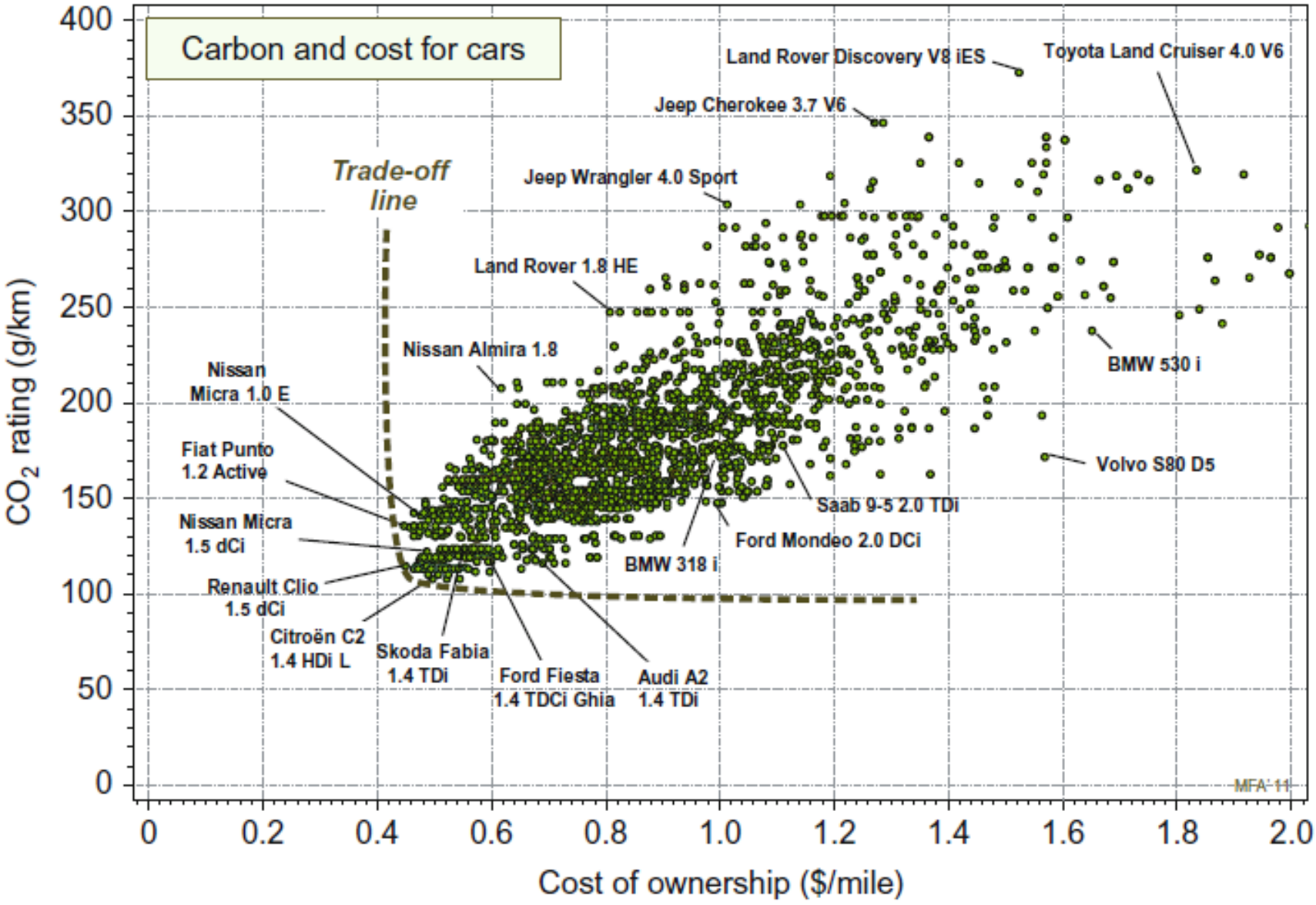
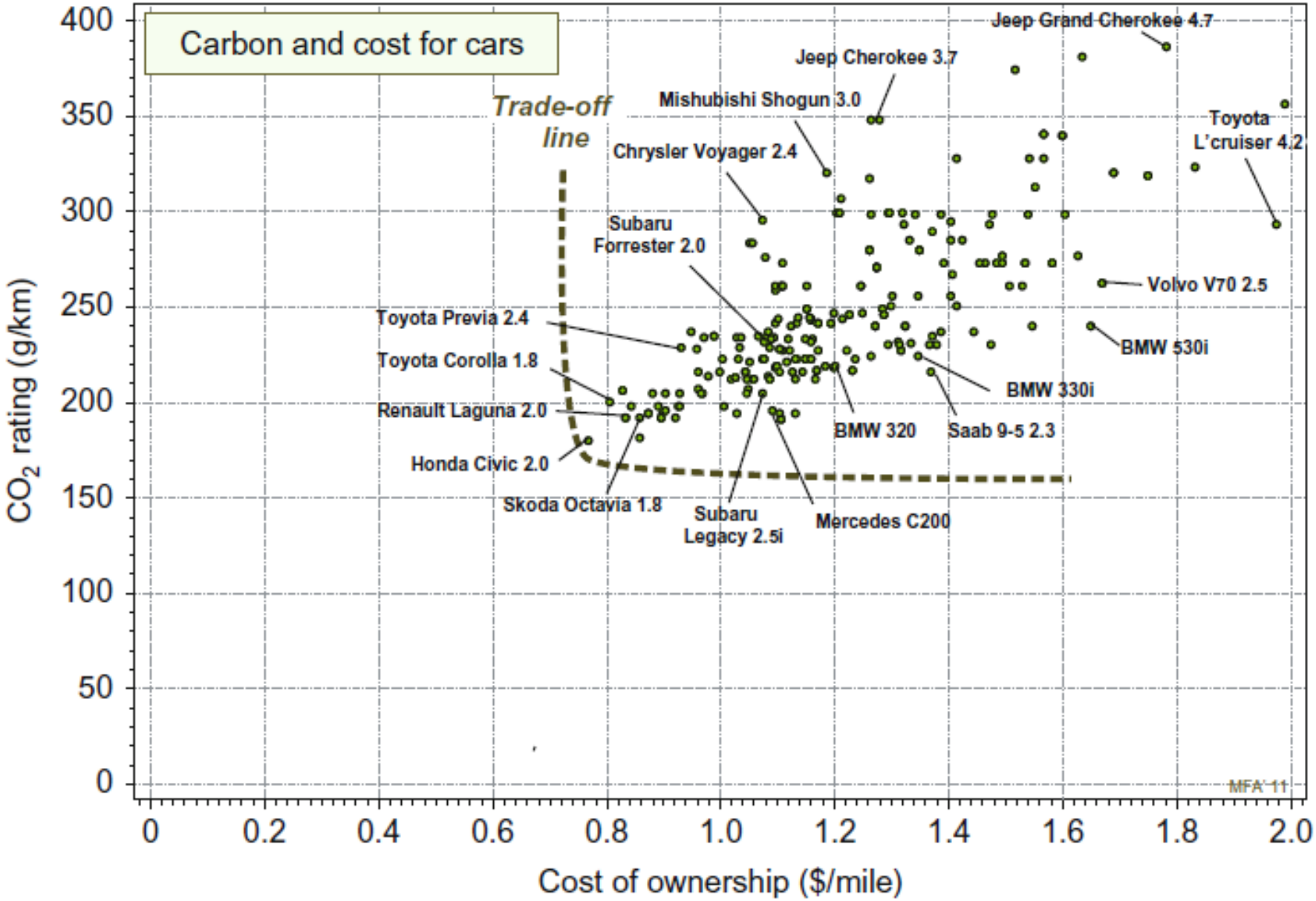
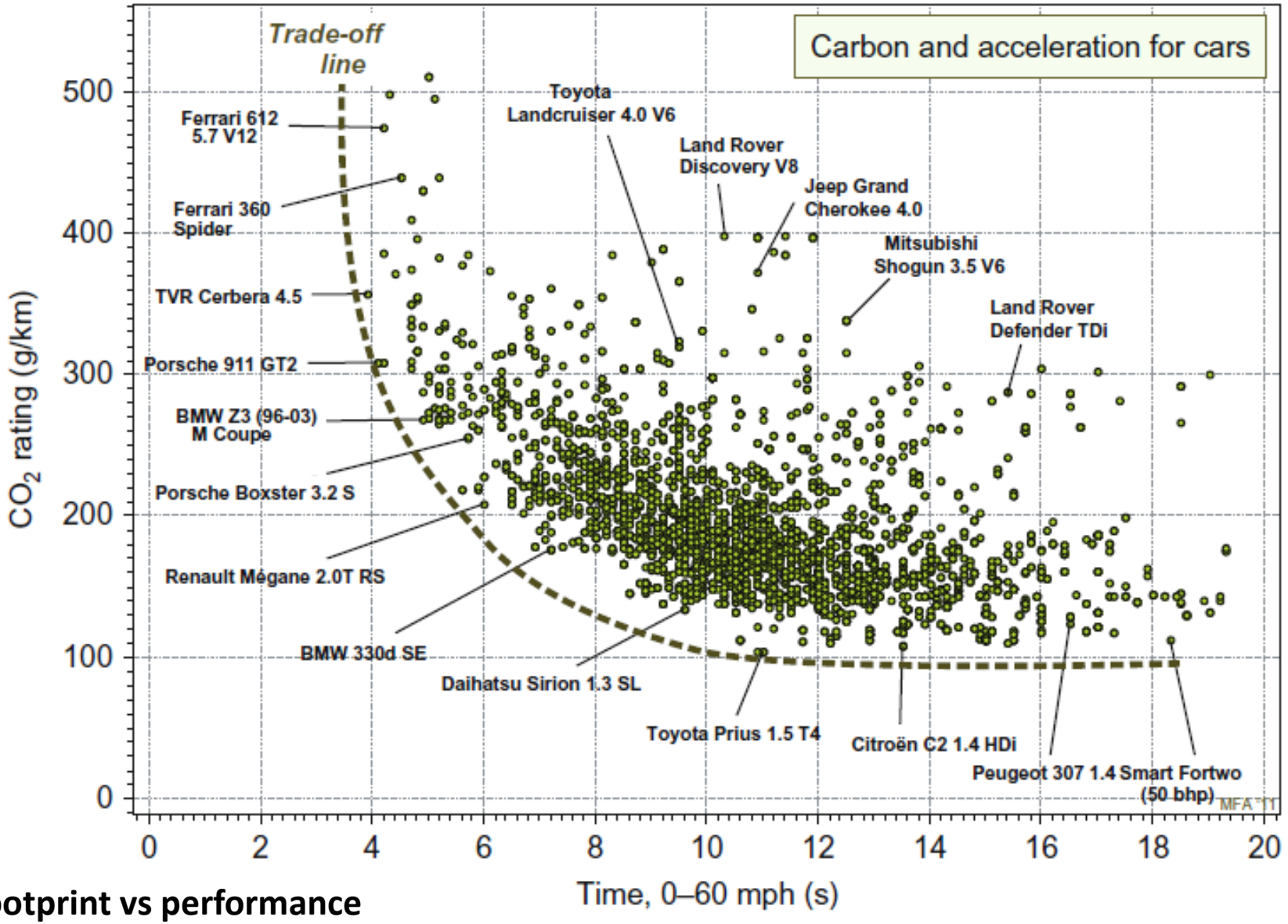
Simple, but important trade-off conditions: Transportation





