Performance of natural fibre-reinforced plastics: What are the theoretical potentials and how do they translate into practical values?

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PhD Workshop Hamburg – COST Action FP1407

– Think outside of the wooden box! –

Hamburg (Germany)
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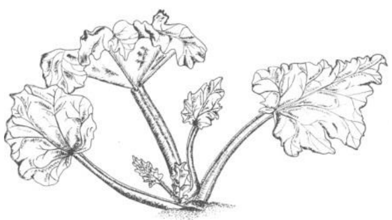
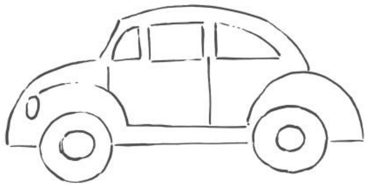
University Hamburg
Centre of Wood Science
& Technology

Content

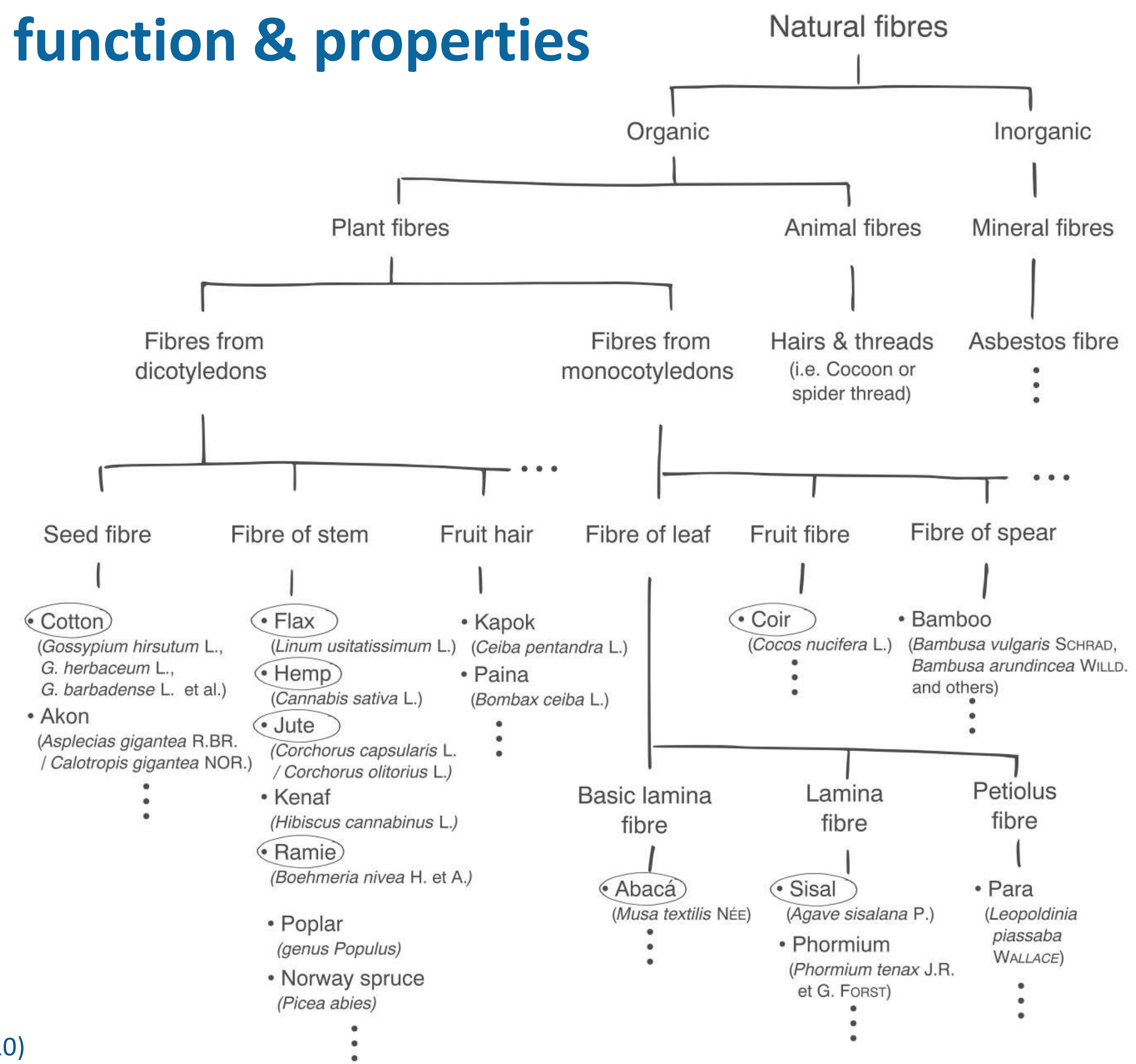
Performance of natural fibre-reinforced plastics: What are the theoretical potentials and how do they translate into practical values?

- Natural fibres & their potential for lightweight constructions
- Fibre properties and NFRC
- Material selection for different load cases
- Theoretical potentials & future work to do
- Impact improving of NFRC
- Bioinspired fibre composites
- Conclusion



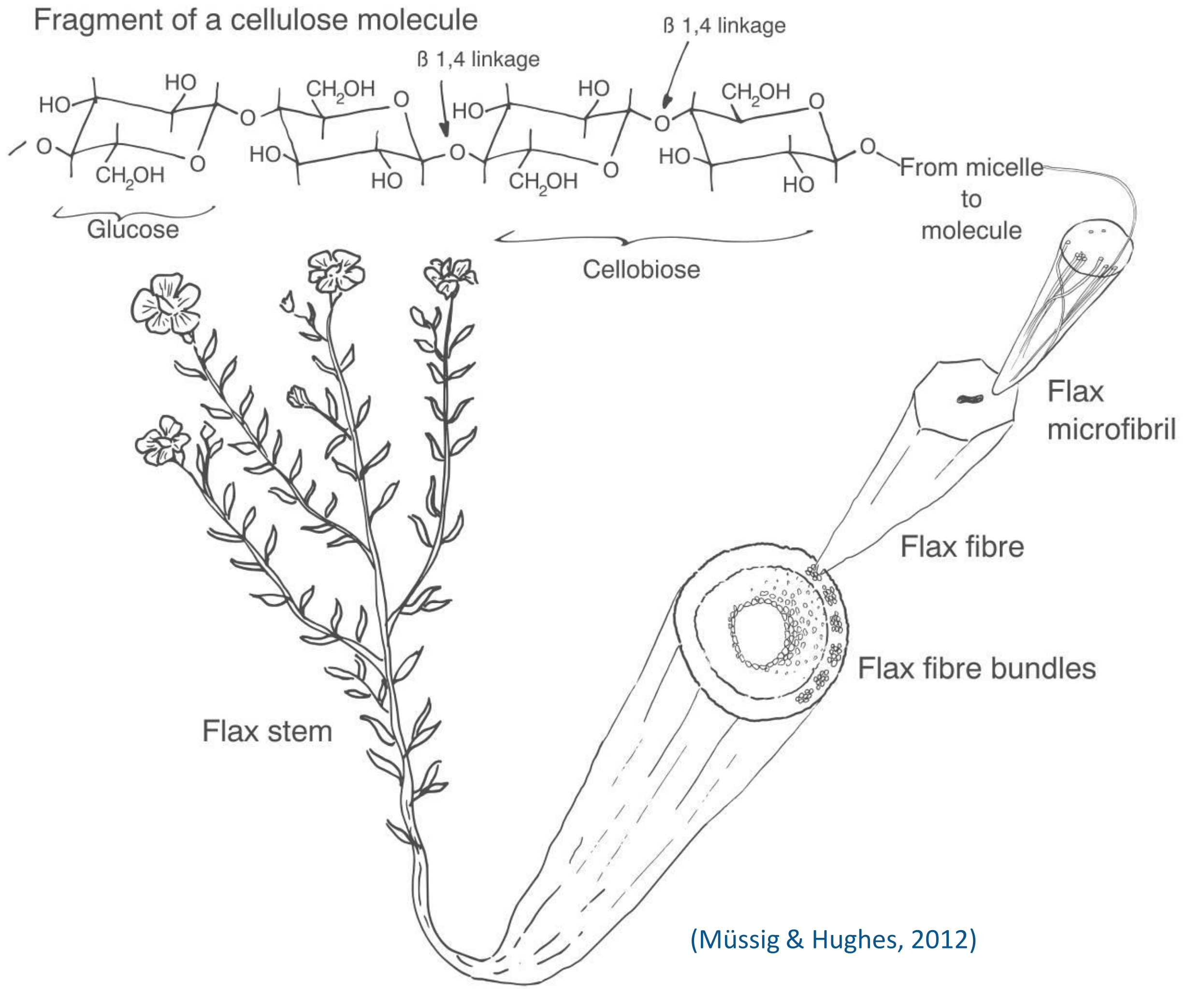


Natural fibres - function & properties



(Müssig 2001 & Müssig, Slootmaker 2010)

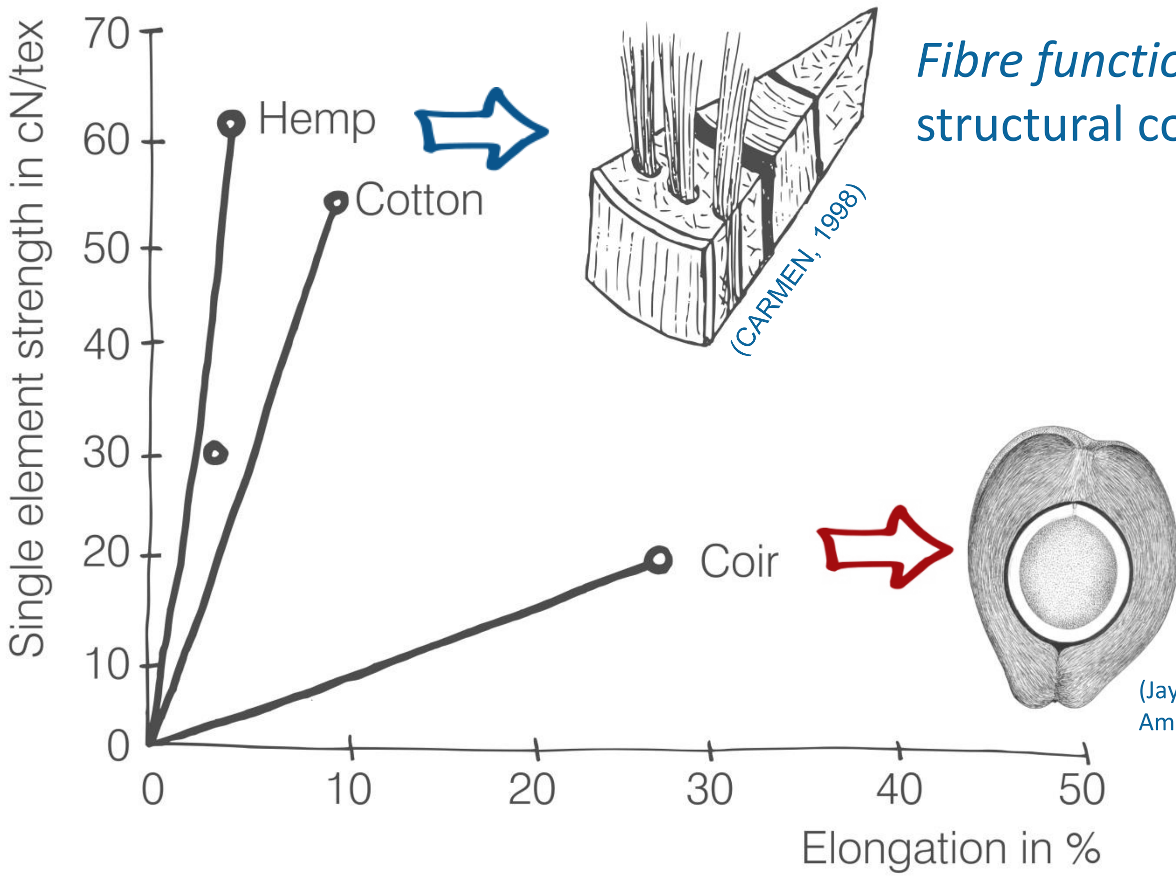
Natural fibres - function & properties



(Müssig & Hughes, 2012)

Schematic representation of the hierarchical structure of flax (*Linum usitatissimum* L.) – from plant to cellulose.

Natural fibres - function & properties



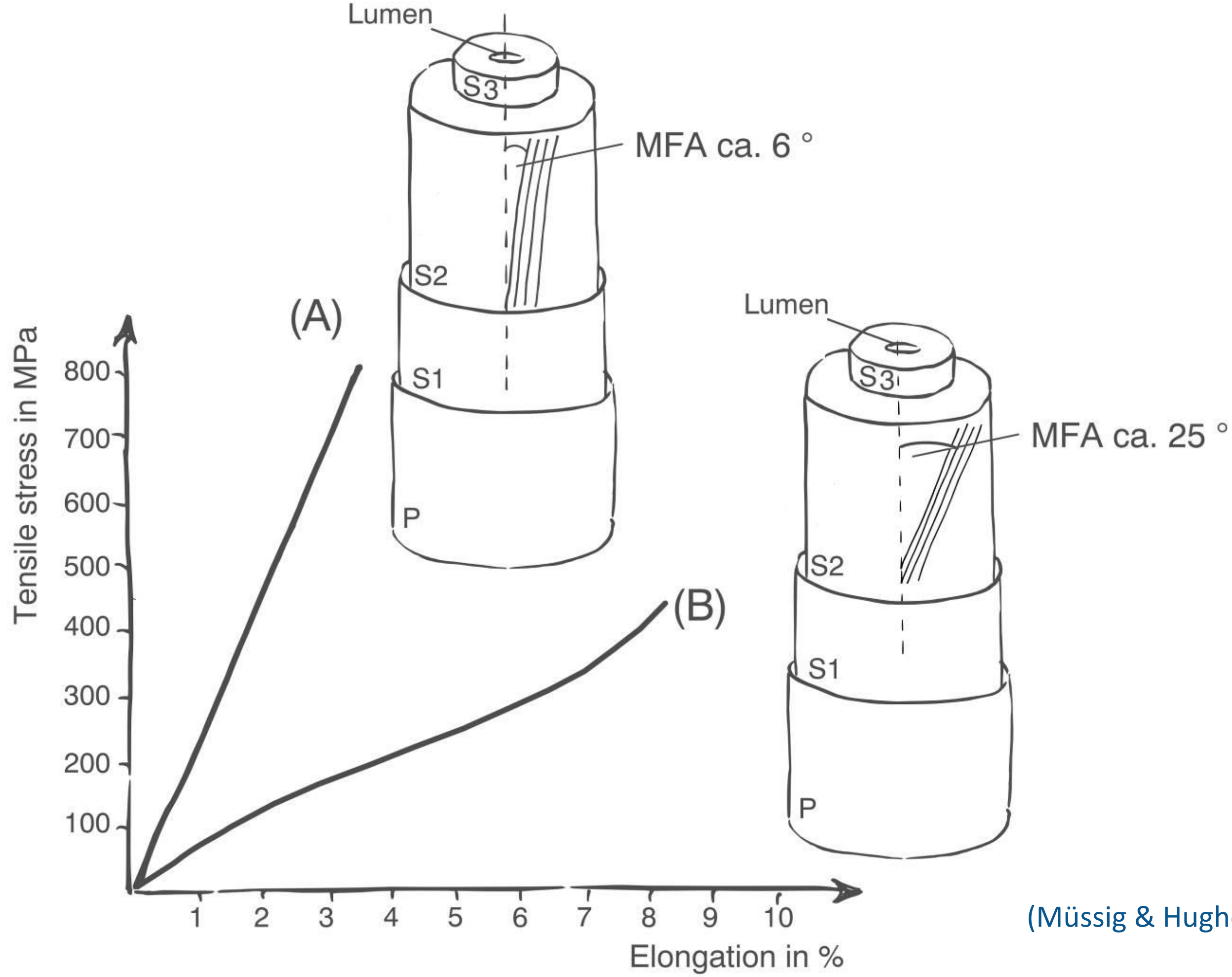
(CARMEN, 1998)

Fibre function:
structural component
(Jayasekara & Amarasinghe, 2010)

Fibre function:
protection of the fruit

Stress-strain relationship of same natural fibres compared to a high-strength steel fibre.

