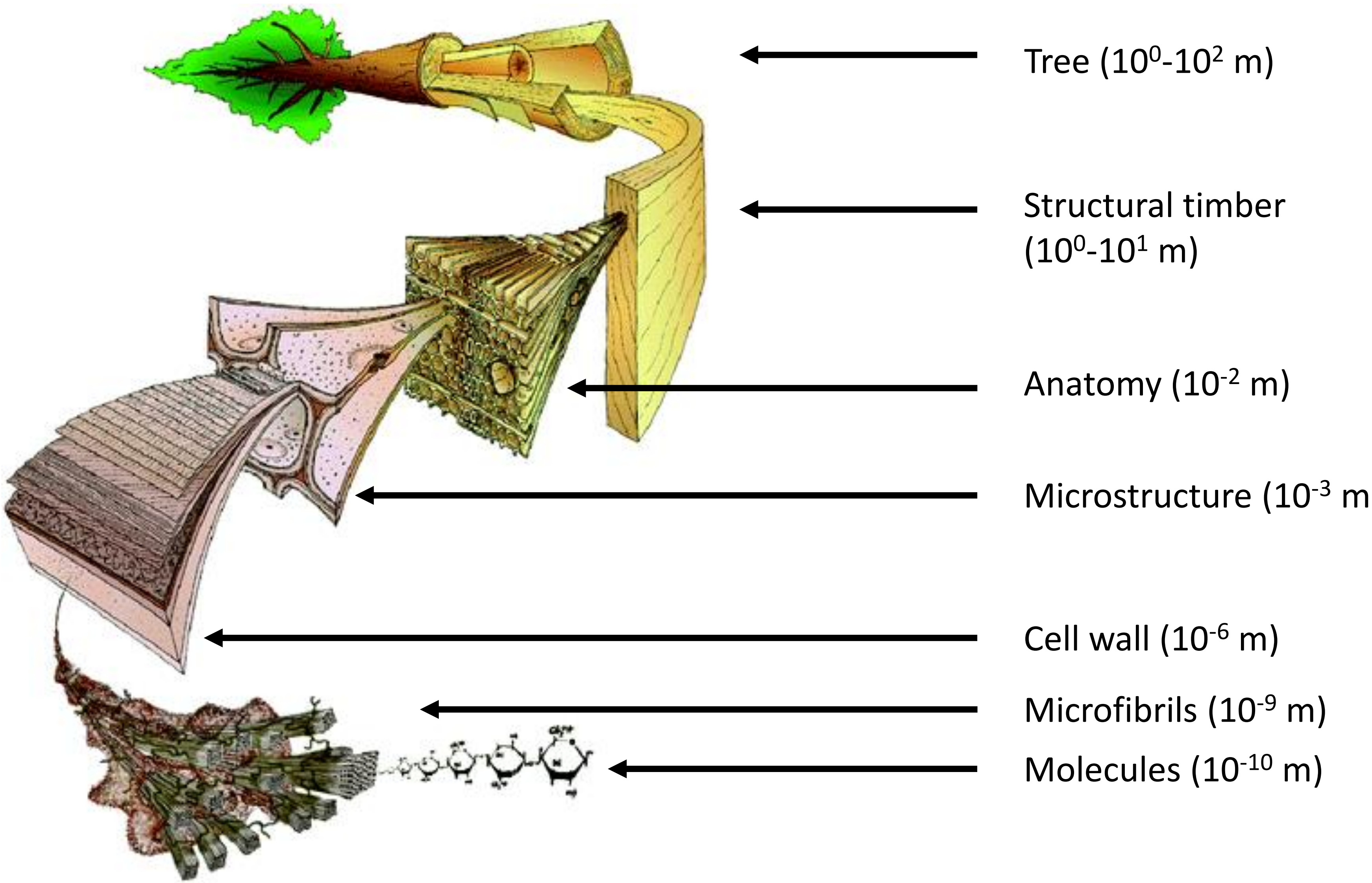
Wood: the ultimate composite material?