New graph, after application of constraints [check analogy with CES]:
4 doors, gasoline fuel, >150 hp



C footprint vs performance

Refinements: further trade-off

through which it is passing; and as rolling friction in bearings and the contact between wheels and road. Imagine (following MacKay (2008)) that a vehicle, with mass m accelerates to a cruising velocity v acquiring kinetic energy

$$E_{ke} = \frac{1}{2}mv^2 \tag{10.19}$$

It continues over a distance d for a time d/v before braking, losing this kinetic energy as heat and dissipating energy per unit time (*power*) of

$$\frac{dE_{ke}}{dt} = \frac{E_{ke}}{d/v} = \frac{1}{2}\frac{mv^3}{d} \tag{10.20}$$

While cruising, the vehicle drags behind it a column of air with a cross-section proportional to its frontal area A. The column created in time t has a volume $c_d Avt$ where c_d is the drag coefficient, typically about 0.3 for a car, 0.4 for a bus or truck. This column has a mass $\rho_{air} c_d Avt$ and it moves with velocity v, so the kinetic energy imparted to the air is

$$E_{drag} = \frac{1}{2} m_{air} v^2 = \frac{1}{2} \rho_{air} c_d A v^3 t \qquad (10.21)$$

$$\frac{dE_{drag}}{dt} = \frac{1}{2} \rho_{air} c_d A v^3$$

If this cycle is repeated over and over again, the power dissipated is the sum of these two:

$$Power = \frac{1}{2} \left(\frac{m}{d} + \rho_{air} c_d A \right) v^3 \qquad (10.23)$$



Environmentally sound?