Cell Wall Structure & Properties



(Müssig & Hughes, 2012)

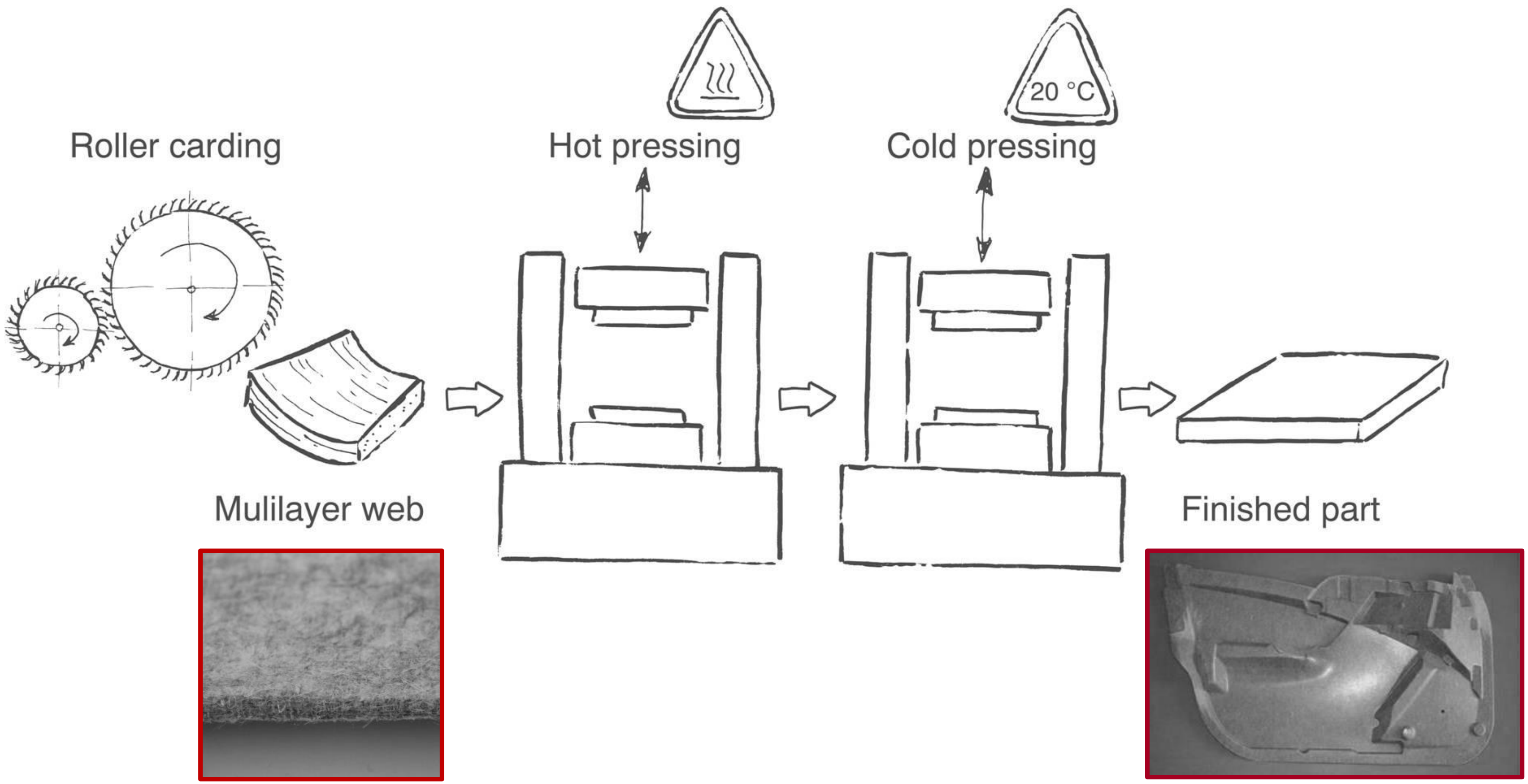
Influence of the cellulose microfibril angle (MFA) on the mechanical properties of plant fibres. (A) A fibre like hemp. (B) A fibre like cotton.

Polymeric composites in automobiles

(Sonntag & Barthel, 2002)

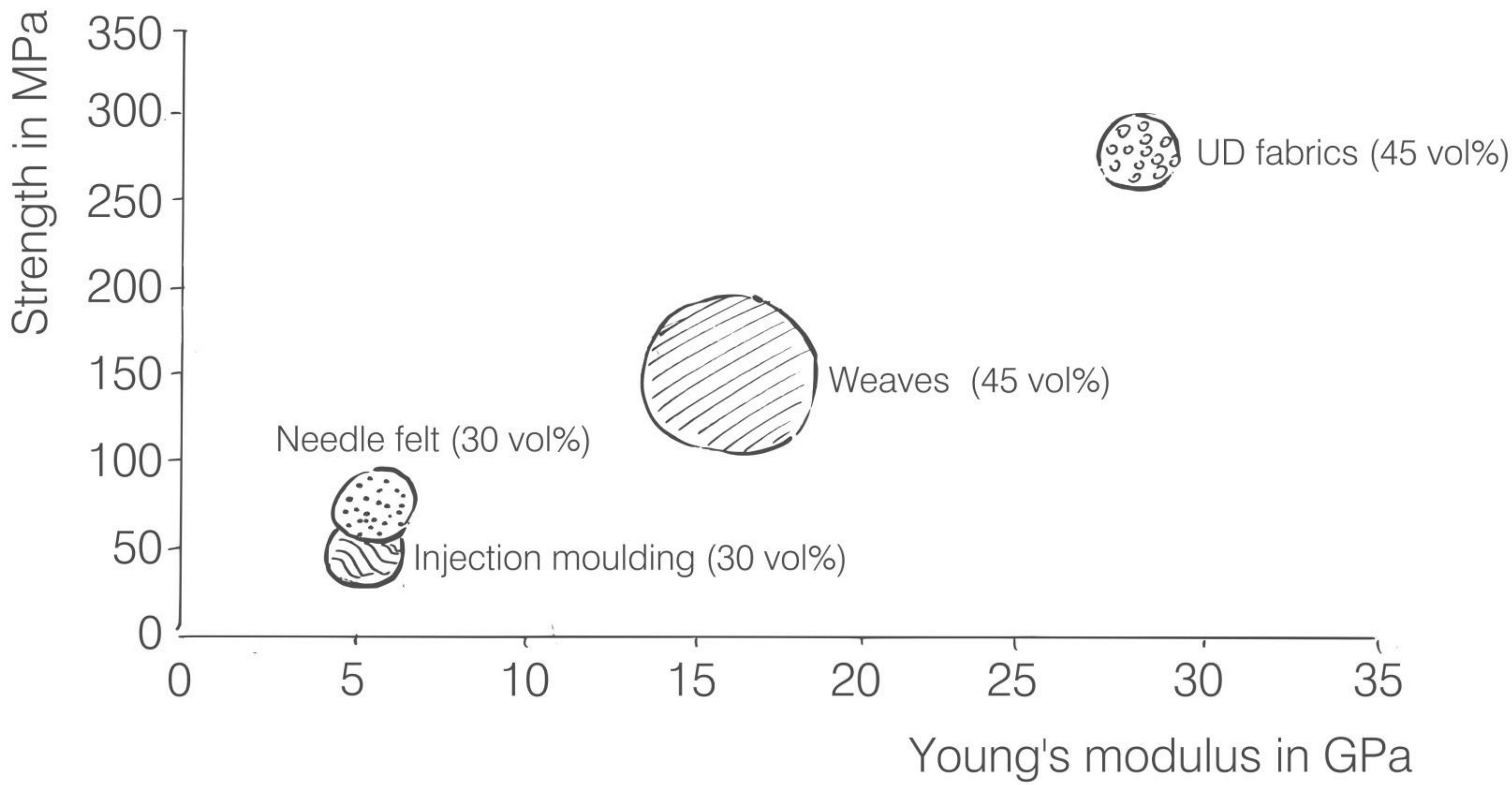
⇨ Successful application of natural of fibre-reinforced polymeric composites in exterior automotive parts.

NFRC: lightweight performance & mechanical properties



Needle felt production for the manufacturing of NFRCs.

NFRC: lightweight performance & mechanical properties



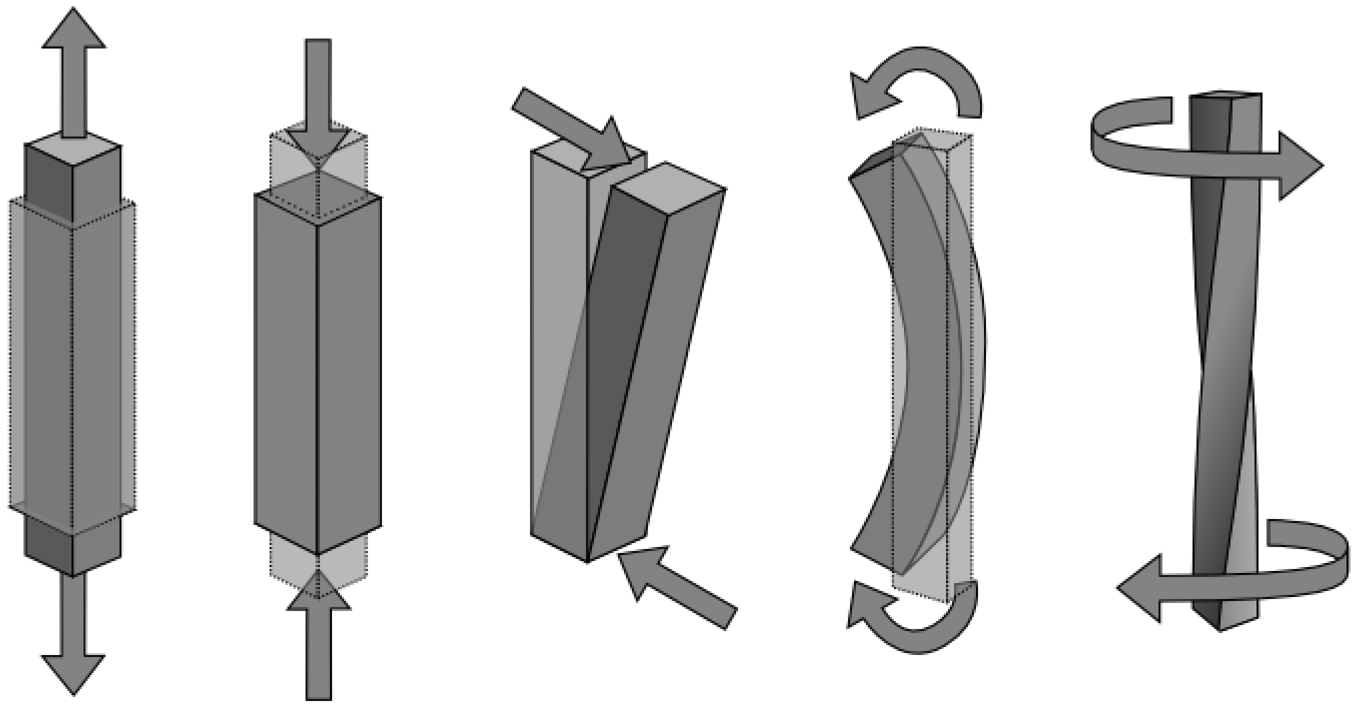
The performance playground for flax composites: NFRC have the potential to be used as a structural material to replace technical polymers or glass fibre-reinforced plastics.

(adapted from Verpoest & Baets, 2012)

Natural fibres & composites

(JEC Conferences, 2012)

Material selection & different load cases



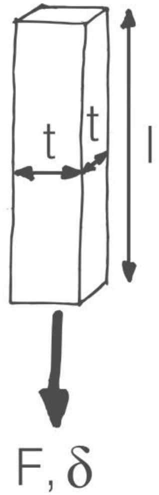
(A) (B) (C) (D) (E)

(Agerer, 2009)

Different load cases: a specimen loaded in (A) in tension, (B) axially, (C) in shear, (D) in bending and (E) in torsion.