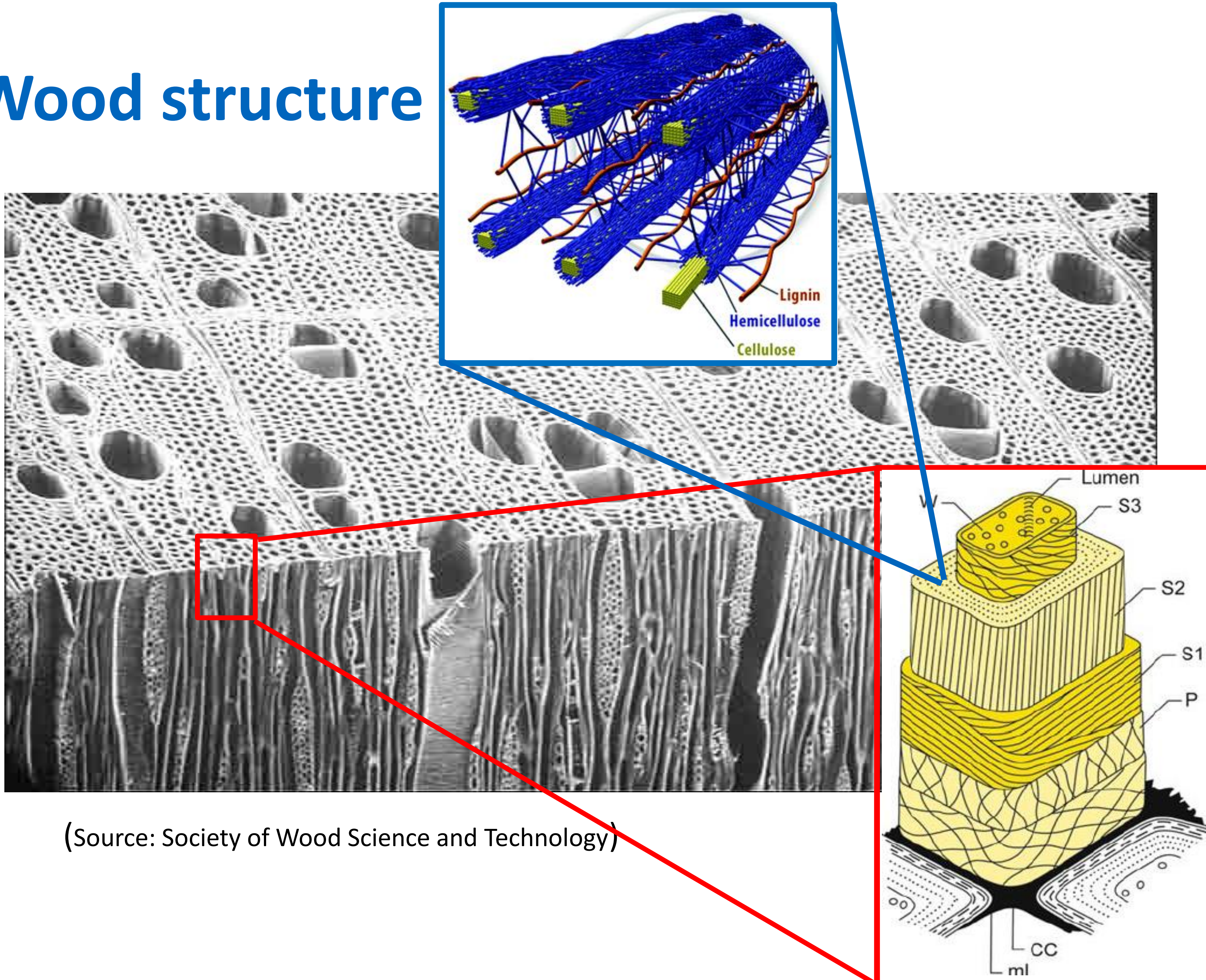
Howard Hughes' "Spruce Goose"

- Excellent specific mechanical properties
- Synthesized from CO_2 and H_2O (+sunlight)
- Completely biodegradable when required, but can last for millennia!