The first term in the brackets is proportional to the mass m of the vehicle and inversely proportional to the distance d it moves between stops. The second depends only on the frontal area A and the drag coefficient c_d. Thus for a short haul, stop-and-go, or city driving, the way to save fuel is to make the vehicle as light as possible. For long haul, steady cruising, or highway driving, mass is less important than minimizing drag, making frontal area A and drag coefficient c_d of central importance.

Saving mass, keeping mechanical functionality

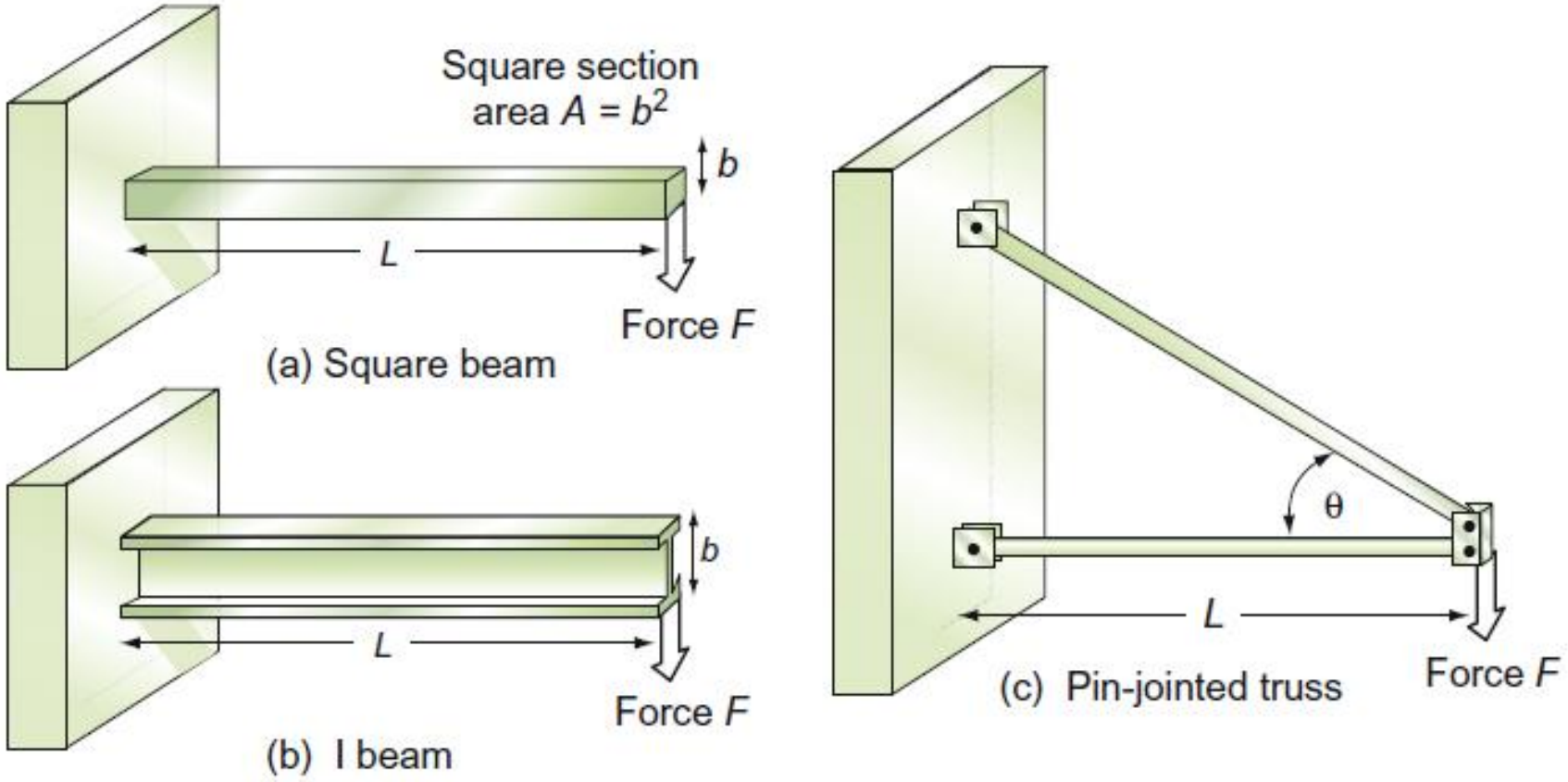


FIGURE 10.17 *A square-section beam, an I-beam, and a truss, all supporting the same load* F *at the same overhang* L

Table 10.13 Properties of materials for light weight structures

Material	ρ (kg/m^3)	σ_y (MPa)	$\frac{\rho}{\sigma_y}$	$\frac{\rho}{\sigma_y^{2/3}}$	Φ^f	$\frac{\rho}{(\Phi^f \sigma_y)^{2/3}}$	$\frac{m_2}{m_1}$
1020 Steel, normalized	7,850	330	23.8	164	13	30	0.18
6061-T4 Al	2,710	113	24	116	10	25	0.22
GFRP SMC 30% glass	1,770	83	21	93	6	28	0.30
Wood (oak), along grain	760	40	19	65	3	31	0.48

Can we do better still? To do so we have to think not only of shape but also of configuration. A beam is a configuration. There are others. One is a pin-jointed truss (Figure 10.17(c)). The truss can support bending loads, but neither of its members is loaded in bending: the upper one is in simple tension, the lower one in simple compression. If both have the same cross-section and are made of the same material, the mass of the truss needed to support a load F without failing is

Truss configuration

$$m_3 = FL\frac{\rho}{\sigma_y}\frac{1}{\sin\theta}\left(1+\frac{1}{\cos\theta}\right) \tag{10.29}$$