Material selection & different load cases

Beam under tension



$$\delta = \frac{F \cdot l}{E \cdot t^2}$$

$$M = \rho \cdot l \cdot t^2$$

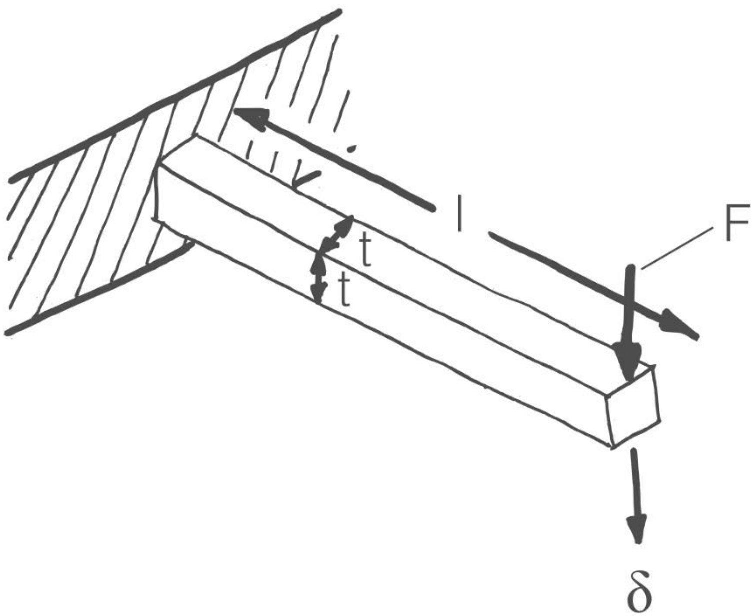
$$= \left(\frac{F \cdot l^2}{\delta} \right)^{\frac{1}{2}} \cdot \left(\frac{\rho}{E} \right)$$

Maximise ⇨ $\left(\frac{E}{\rho} \right)$

⇨ Combination of properties for which the ratio of stiffness to density becomes maximal. (adapted from Ashby et al., 2007, p. 223)

Material selection & different load cases

Beam under bending



$$\delta = \frac{4 \cdot F \cdot l^3}{E \cdot t^4}$$

$$M = \rho \cdot l \cdot t^2$$

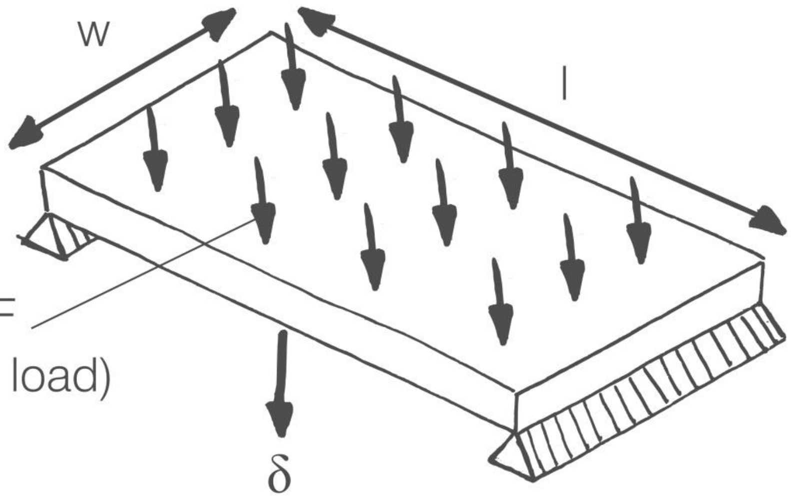
$$= 2 \cdot \left(\frac{F \cdot l^5}{\delta} \right)^{\frac{1}{2}} \cdot \left(\frac{\rho}{E^{\frac{1}{2}}} \right)$$

Maximise ⇨ $\left(\frac{E^{\frac{1}{2}}}{\rho} \right)$

⇨ Combination of properties for which the ratio of stiffness to density becomes maximal. (adapted from Ashby et al., 2007, p. 223)

Material selection & different load cases

Plate under bending



$$\delta = \frac{5 \cdot F \cdot l^3}{32 \cdot E \cdot w \cdot t^3}$$

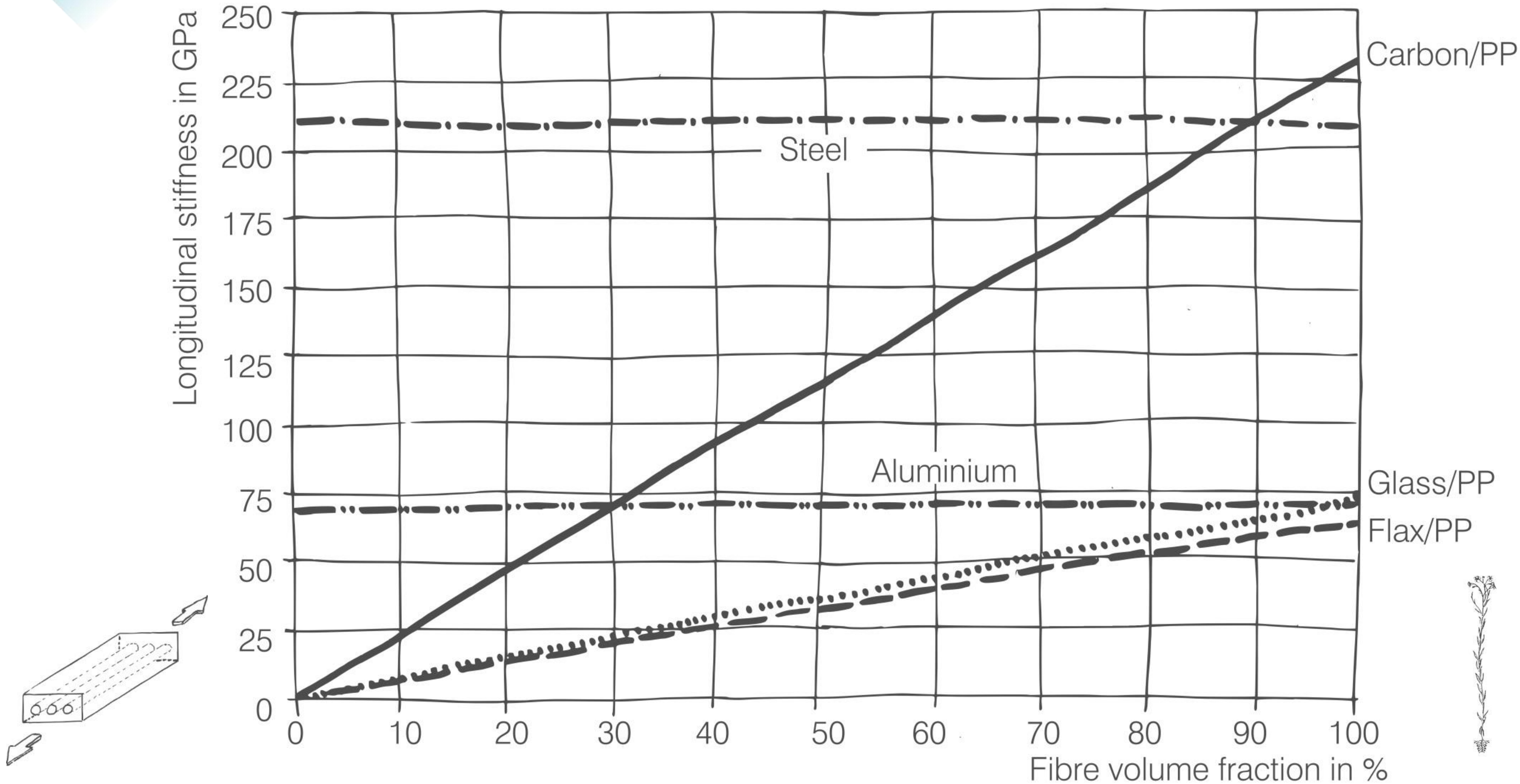
$$M = \rho \cdot l \cdot w \cdot t$$

$$= l^2 \cdot \left(\frac{5 \cdot F \cdot w^2}{32 \cdot \delta} \right)^{\frac{1}{3}} \cdot \left(\frac{\rho}{E^{\frac{1}{3}}} \right)$$

Maximise ⇨ $\left(\frac{E^{\frac{1}{3}}}{\rho} \right)$

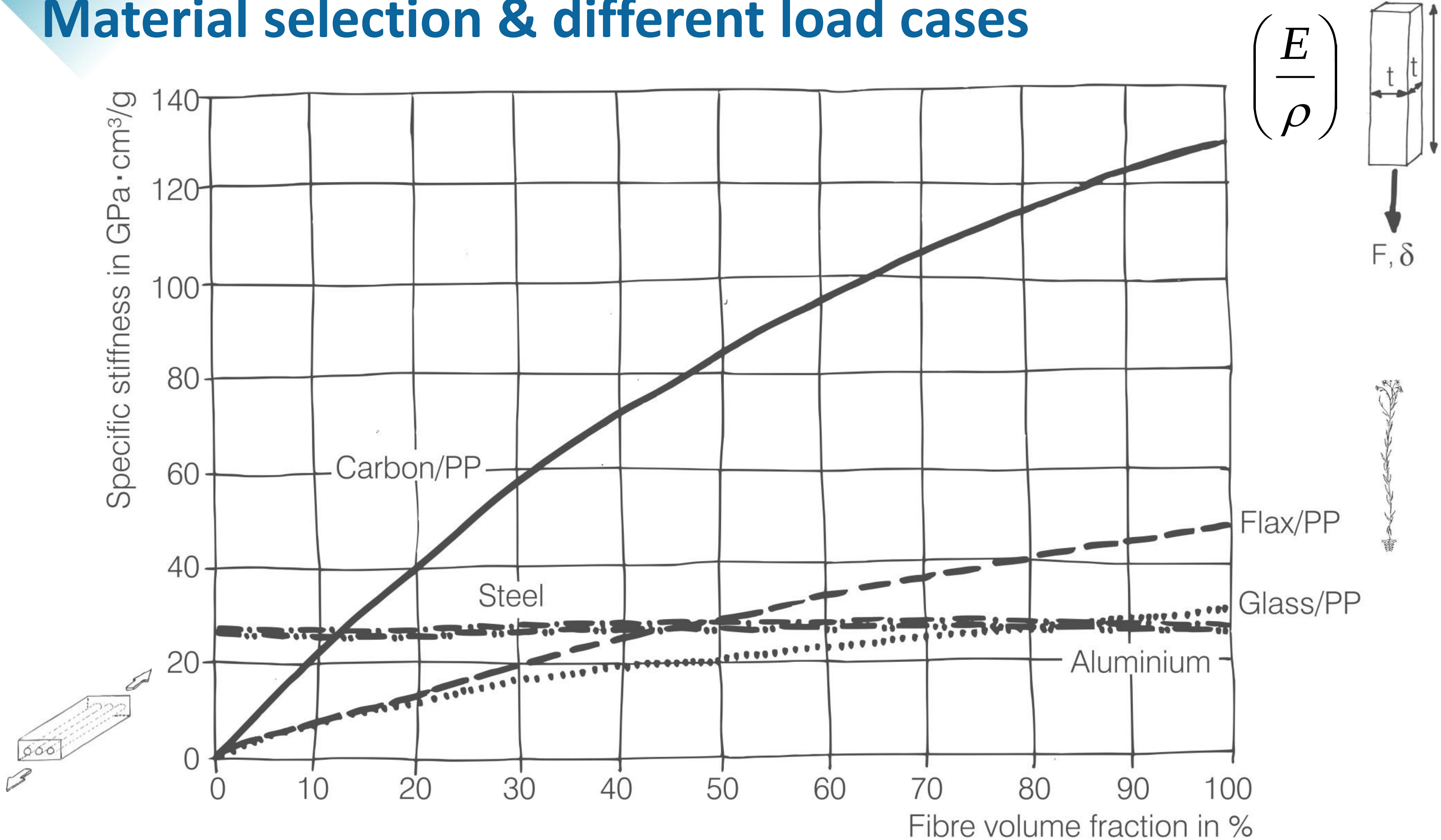
⇨ Combination of properties for which the ratio of stiffness to density becomes maximal. (adapted from Ashby et al., 2007, p. 223)

Material selection & different load cases



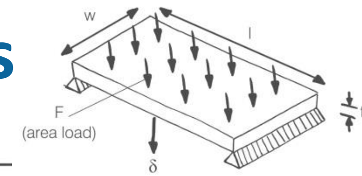
Fibre volume fraction dependent stiffness values of composites compared to metals. (adapted from Verpoest & Baets, 2012)

Material selection & different load cases

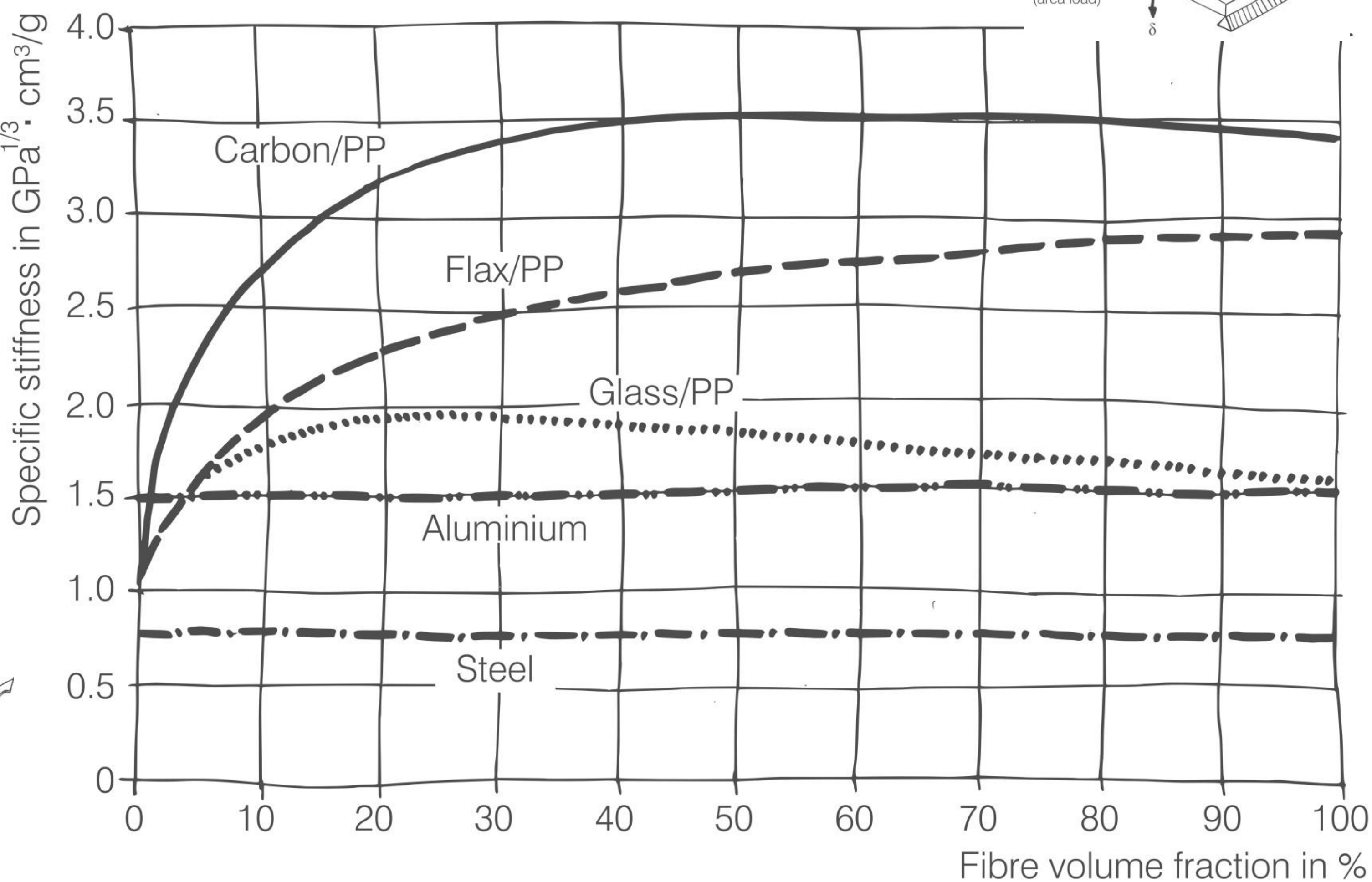


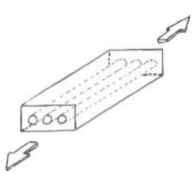
Fibre volume fraction dependent longitudinal specific stiffness values of composites compared to metals. (adapted from Verpoest & Baets, 2012)