The hierarchical composite structure of wood



Wood structure



(Source: Society of Wood Science and Technology)

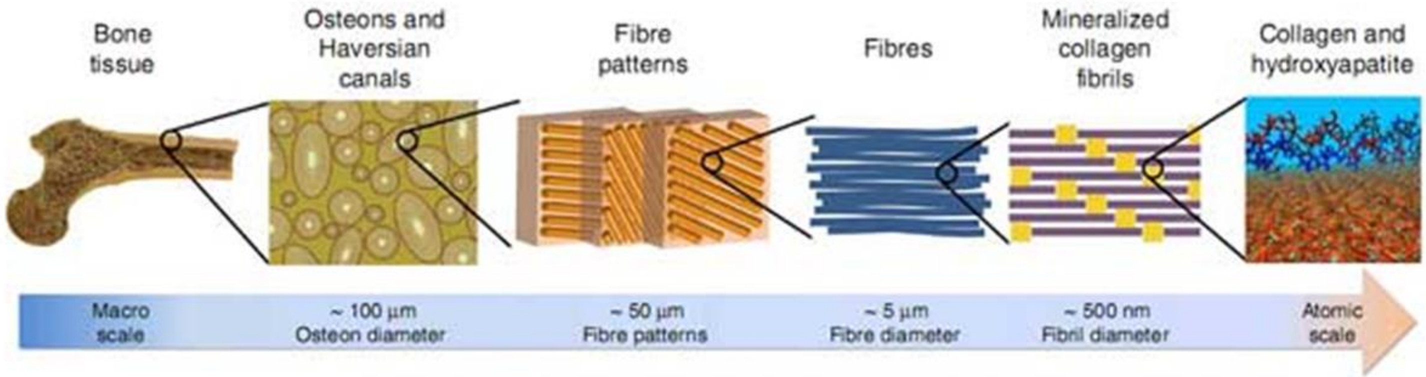
Composite materials

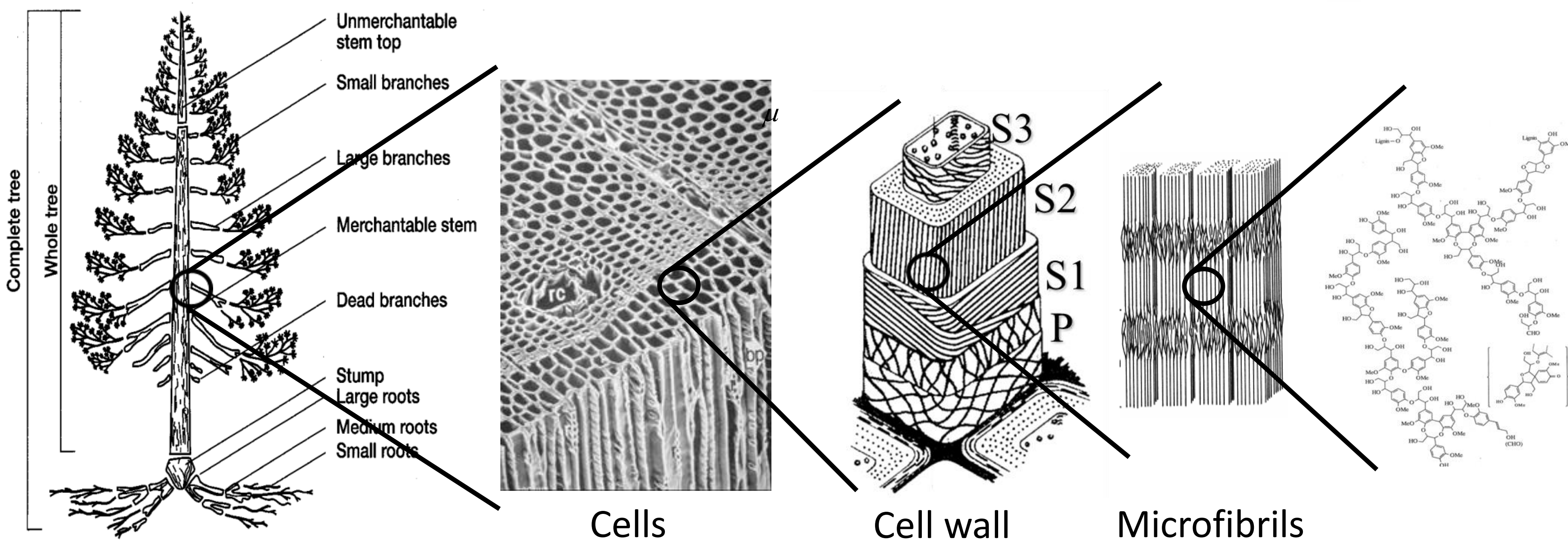
- Composite materials are nowadays widely used by humankind in many diverse applications
- Nature also uses composites extensively and many elegant hierarchical composite structures have evolved that are far more complex than any synthetic equivalents – we can learn a lot from these natural materials!
- Natural composites have been, and are, used extensively by humankind
- Many of the earliest forms of composite were based on natural materials