There is a new variable: it is the angle θ between the two members of the truss. If the lower one is normal to the loading direction the angle that minimizes the mass is 52°, and for this value, the terms involving θ reduce to the factor 3.3, giving

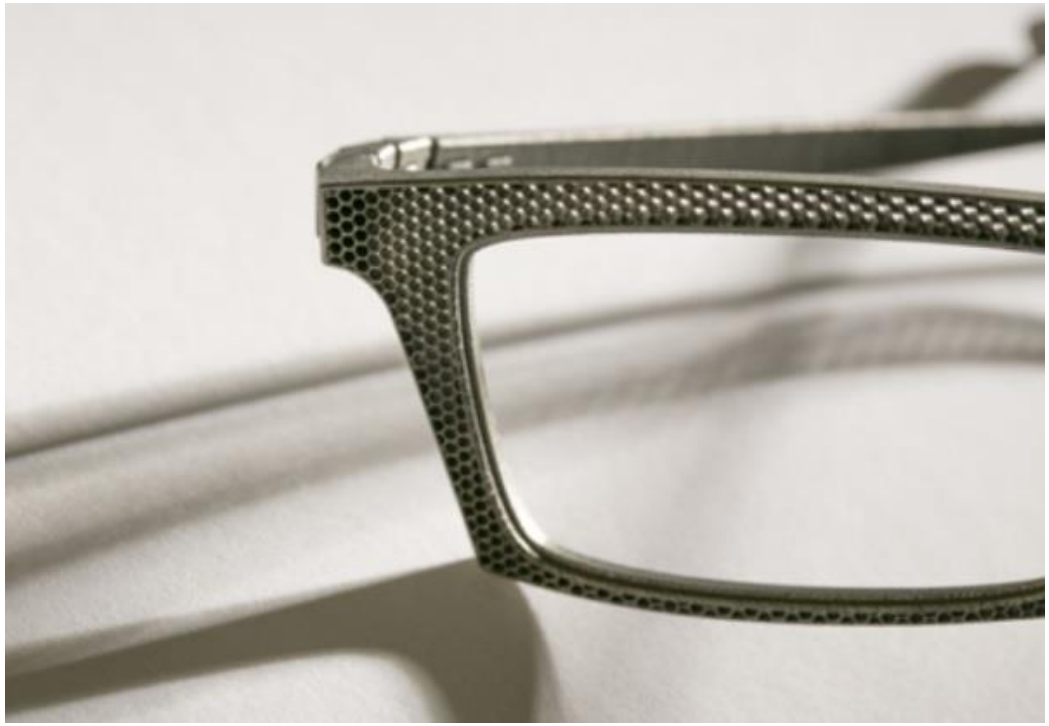
$$m_{3\,2} = 3.3FL\frac{\rho}{\sigma_y} \tag{10.30}$$

The best material for the lightest truss is that with the smallest value of ρ/σ_y, the same as that for simple tension and compression. Not surprising—it is because the truss turns bending loads into axial loads. The truss is lighter than the original square beam by the factor

$$\frac{m_3}{m_1} = 0.55\left(\frac{F}{L^2\sigma_y}\right)^{1/3} \tag{10.31}$$

Answer: The table shows that, for the combination of load and span given, the truss is much lighter than beams of any shape. The titanium alloy truss is the lightest of all.

Material	ρ (kg/m^3)	σ_y (MPa)	Φ^f	m_1 (kg)	m_2 (kg)	m_3 (kg)
1020 Steel, normalized	7,850	330	13	9.8	1.8	0.078
6061-T4 Al	2,710	113	10	6.9	1.5	0.079
GFRP SMC 30% glass	1,770	83	6	5.6	1.7	0.069
Ti-6%Al-4%V, aged	4,430	1050	11	2.6	0.53	0.025



Truss architecture can be applied easily by 3D-printing

http://www.3ders.org/articles/20131103-first-3d-printed-custom-titanium-eyewear.html

Shape factors for panels: wavy surfaces









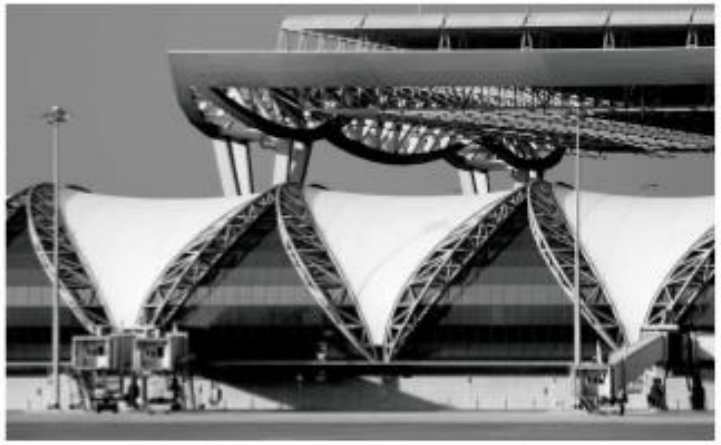


Improvement of PET
Less mass, less energy, less CO_2



Improvement of CFRP
Less mass, less cost (expensive material!), less primary production energy