Material selection & different load cases



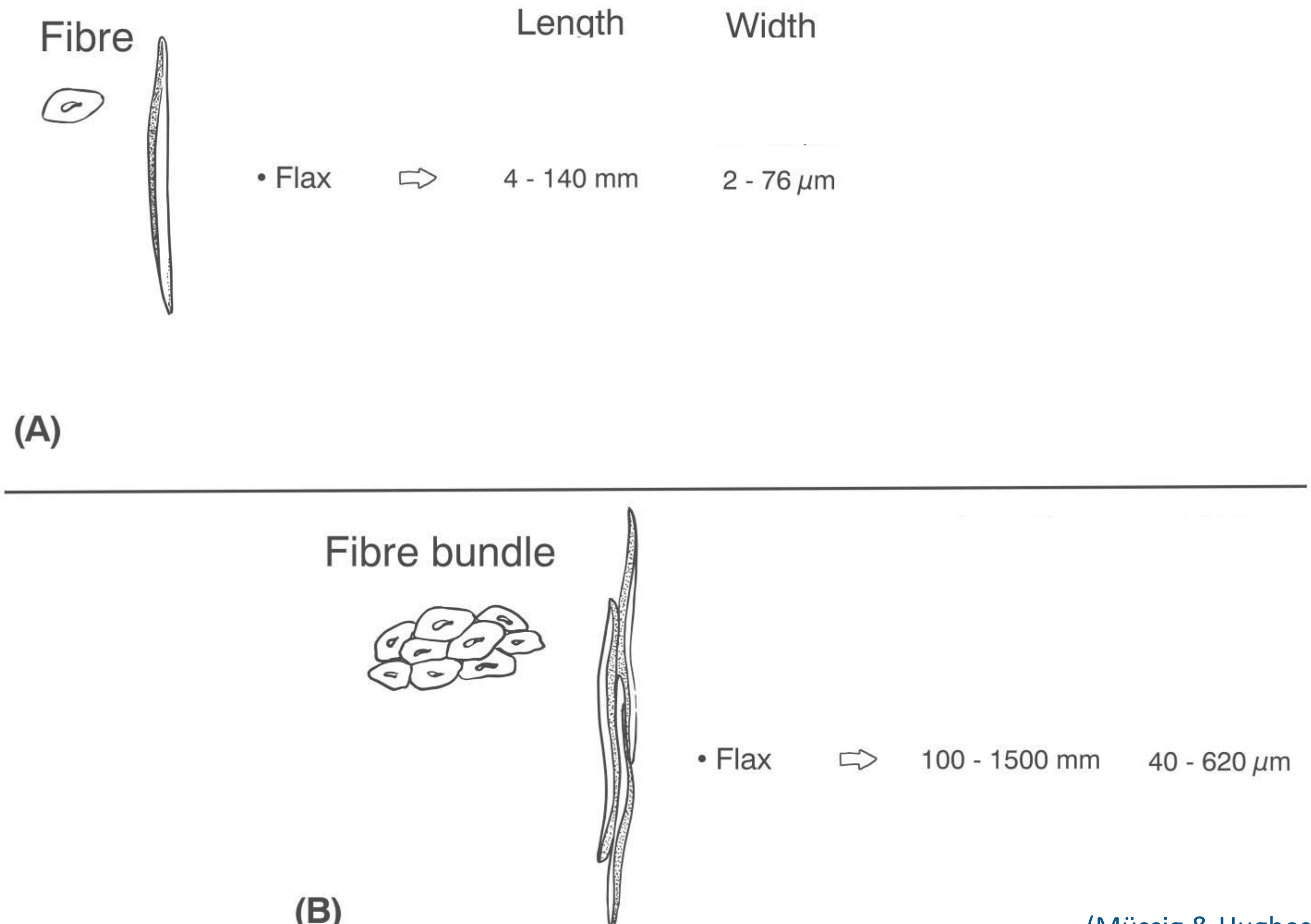
$$\left(\frac{E^{\frac{1}{3}}}{\rho}\right)$$





Fibre volume fraction dependent longitudinal specific stiffness values of composites compared to metals. (adapted from Verpoest & Baets, 2012)

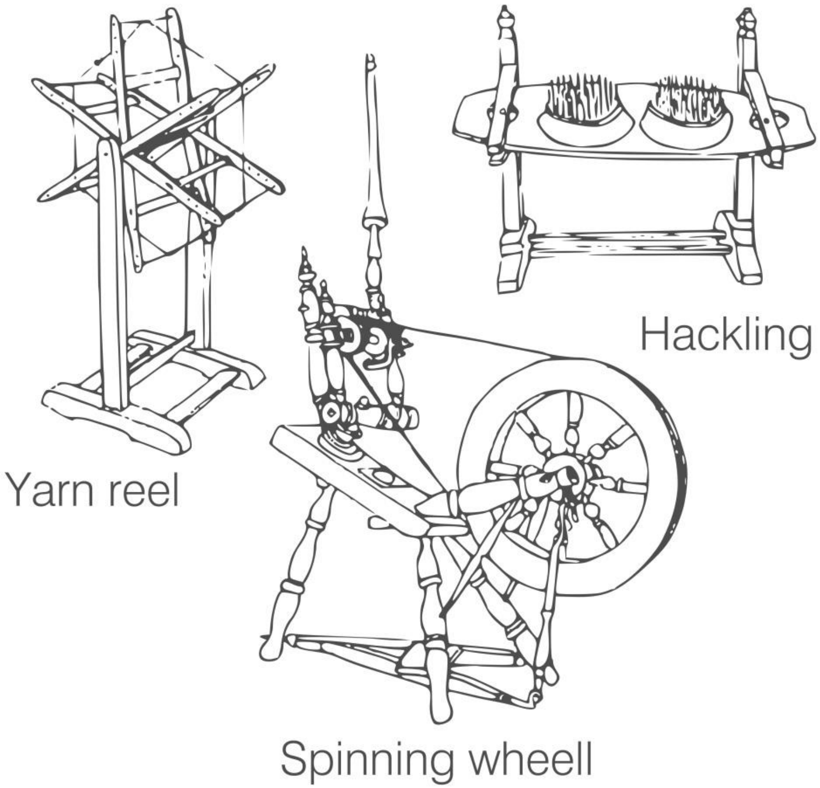
Fibre Morphology



(Müssig & Hughes, 2012)

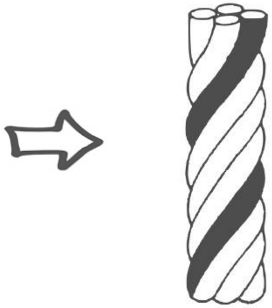
(A) Length and width values of single flax fibres. (B) Length and width values of flax fibre bundles.

From fibre to yarn



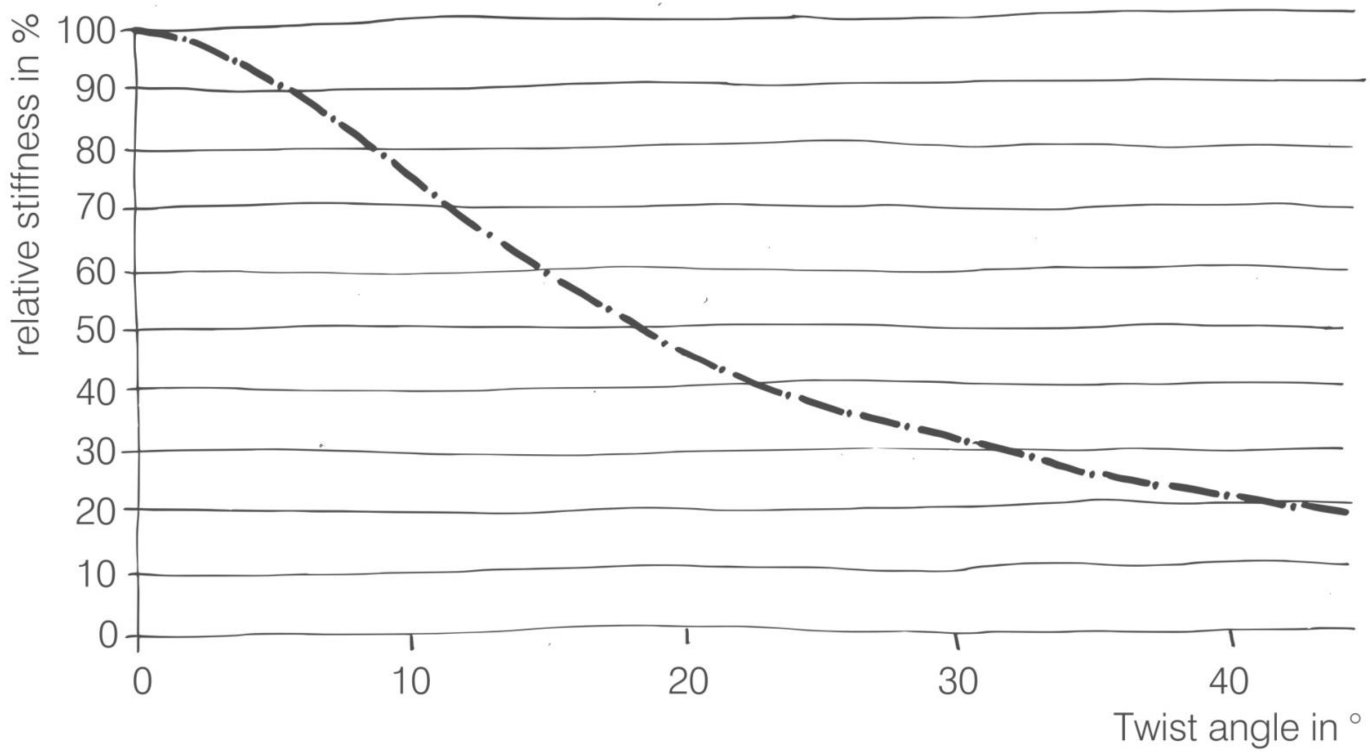
(adapted from Sendenhorster, 2011)

(Vanneste, 2013)



⇨ From plant fibre to textile structure for composite application.

Calculated effect of twist on composite stiffness



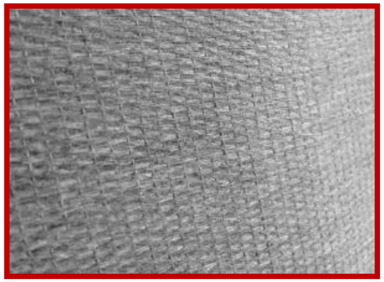
Yarn twist angle dependent stiffness values of composites.

(adapted from Verpoest & Baets, 2012)

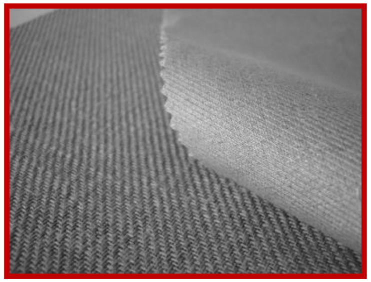
The higher the twist angle, the lower the strength & stiffness of the composite.

NFRC: yarns & textiles for composite applications

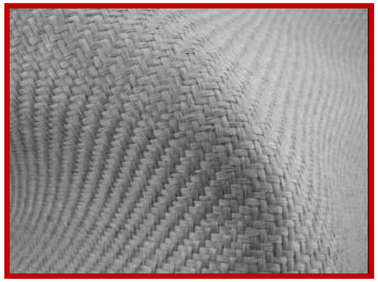
Roving



Pre-impragnated weaves

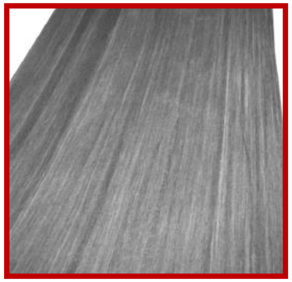


Weaves



Hybrid weaves

Non-crimp fabric

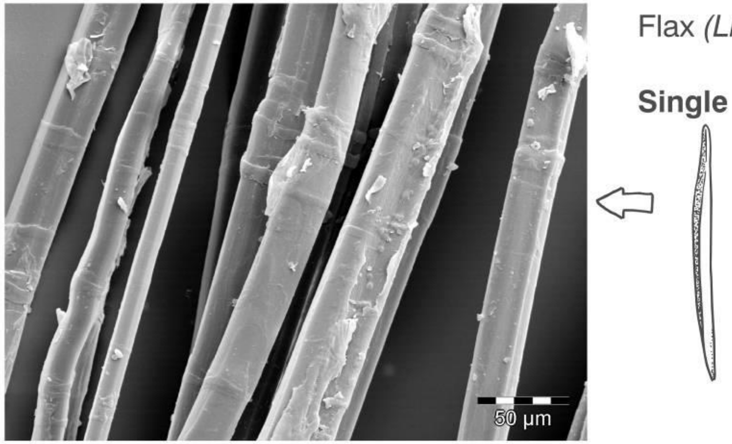


UD prepregs

⇨ Complete absence of twist and crimp

(Baets & Pariset, 2012)

Fibres properties and NFRC

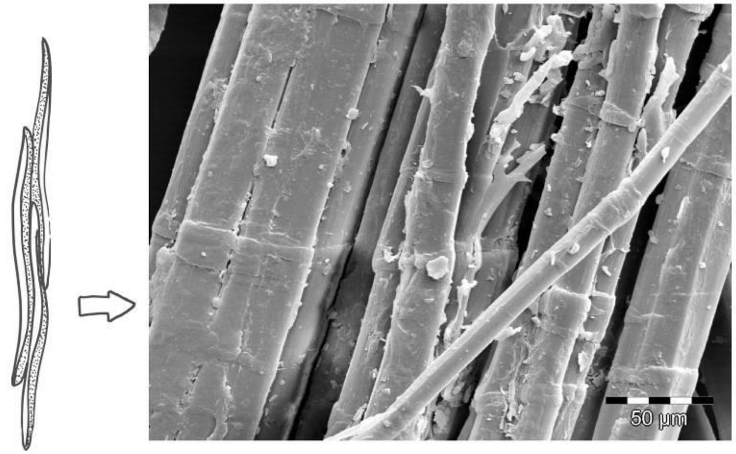


Flax (*Linum usitatissimum* L.)