Composites: natural, synthetic and natural-synthetic hybrids…..

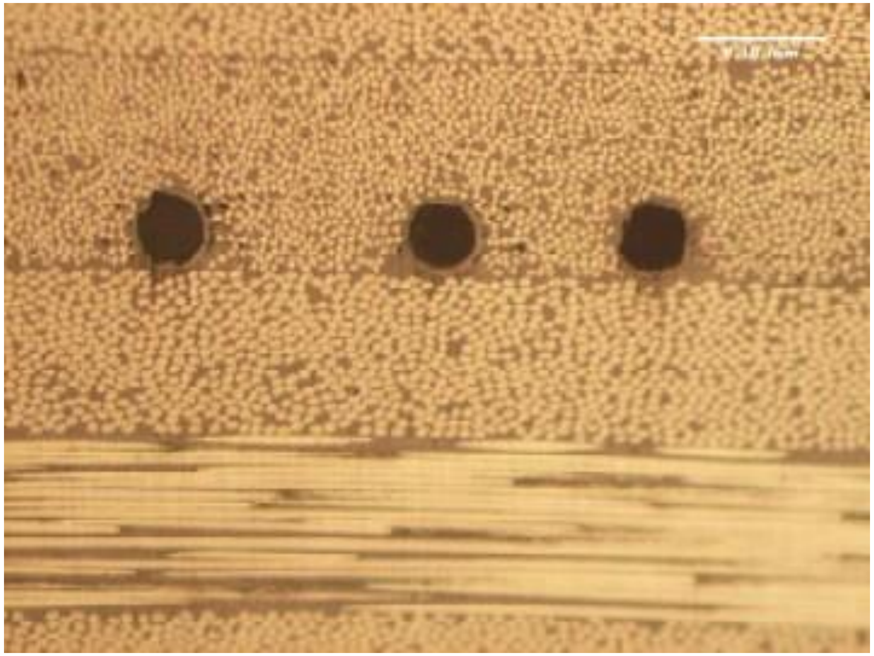
- FRPs - Fibre Reinforced Plastics: carbon, glass, aramid fibre: epoxy, phenolic, unsaturated polyester resin
- Metal matrix composites - MMC
- Wood: cellulose embedded in hemicellulose and lignin
- Bone: hard crystalline mineral, hydroxyapatite, embedded in a matrix of collagen
- Teeth, skin….. almost all biological materials are composites of one sort or another….
- “Biocomposites” (the first manmade composites) combine at least one “natural” component