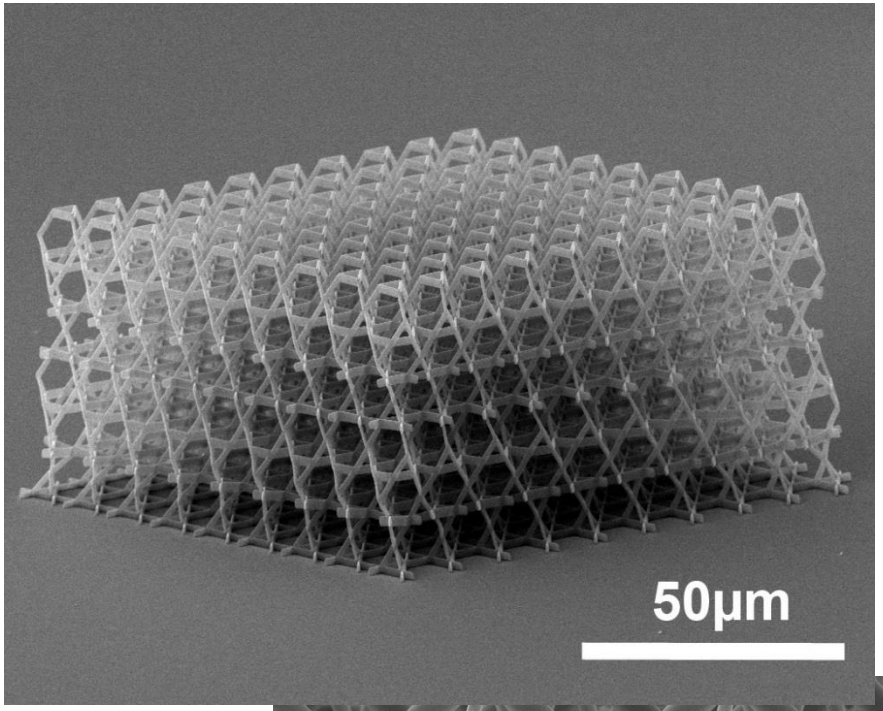






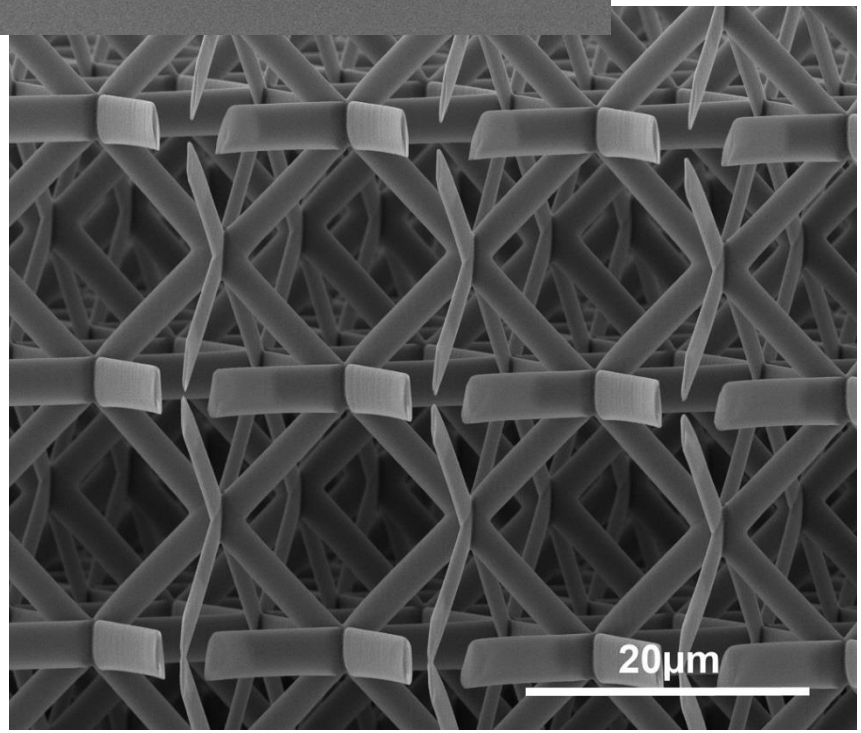


Truss structure: macro-scale….