Single fibres
after mechanical separation

Flax (*Linum usitatissimum* L.)

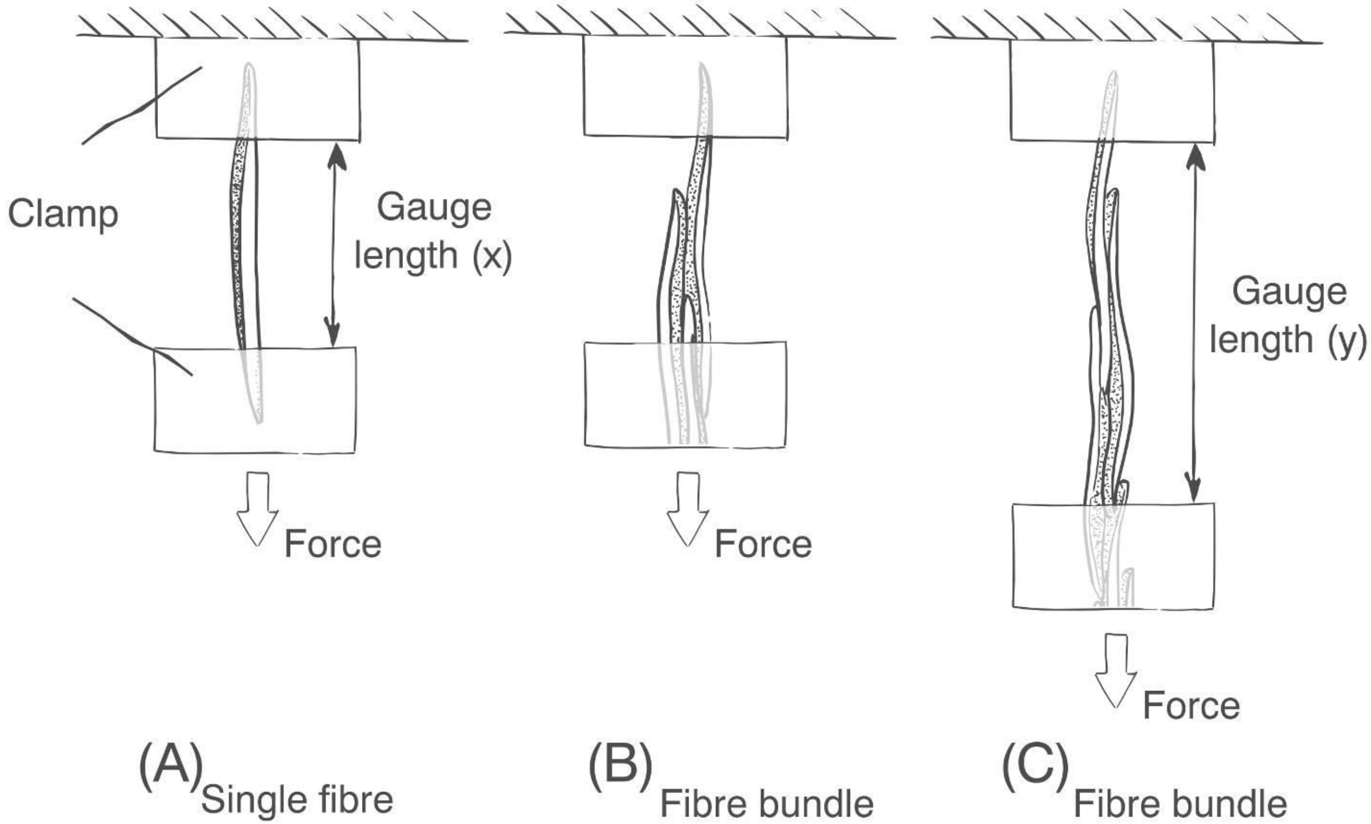
Fibre bundles
after mechanical separation



(Müssig & Hughes, 2012)

Scanning electron micrographs of single flax (*Linum usitatissimum* L.) fibres (upper image) and flax fibre bundles of variable width and a single fibre in front (lower image).

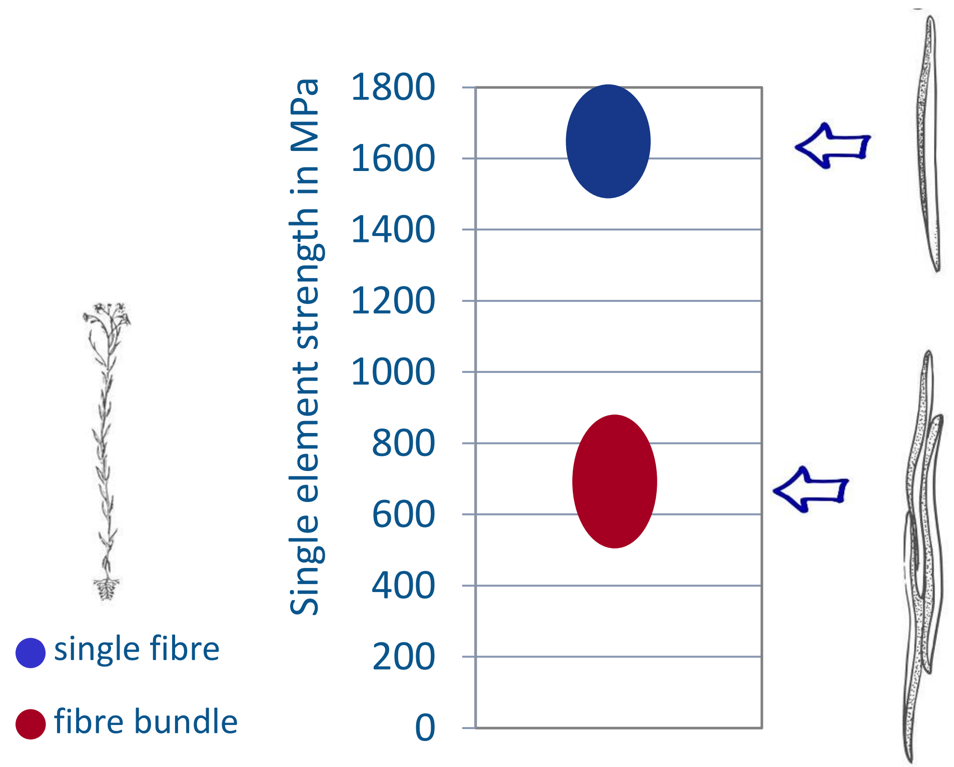
Fibres properties and NFRC



(Müssig & Hughes, 2012)

Various testing methods to determine the tensile properties of plant fibres and fibre bundles. (A) Single fibre fixed in clamps at a gauge length (x). (B) A fibre bundle prepared for tensile testing with the same gauge length (x) as the single fibre. (C) Fibre bundle with a greater gauge length (y).

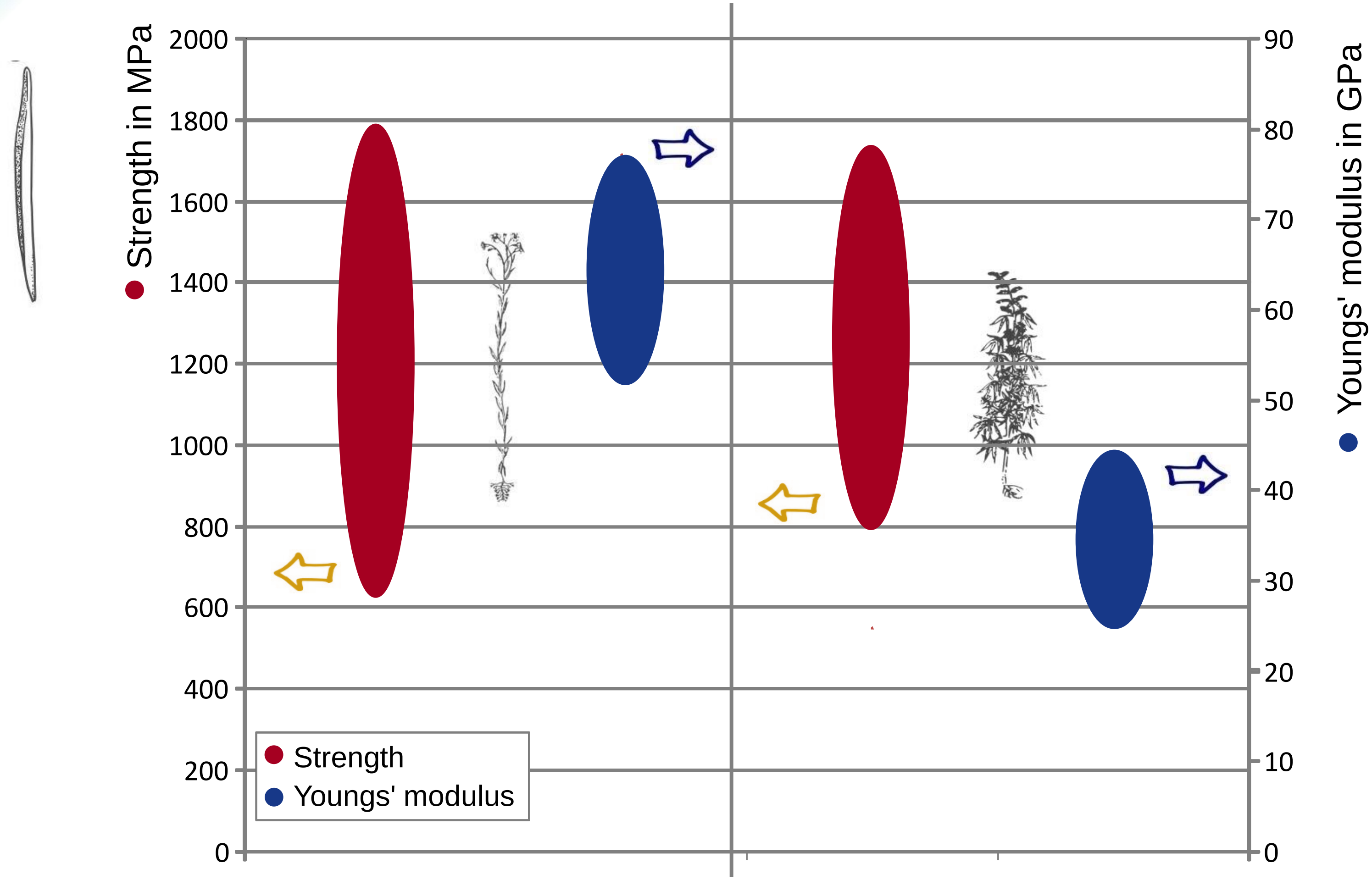
Fibres properties and NFRC



(Müssig & Graupner, 2015b .–
values taken from Bos et al., 2002)

Strength values for single flax fibres and single flax fibre bundles.

Fibres properties and NFRC



Tensile properties of single bast fibres – flax versus hemp.

(Müssig & Graupner, 2015b .– (values taken from Bourmaud & Baley, 2009; Eder & Burgert, 2010 for hemp / Baley, 2002; Charlet et al., 2006 & 2007; Eder & Burgert, 2010 for flax)

HSB

Scatter in tensile properties of flax fibre bundles: influence of determination and calculation of the cross-sectional area

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ABSTRACT

The scatter in tensile properties induced by the determination and calculation method of the cross-sectional area (CSA) of bast fibre bundles is almost as high as the scatter found in the literature. Different methods (light microscopy, high resolution flat-bed scanning, and laser-based fibre dimensional analysis) were applied to exactly the same flax fibre bundles prior to tensile testing, and different approaches for the calculation of the CSA were applied. The CSA method alone is introducing up to 300 % of variation in tensile strength data. These results show that there is a strong need for standards and standardisation of fibre bundle testing. Care has to be taken when comparing results from studies using slightly different methods.

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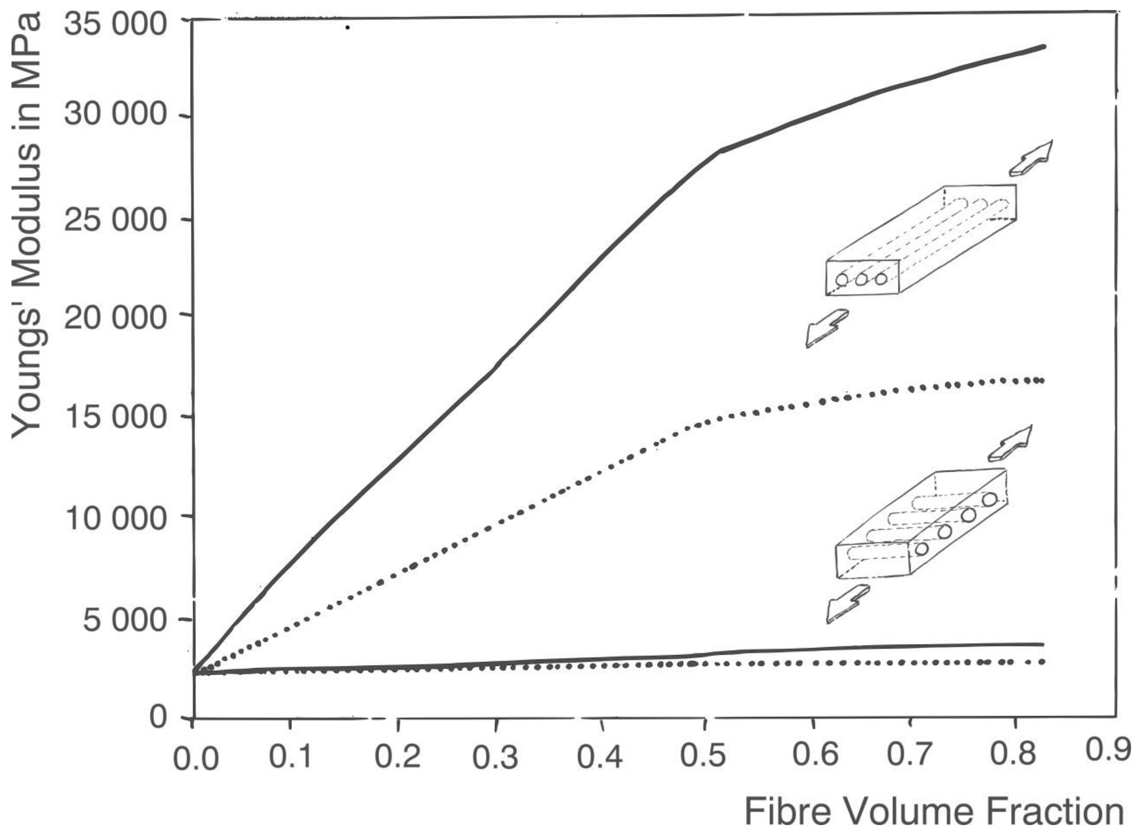
⇨ Scatter in Tensile Strength and Young's modulus of different natural fibres from the plant stem.