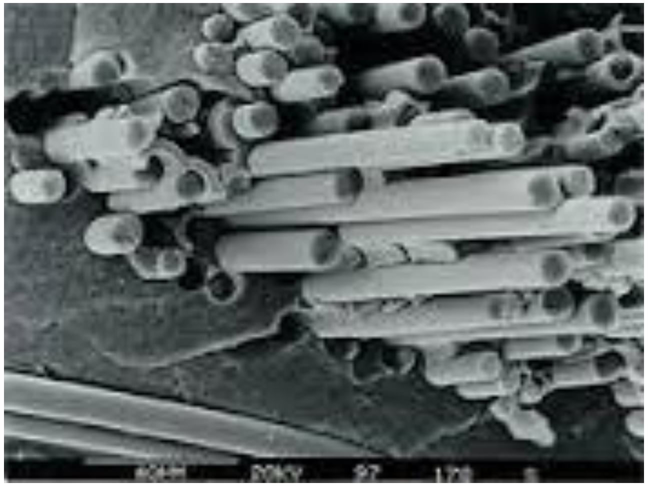
Composites in Nature: their hierarchical structure





Synthetic composites: simpler microstructures





Synthetic composites

Natural composites used by humans

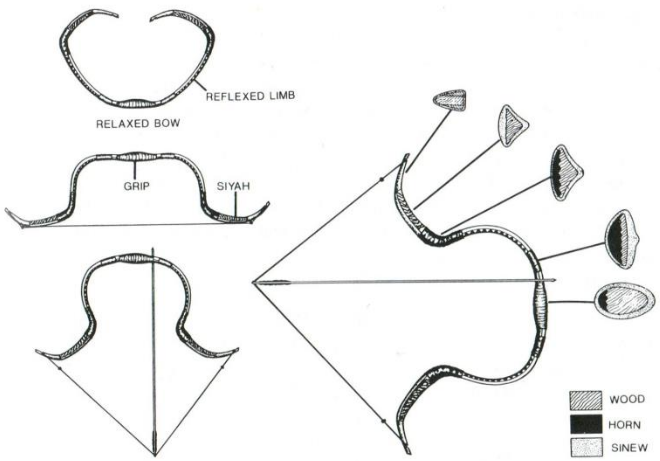
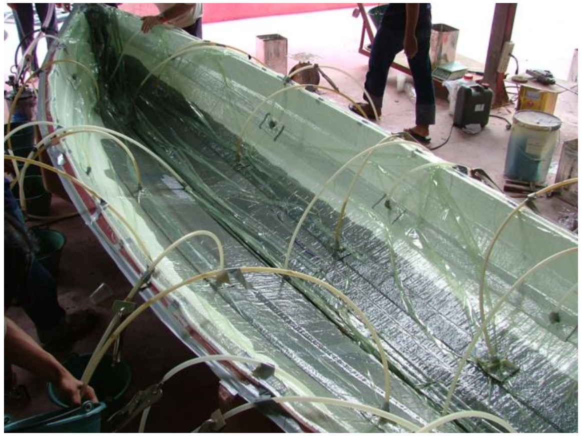


Figure 3. Asian composite bow illustrating extreme reflex and recurve in the limbs, as well as materials used in construction.

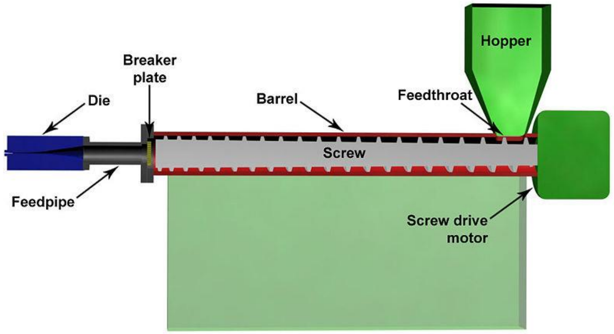
Hybrids: wood plastic composites (WPC)