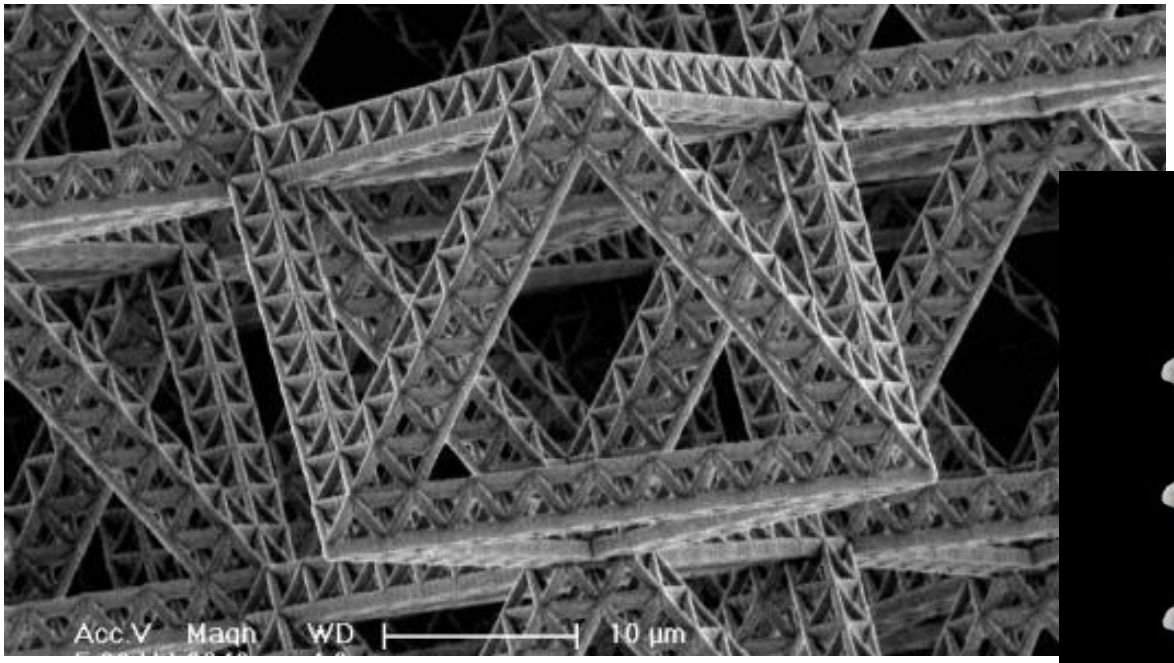


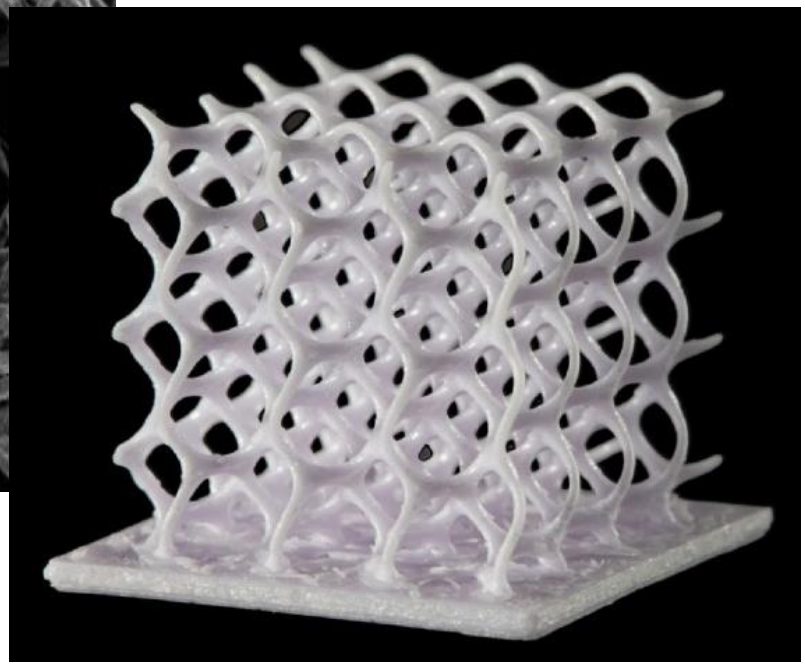
http://www.**jrgreer.caltech**.edu/truss_images.php
Prof. Julia Greer

We explore the **potential of using micro and nanoscale truss materials** for the development of materials for advanced energy applications. Using a technique known as **Two Photon Lithography (TPL) Direct Laser Writing (DLW),** we create arbitrarily complex 3D structures with features on nanometer length scales in a process analogous to rapid prototyping. TPL DLW technology has now matured to a point where there are reliable commercial products that are capable of creating nanostructures with ~100 nm lateral feature sizes. We use these structures as a scaffold to deposit materials onto using techniques like ALD, CVD, and electroless deposition. The polymer can then be etched out, leaving behind a hollow nanoscale truss structure



…and nano-scale





3D printing (Additive manufacturing) as fundamental reference technology

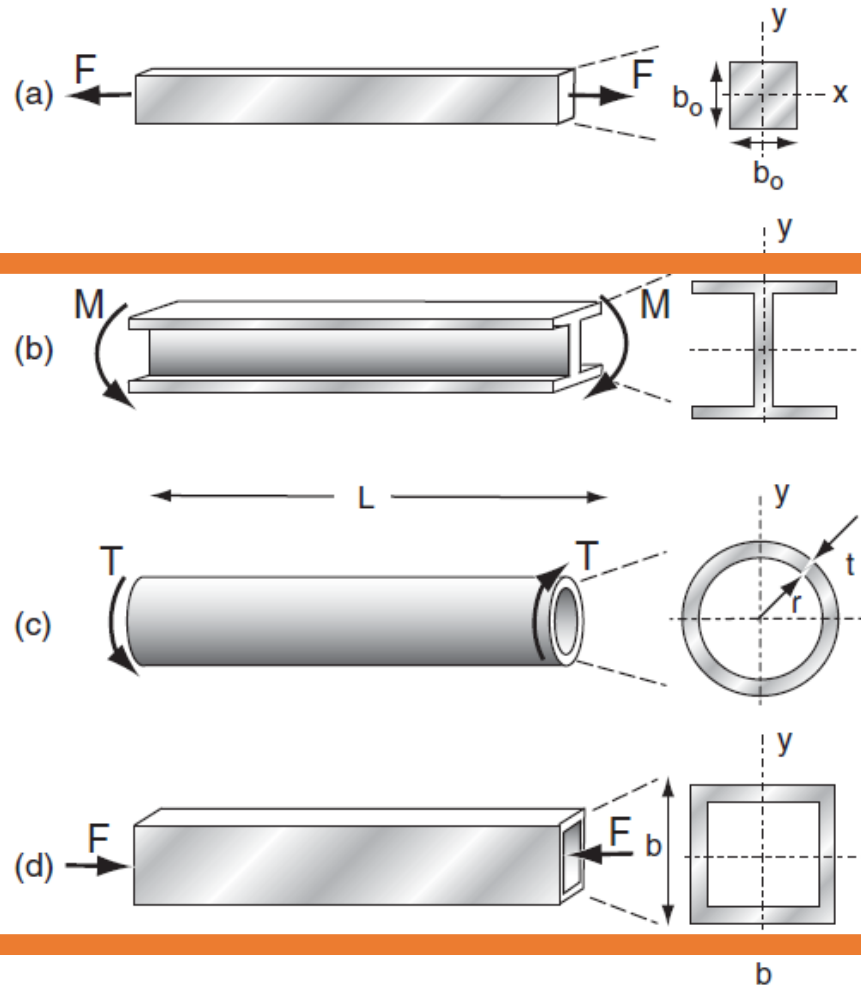
http://www.lithoz.com/



Selection of material & shape

Stiffness and strength indices previously defined valid for **'rough' cross-sections (square, circle)**

In many cases the shape supports the material performance



Bending

Torsion

Buckling

Section maximizing the moments of inertia

Shape factor for stiffness of bars

Key point: J/A correlation

$$J = \frac{b \cdot w^3}{12}$$

For a square cross-section, b=w

Standardized J

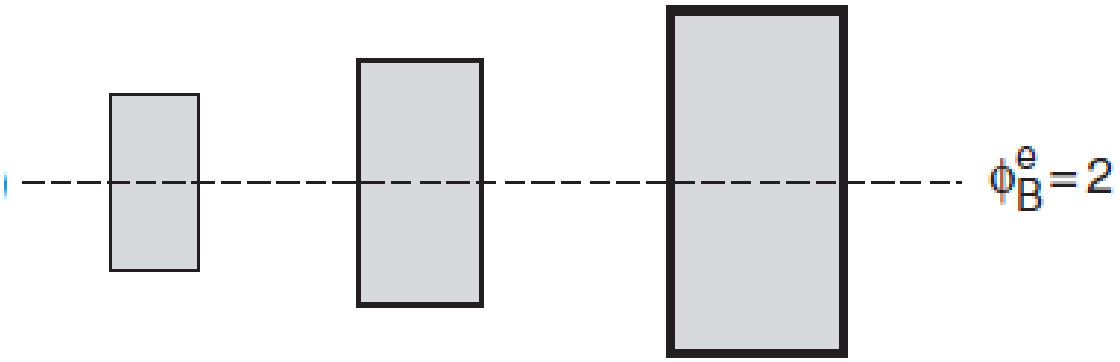
$$J_0 = \frac{b \cdot b^3}{12} = \frac{b^2 \cdot b^2}{12} = \frac{A^2}{12}$$