Fibres properties and NFRC

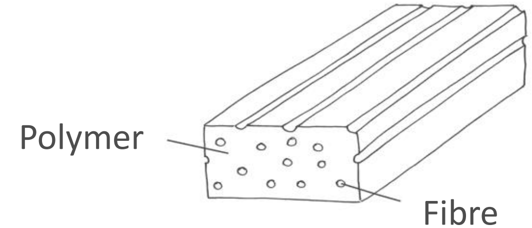


- Calculation model (from Madsen & Lilholt, 2013)

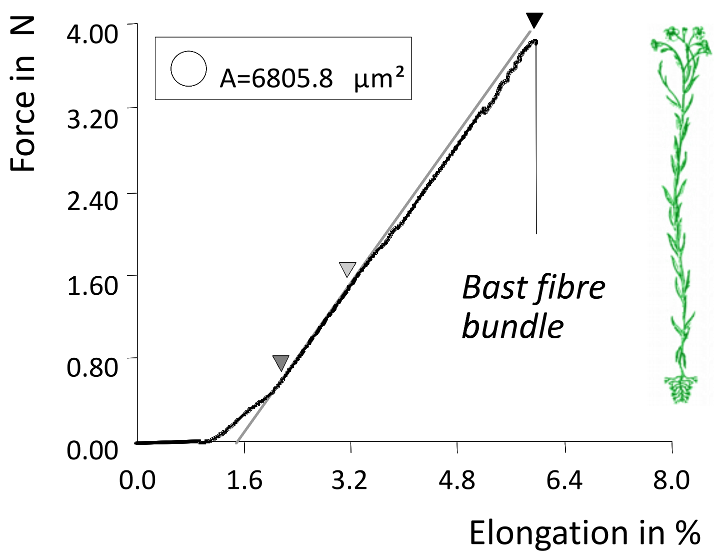
- Flax fibre reinforced polypropylene
- Dotted lines: flax Young's modulus: 30 GPa
- Solid lines: flax Young's modulus: 60 Gpa
- porosity content & fibre anisotropy ratio of 1/7 considered

⇨ Composite mechanical properties. Young' modulus is plotted as a function of composite fibre volume fraction.

Fibres properties and NFRC



Bast fibre



High stiffness, <u>low elongation</u>

Bast fibre-reinforced polymer

\+ **High stiffness**

− **Low toughness**

Nature as inspiration?

Why use nature as inspiration?

Biological structures:

- Are multifunctional

  - For example impact & saltwater resistant & biodegradable

A coconut can fall and hit you on the head,
And if it falls from high enough can kind of knock you dead
Dead beneath the coconut palms, that's the life for me!

Frederick Seidel: „Coconut“

(Visbek, 2008)

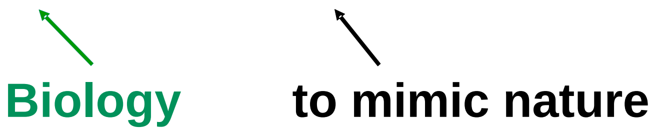
(Offnfopt, 2015)

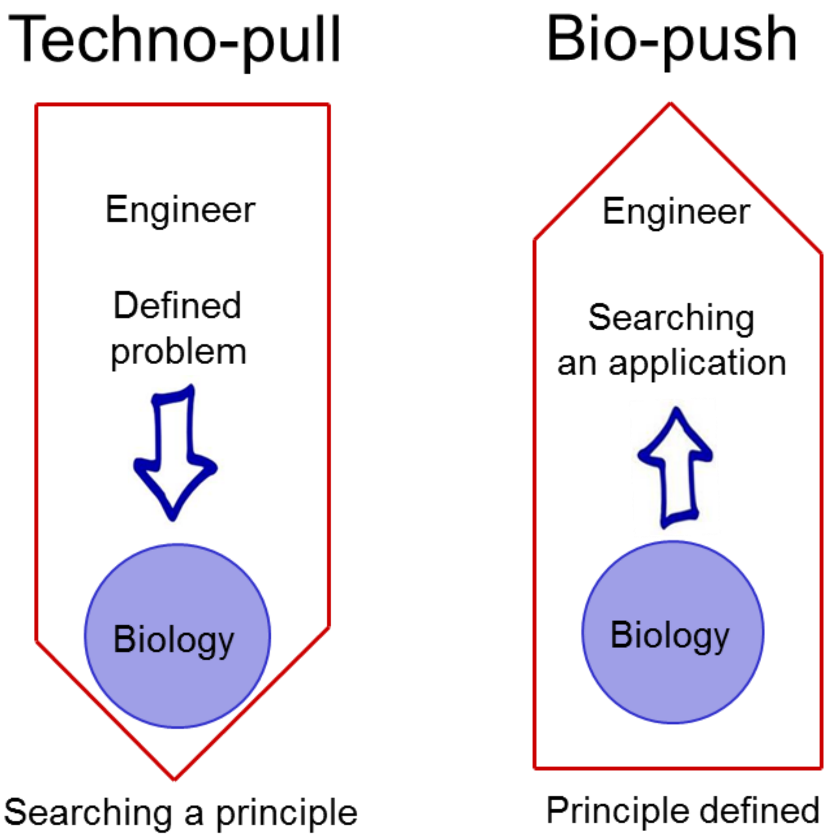
Biomimetic materials ≠ biological materials

- Biomimetic materials use functional and structural characteristics of biological materials.
- Biomimetic materials are inspired by natural examples.
- Applying *natural, bio-based and biological materials* would be optimal but not always possible.

Biomimetic work processes

***Bio**mimetics*





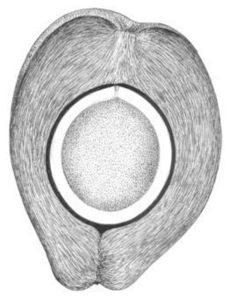
Biomimetic work processes

(Harder, 2007, S. 119 .- adapted)

Biomimetic work processes

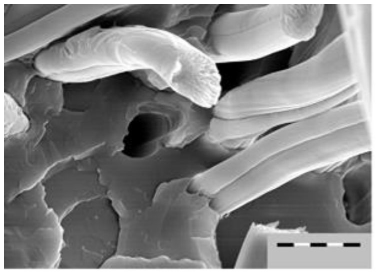
Techno-pull

Technical problem



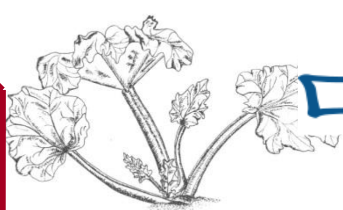
Natural model

Technical solution

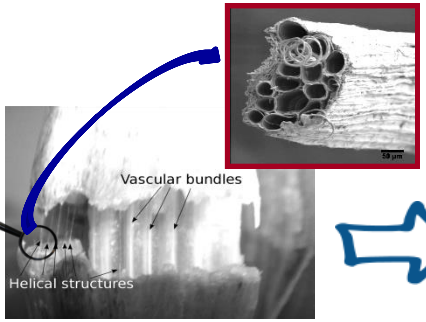


Biomimetic Fibre Composite

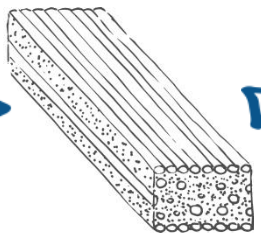
Bio-push



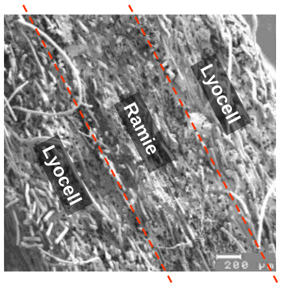
Basic biological research



Structure-function relation

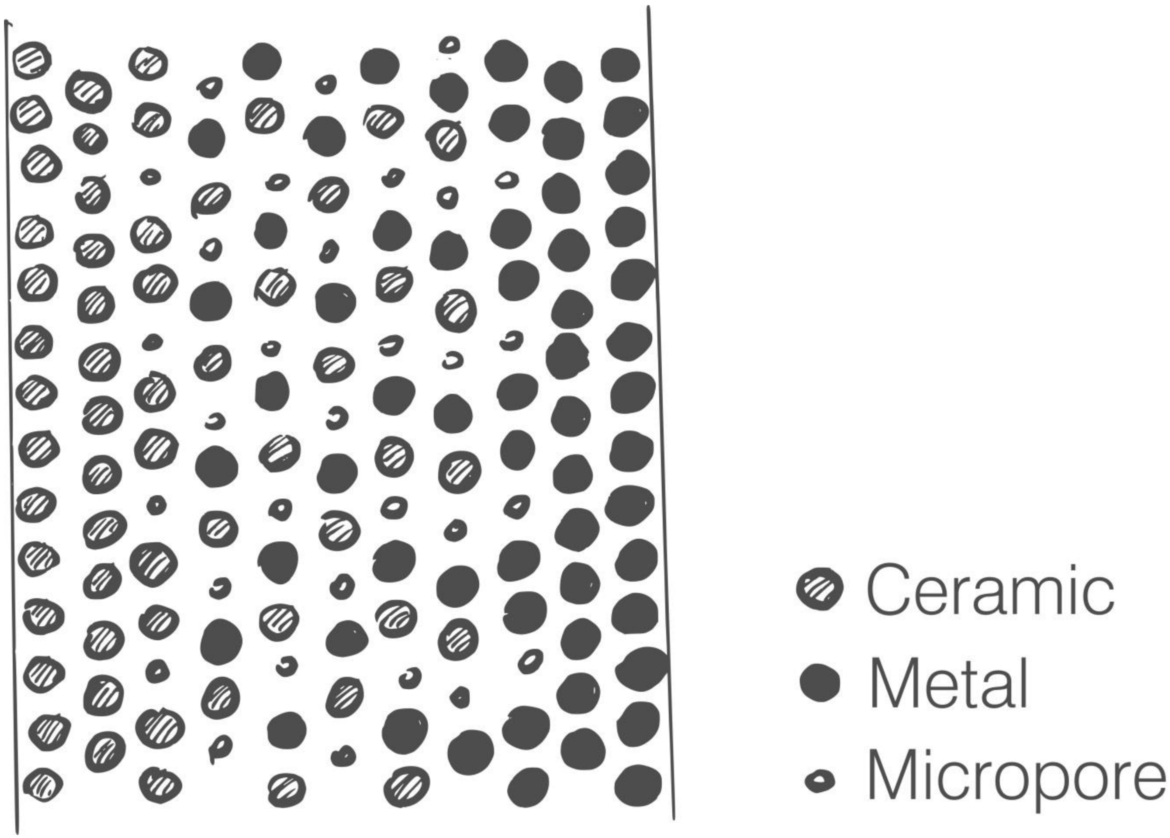


Transfer to composites



Biomimetic Fibre Composite

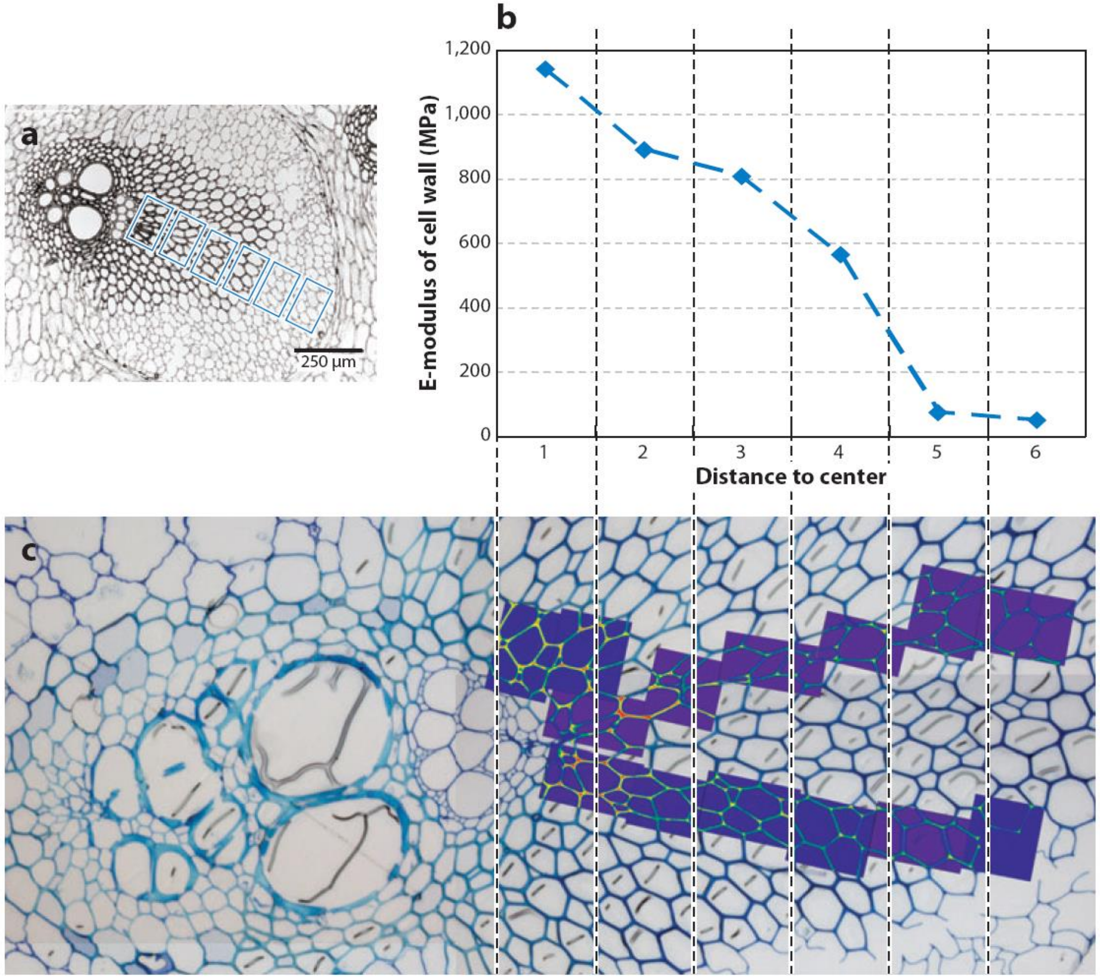
Material gradient in a man-made composite structure

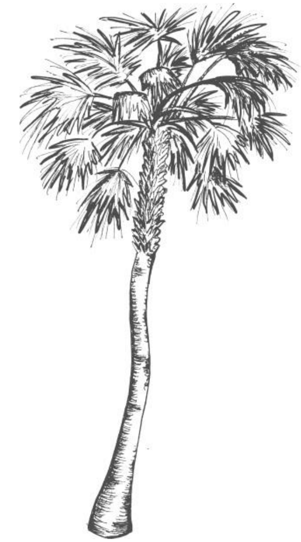


(Adapted and modified from Meyers & Chawla, 2009)

Schematic of a functionally graded material between a ceramic and a metal.