- Now in commercial production in many countries, especially in N. America
- Europe slow to take-off, but now strong interest. E.g. UPM ProFi and UPM Formi products
- Applications are mainly in the construction sector, where they can replace materials such as treated timber, but are extending into other areas including biomedical and other consumer applications

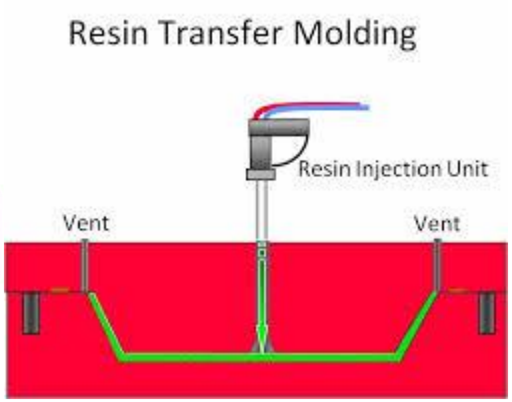
Many manufacturing options depending on material, application and production volume

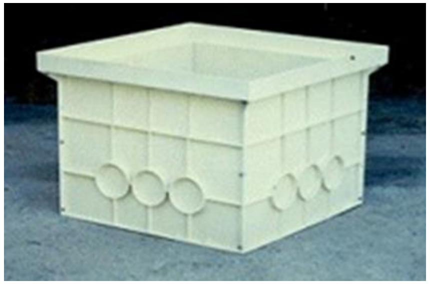


Resin infusion

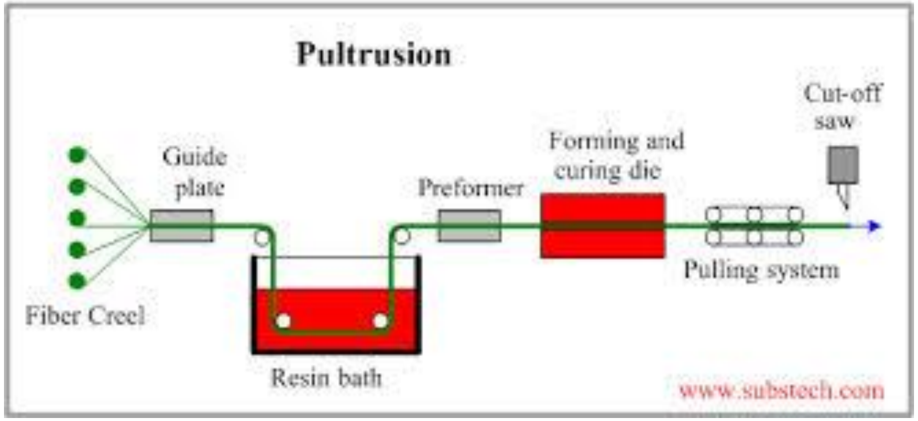


Extrusion





Dough moulding compound



Thermosetting and thermoplastic polymer matrices

Composites in history

- Hemp fibre found in ancient pottery from China dating back to 10 000 BC
- Straw reinforced mud bricks of ancient times
- Really begins with the advent of synthetic resins (Bakelite) during the early part of twentieth century
- Wood flour or waste string and rags used as reinforcement to form the earliest synthetic composites
- Applications in consumer items such as radio and speaker cases