Definition of shape factor: J of a generic cross-section against square standard

$$\Phi_B^e = \frac{J}{J_0} = \frac{J}{\frac{A^2}{12}} = 12 \cdot \frac{J}{A^2}$$

$$J = \Phi_B^e \cdot \frac{A^2}{12}$$

Measuring J is normally quite difficult
An estimation of J is now immediate, after (easy) measurement of A



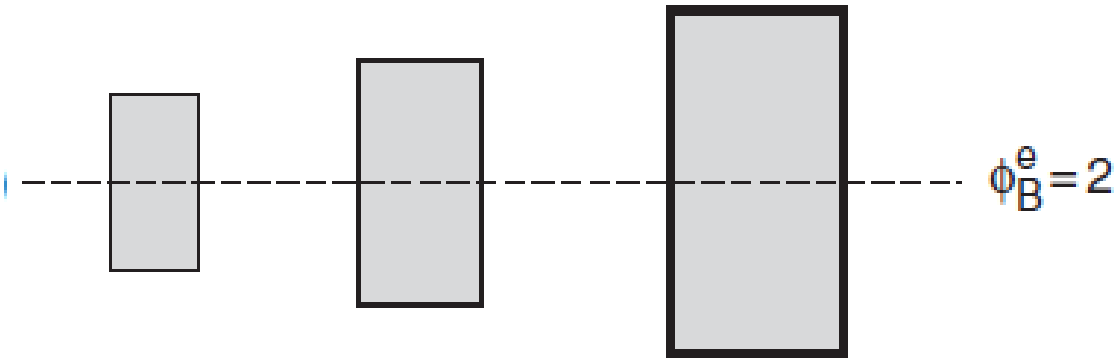
A'=A=b² [square cross-section]

Beam with w'= 2 b' $b' = \frac{b}{\sqrt{2}}$ $w' = b\sqrt{2}$

$$A' = b' \cdot w' = \frac{b}{\sqrt{2}} \cdot b\sqrt{2} = b^2$$

$$J = \frac{b' \cdot (w')^3}{12} = \frac{\frac{b}{\sqrt{2}} \cdot \left(b\sqrt{2}\right)^3}{12} = \frac{2 \cdot A^2}{12}$$

$$\Phi_B^e = \frac{J}{J_0} = \frac{\frac{2 \cdot A^2}{12}}{\frac{A^2}{12}} = 2$$



The shape factor depends on the proportions, NOT on the absolute value of A

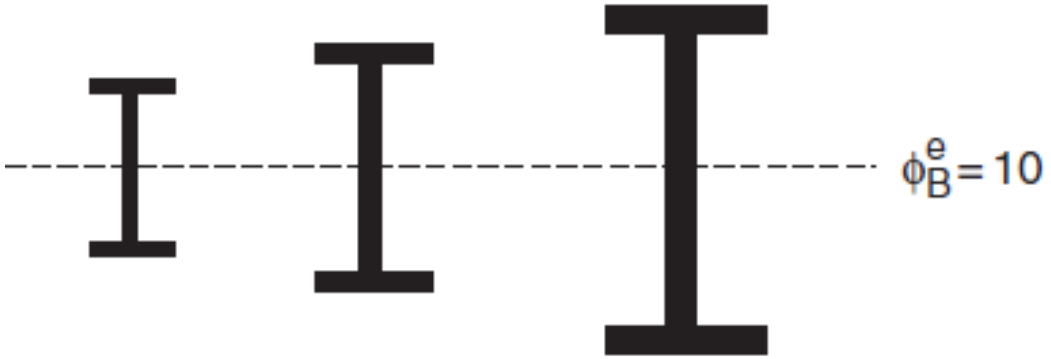
A'=A=b² [square cross-section]

Beam with w'= 2 b' $b' = \frac{b}{\sqrt{2}}$ $w' = b\sqrt{2}$

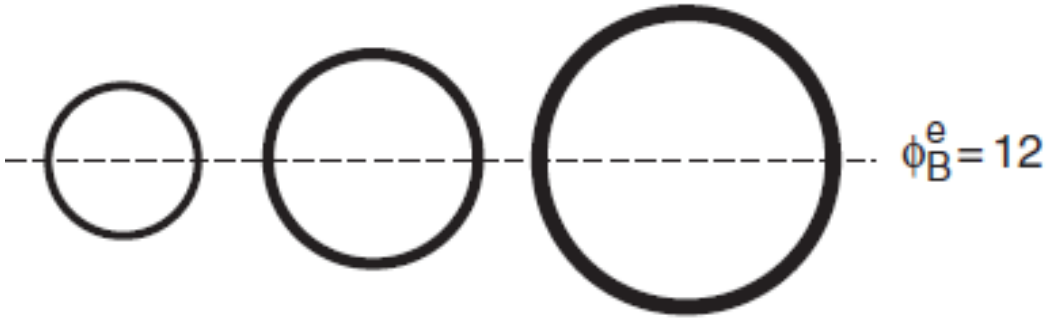
$$A' = b' \cdot w' = \frac{b}{\sqrt{2}} \cdot b\sqrt{2} = b^2$$

$$J = \frac{b' \cdot (w')^3}{12} = \frac{\frac{b}{\sqrt{2}} \cdot \left(b\sqrt{2}\right)^3}{12} = \frac{2 \cdot A^2}{12}$$