Mechanical gradient in plants

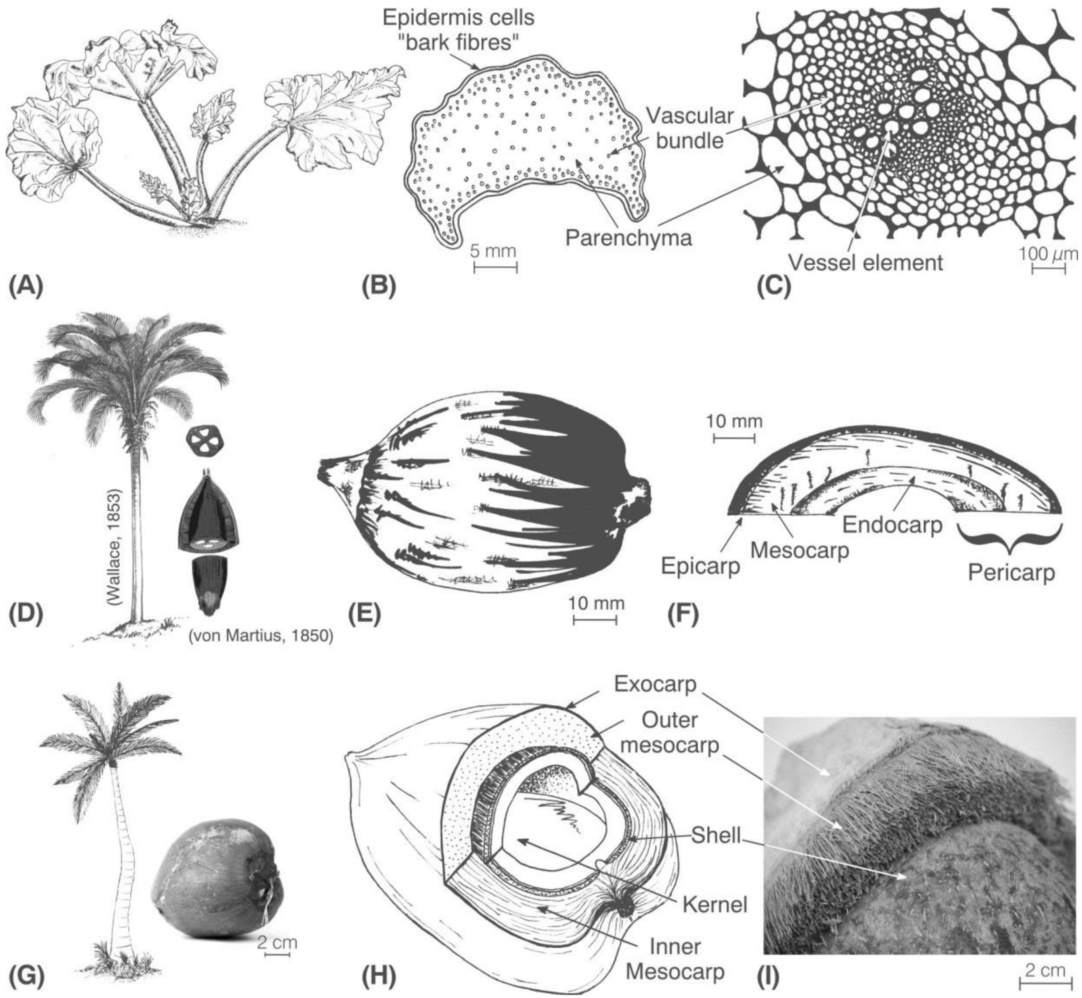




(Speck & Burgert, 2011 .– Adapted from Rüggeberg et al. 2008)

Stiffness gradient in the fibre cap of a specific vascular bundle type of the palm *Washingtonia robusta.*

Natural role models



(Huber et al., 2009)

(Graupner et al. 2017b)

(Staufenberg et al. 2015)

(Graupner et al. 2017a)

(A-C) Red rhubarb petioles, (D-F) the babassu nut and (G-I) the drupes of coconut palm trees as examples for biological composites.

Objective

We identified outstanding design features in biological composites and transferred these into simplified technical composites. This approach will allow us to:

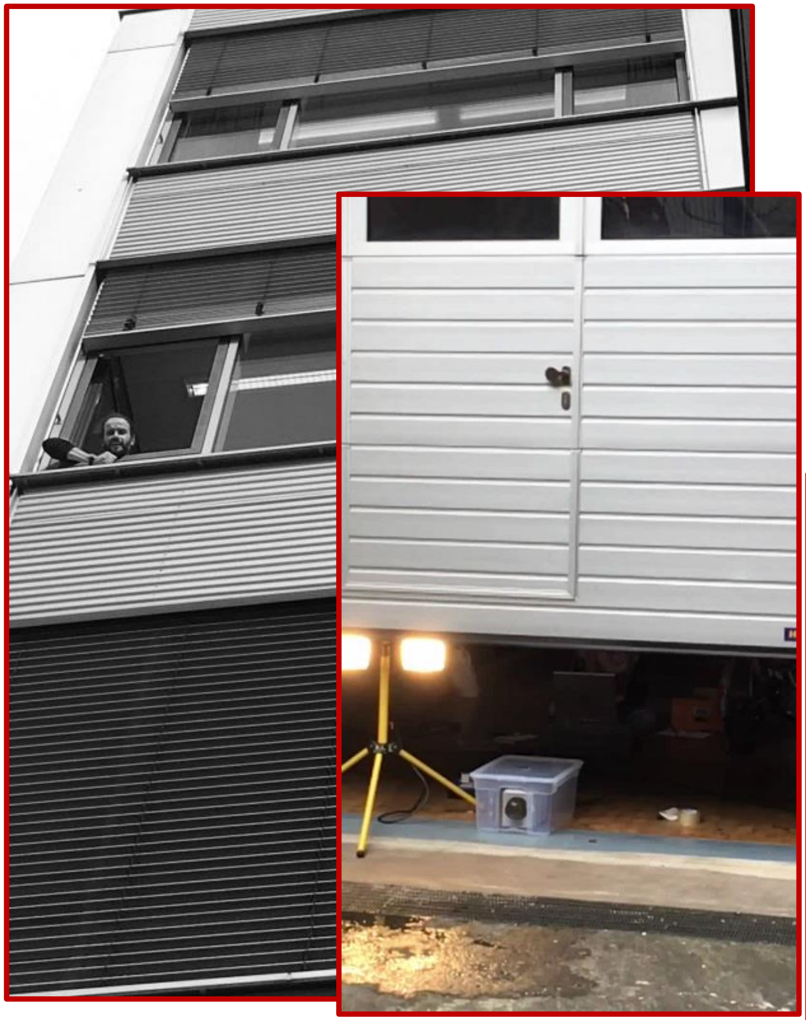
⇨ (i) test the role of selected design features in isolation,

(ii) gain control over their exact quantitative implementation for example, the magnitude of a gradient in Young's modulus,

(iii) hence perform hypothesis-driven tests of their mechanical importance in technical composites and thereby

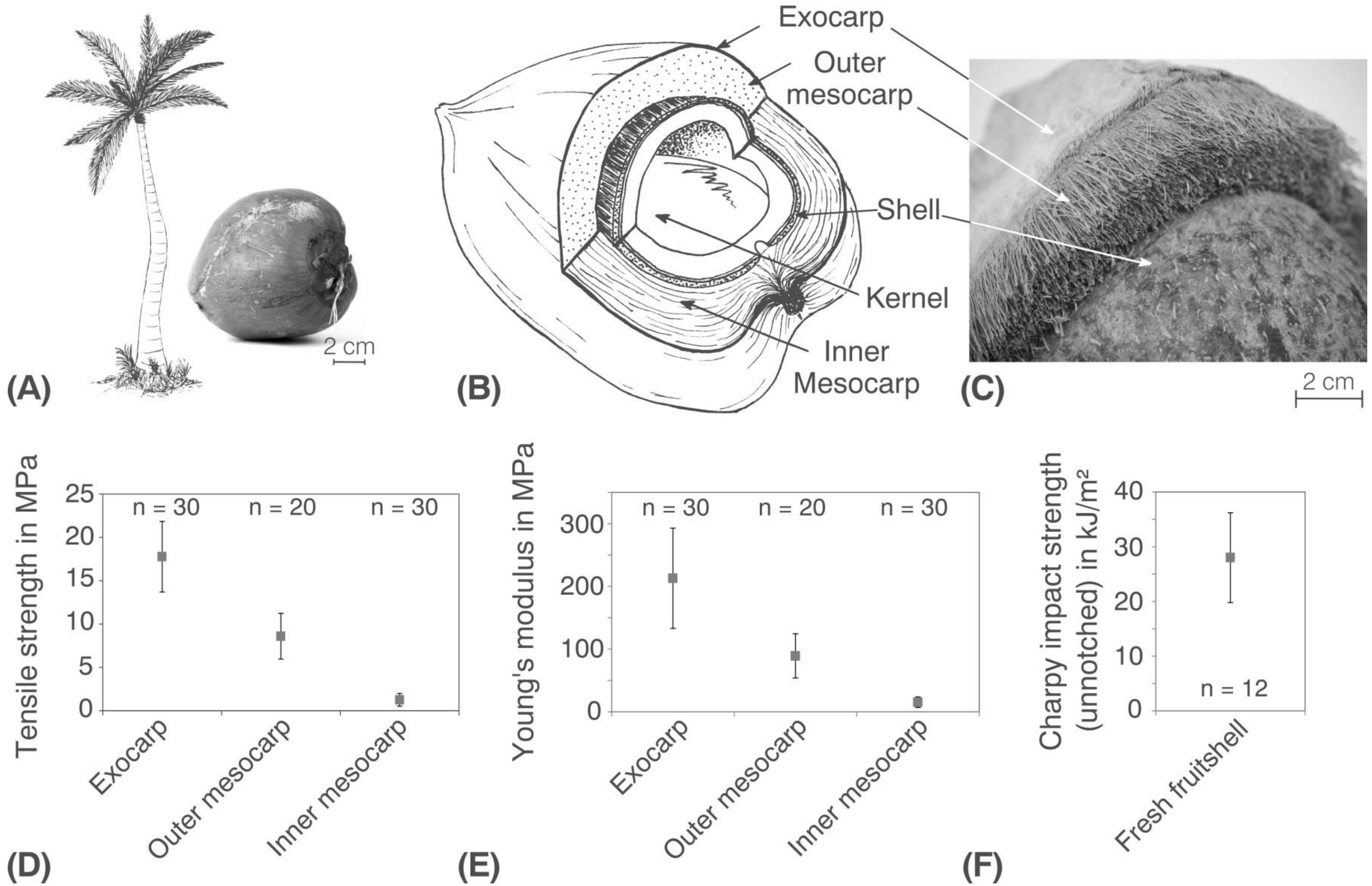
(iv) improve our understanding of structure-function relationships in complex biological materials.

Natural role model: drupes of coconut palm trees



Coconuts have to survive falls from great heights.

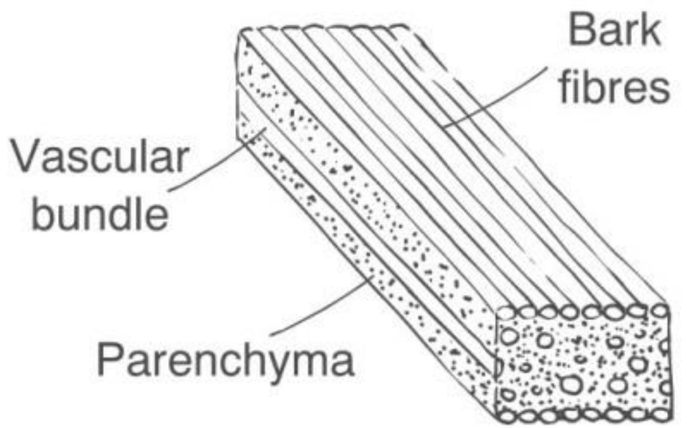
Natural role model: drupes of coconut palm trees



(Graupner et al. 2017a)

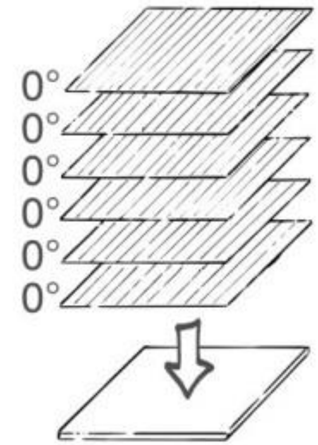
Coconuts have to survive falls from great heights.