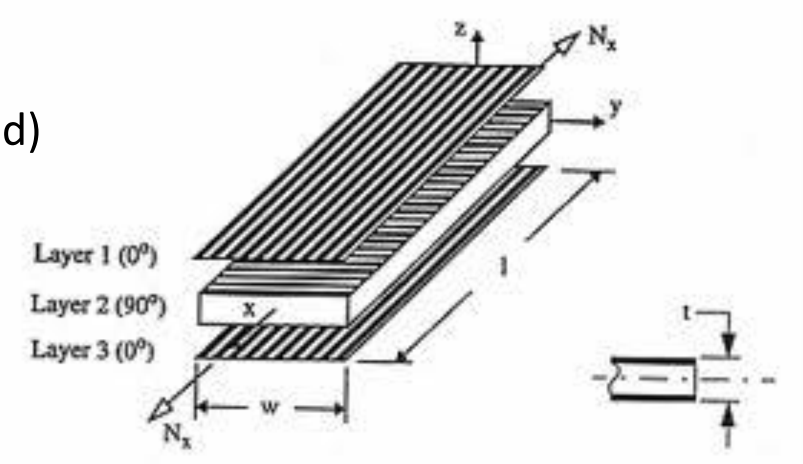
Other early biocomposites

- Henry Ford first raised the possibility of using hemp fibre reinforced soybean resin in cars!
- Famous photograph on the right shows Henry Ford taking an axe to a composite panel!
- The body panels of the Trabant were produced from cotton reinforced unsaturated polyester resin

"Gordon Aerolite"

- Produced by laying up strips of resin impregnated unbleached flax yarn to form a **cross-ply** laminate structure, or **unidirectional** bar or strip of material
- Heated and pressed to form the composite
- Around 75% by volume was fibre, held together with resin which formed the remaining 25%
- Ultimate tensile strength and Young's modulus of longitudinally loaded material were around 480 MPa and 48 GPa respectively!

Cross-ply laminate
(similar construction to plywood)

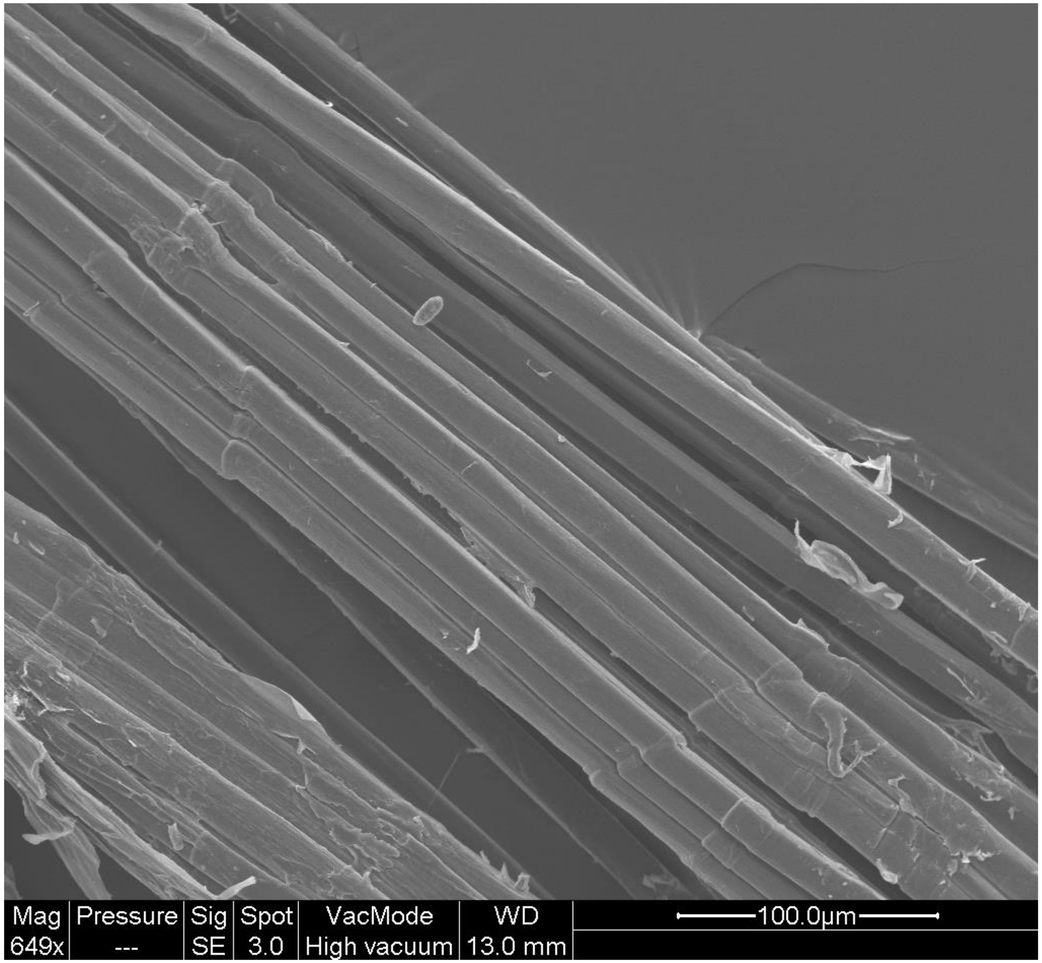


Fundamental concepts: *phases* (reinforcement, matrix, interface) and *volume fraction*

Reinforcement

- Generally much stronger and stiffer than the matrix
- The reinforcement provides the “strength” to the composite
- Reinforcement is often (mainly) in the form of a fibre (glass, carbon, aramid, boron….)
- Fibres are good in **tension** (compare with rope), but poor in **compression** and **shear**, therefore need a “matrix” in which the fibre is embedded to “support” the fibre and to transfer externally applied loads to the reinforcement
- Fibre geometry as we shall see is important. Fibres may be “**short**” (i.e. a defined aspect ratio) or “**long**” (in effect infinitely long)

Flax fibre


Mag
649x
Pressure

Sig
SE
Spot
3.0
VacMode
High vacuum
WD
13.0 mm
100.0µm

Reinforcement properties

Fibre type	Density $(g\ cm^{-3})$	Young's modulus (GPa)	Tensile strength (MPa)	Failure strain (%)
Synthetic fibres				
E-glass	2.56	76	2000	2.6
high strength carbon	1.75	230	3400	3.4
Kevlar™ (aramid)	1.45	130	3000	2.3
boron	2.6	400	4000	1.0
Natural fibres				
flax	1.4-1.5	50-70	500-900	1.3-3.3
hemp	1.48	30-60	310-750	2-4
cotton	1.5	6-10	300-600	6-8
cellulose	1.5	135	10000	-

Matrices

- Can be metals, ceramics or, most commonly, **polymers**
- Most often weaker and less stiff than the reinforcement (especially if it is polymer)
- In addition to transferring externally applied loads to the reinforcement, the matrix protects the reinforcement from mechanical, physical, chemical (and biological) degradation, which would lead to a loss in performance

Some matrix properties (polymers)

Polymer	Density ($g\ cm^{-3}$)	Young's modulus (GPa)	Tensile strength (MPa)	Failure strain (%)
THERMOSET				
epoxy resins	1.1-1.4	3-6	35-100	1-6
polyesters	1.2-1.5	2.0-4.5	40-90	2
THERMOPLASTIC				
Nylon 6.6	1.14	1.4-2.8	60-70	40-80
polypropylene	0.9	1.0-1.4	20-40	300
PEEK	1.26-1.32	3.6	170	50

Interface

- Interface (or “interphase”), transmits the externally applied loads to the reinforcement via shear stresses at the interface
- The interface is analogous to a glue bond
- If there is no bonding (adhesion) between the matrix and the reinforcement, then stress transfer will be poor and it will lead to impaired composite properties
- On the other hand bonding may be too good!
- The interface is therefore a crucial factor in the short and long-term performance of composites
- Optimising the properties of the interface is a key step in the development of composites

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)

Further reading

- Historical aspect covered in Chapter 14 of ‘Green Composites’
- Callum Hill and Mark Hughes (2010). Natural Fibre Reinforced Composites: Opportunities and Challenges. Journal of Biobased Materials and Bioenergy, 4: 1–11
- Faruk, O, Bledzki, AK, Fink, HP and Sain, M. (2012) Biocomposites reinforced with natural fibers: 2000-2010. Progress in Polymer Science **37**(11): 1552-1596 (DOI: 10.1016/j.progpolymsci.2012.04.003)