Man-made composites as a model system



Schematic model of the rhubarb petioles as a composite

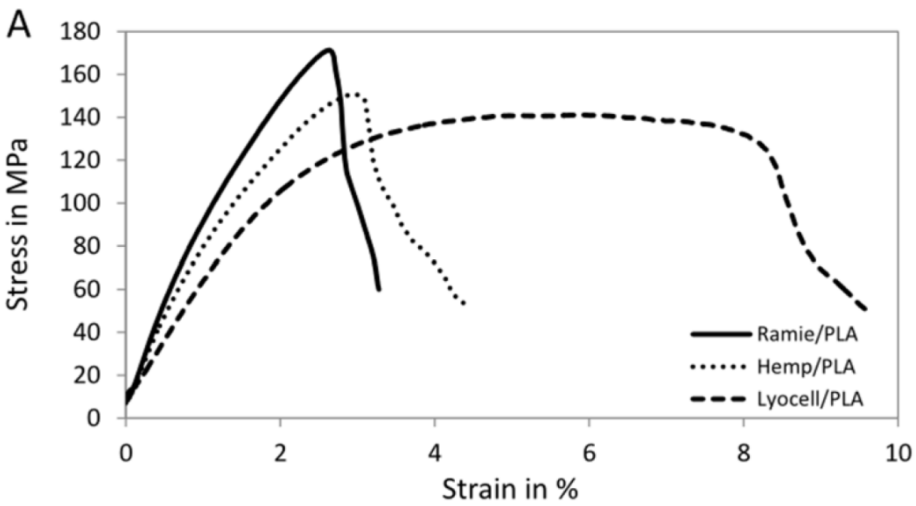
Composites mimicking selected features of the biological striuctures were prepared from fibres having different mechanical properties

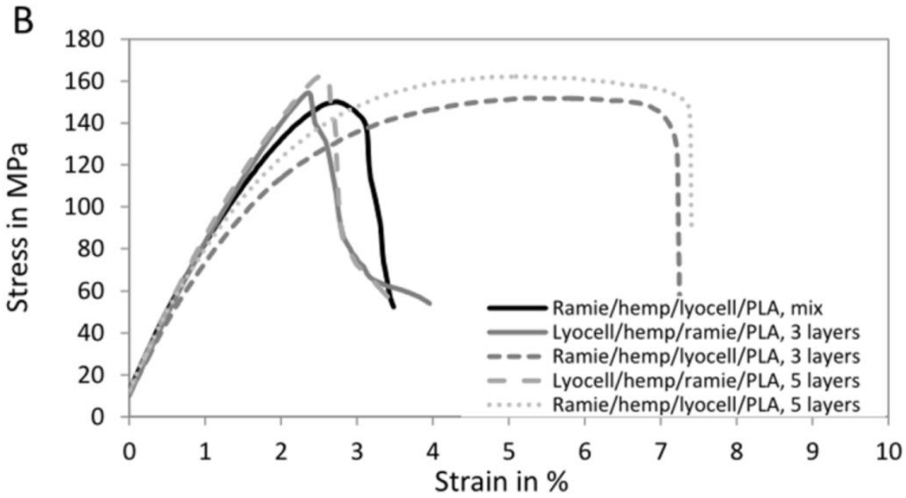


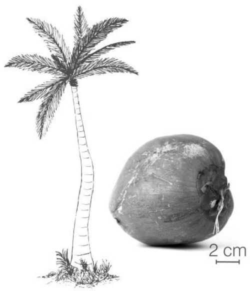
Compression moulded bio-inspired composite used as simple model system

From a simplified biological structure to a bio-inspired fibre-reinforced composite.

Man-made composites as a model system



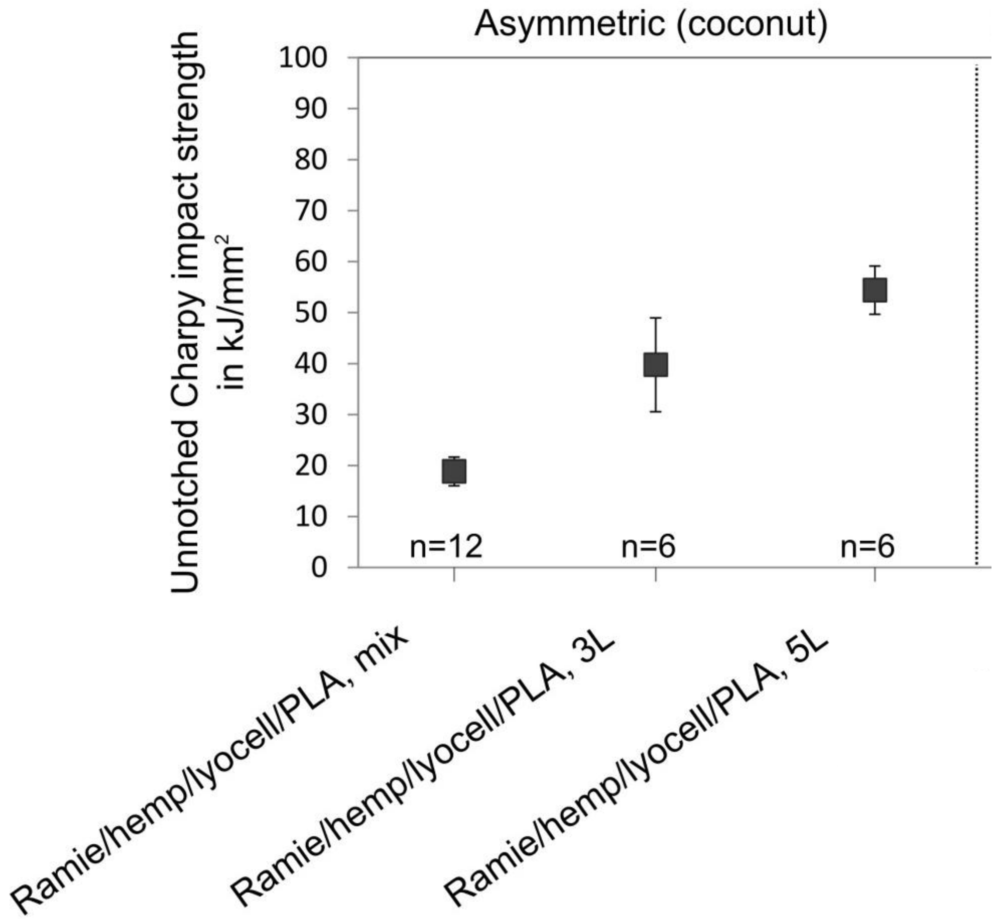




⇨ Stress–strain curves obtained during a bending test of cellulose fibre-reinforced PLA composites.

(Graupner et al. 2017a)

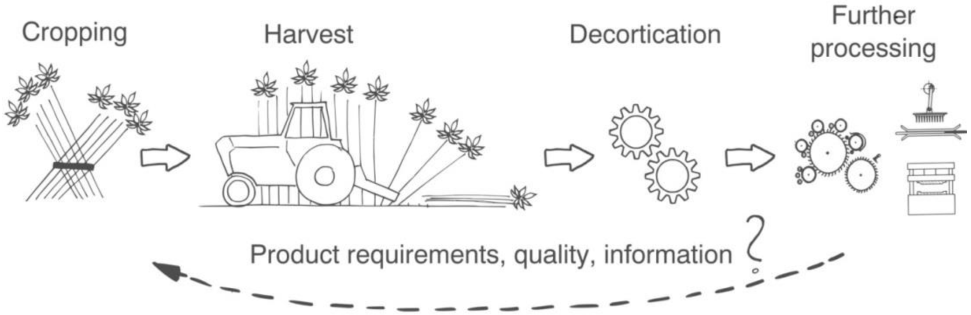
Man-made composites as a model system



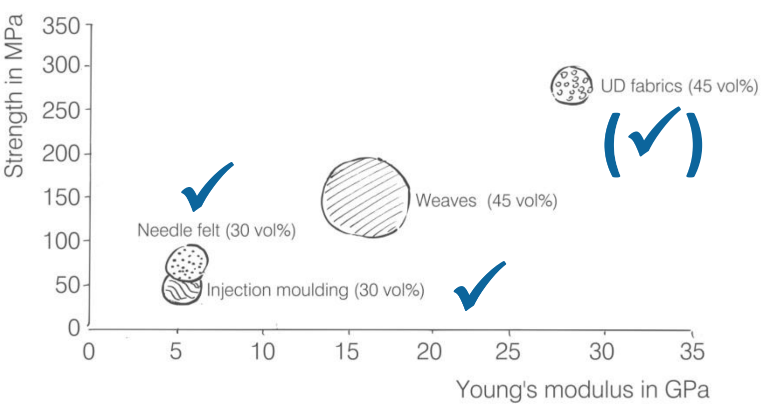
The bio-inspired composites had a significantly enhanced Charpy impact strength compared to composites with the same fibre content but random fibre distribution.

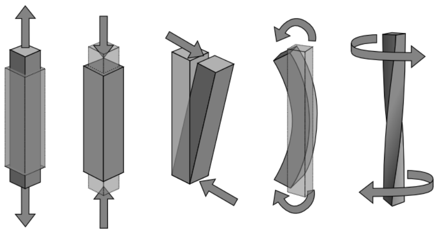
Conclusion & Outlook

Performance of natural fibre-reinforced plastics: What are the theoretical potentials and how do they translate into practical values?



- ✖ NFRC have the potential to be used as a structural material to replace technical polymers or glass fibre-reinforced plastics.





⇨ The performance playground for flax & hemp composites. (adapted from Verpoest & Baets, 2012)

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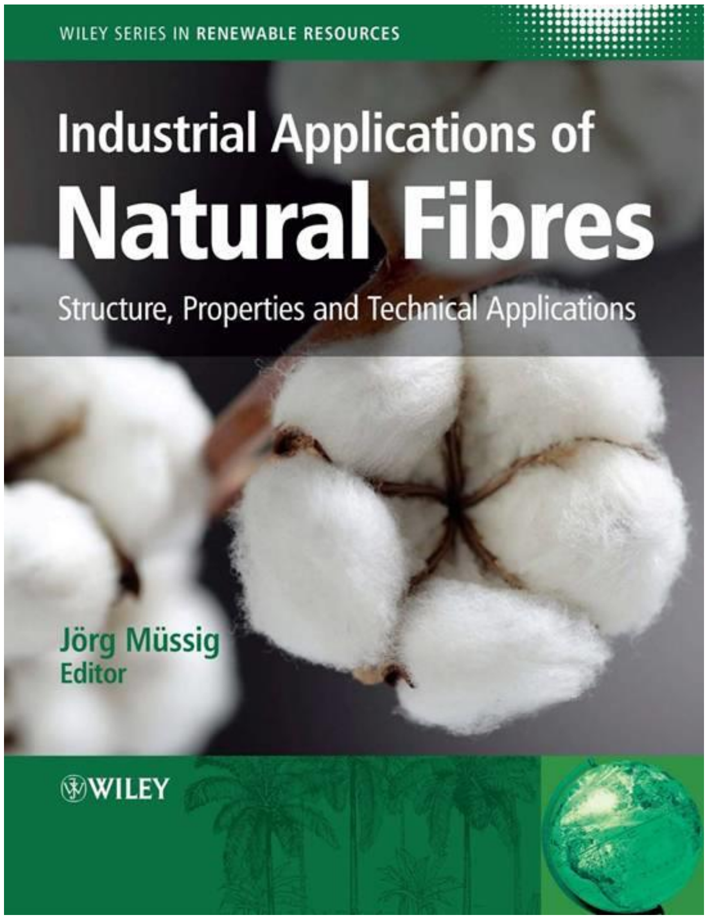
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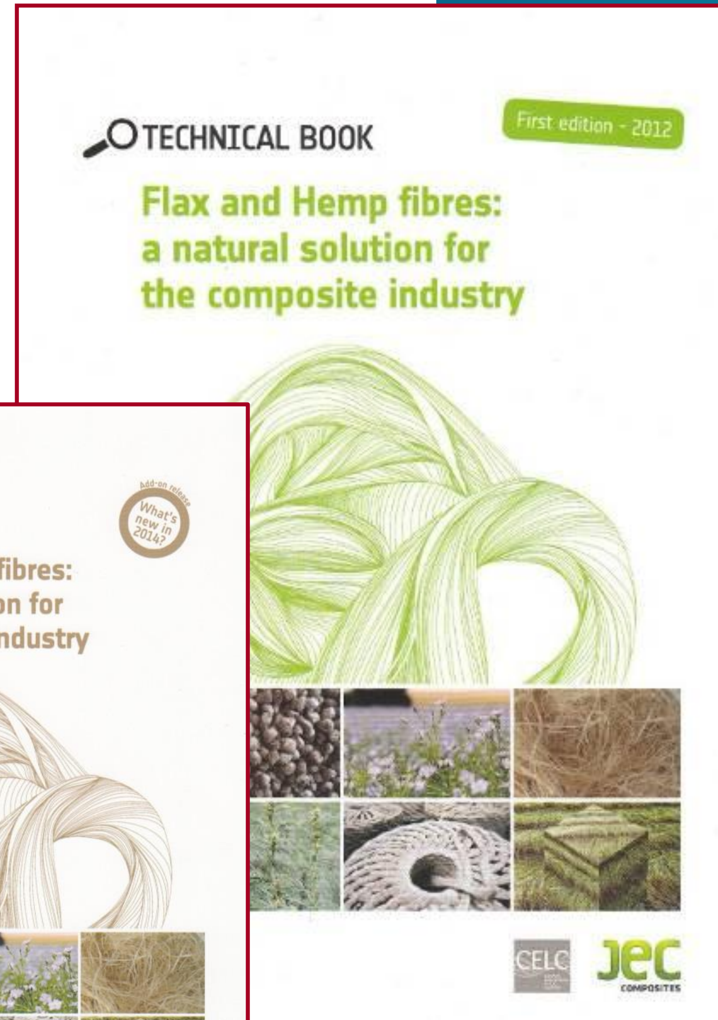
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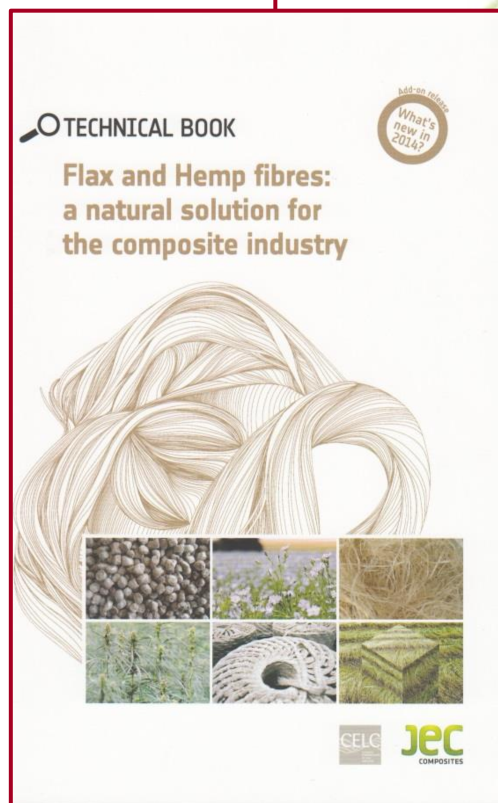
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