$$\Phi_B^e = \frac{J}{J_0} = \frac{\frac{2 \cdot A^2}{12}}{\frac{A^2}{12}} = 2$$

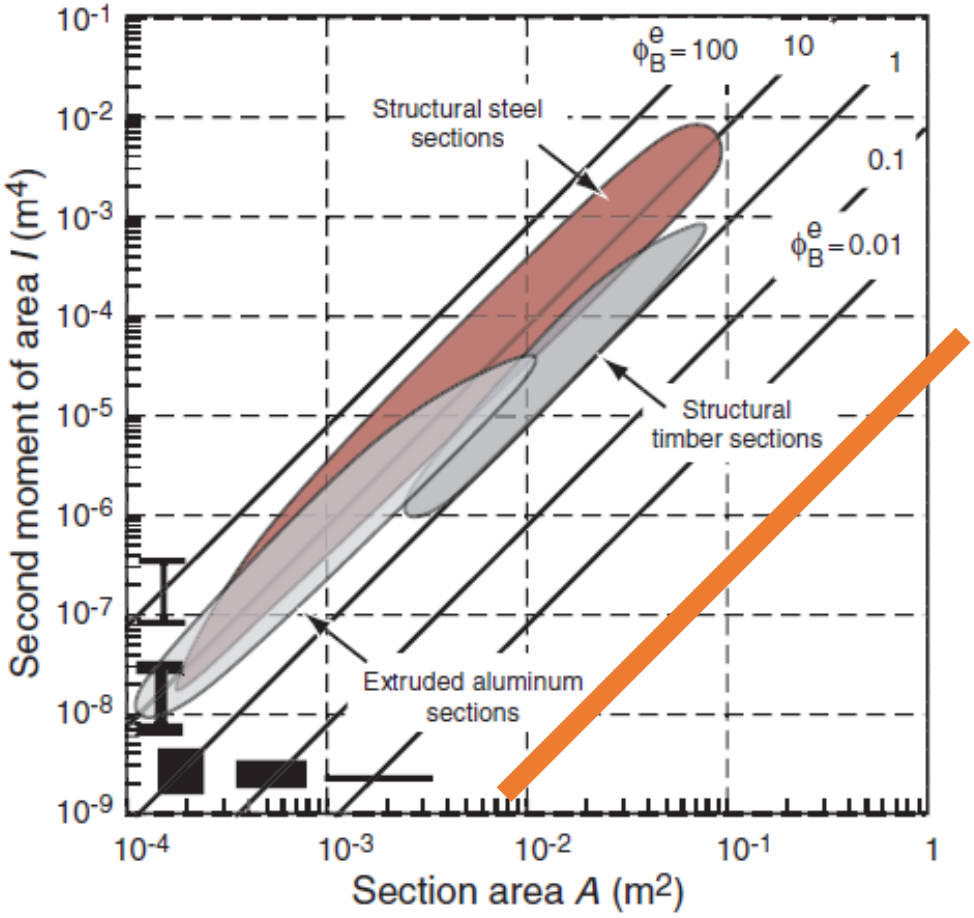








- The shape factor indicates the **distribution of mass**, referred on a given neutral axis (horizontal dashed lines): **anisotropy is possible**
- **The shape factor does depend on neutral axis**: rectangular cross-sections, or «double-T» sections, do not offer improvements (compared to square cross-sections) in ALL cases; **cylindrical tubes offer a homogeneous mechanical response**



Typical shape factors of construction materials

- Shape factors are not “free”, but they are **conditioned** by the nature of the material and by the manufacturing technologies available
- $J=\Phi \cdot A^2/12$ may be transformed…as usual, in

$\text{LogJ}=2\,\text{LogA} + \text{Log}\,\Phi - \text{Log}12$

- **Shape factors have limitations ($\Phi_{max} \approx 60$ for steel, 45 for Al alloys, 40 for fibre-reinforced composites ecc.)**

Manufacturing and theoretical limits

Updating materials performance indices (BARS)

Stiffness problem

How to introduce the shape factor? J/A correlation

$$S = C\frac{E \cdot J}{L^3} \geq S_{min}$$

$$S = C\frac{E \cdot J}{L^3} = C\frac{E \cdot \Phi_B^e \cdot \frac{A^2}{12}}{L^3} = C'\frac{E \cdot \Phi_B^e \cdot A^2}{L^3} \geq S_{min}$$

$$C'\frac{E \cdot \Phi_B^e \cdot A^2}{L^3} \geq S_{min} \rightarrow A \geq \sqrt{\frac{S_{min} \cdot L^3}{C'}} \cdot \frac{1}{(E \cdot \Phi_B^e)^{\frac{1}{2}}}$$

The shape factor supports the modulus in reducing the area

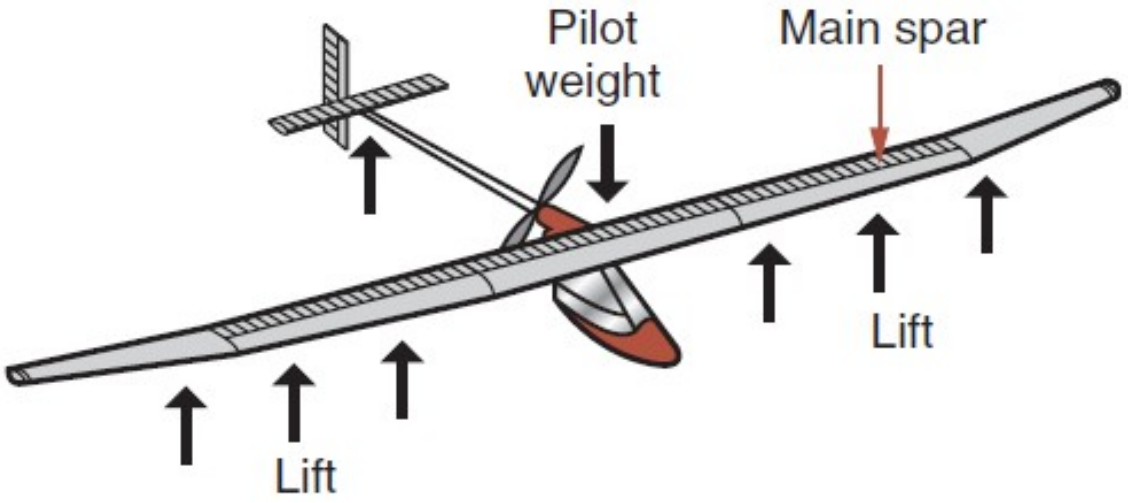
$$m \geq \sqrt{\frac{S_{min} \cdot L^5}{C'}} \cdot \frac{\rho}{(E \cdot \Phi_B^e)^{\frac{1}{2}}}$$

Updated mass index

$$I = \frac{(E \cdot \Phi_B^e)^{\frac{1}{2}}}{\rho}$$

The shape factor supports E in the comparison with ρ, for the mass

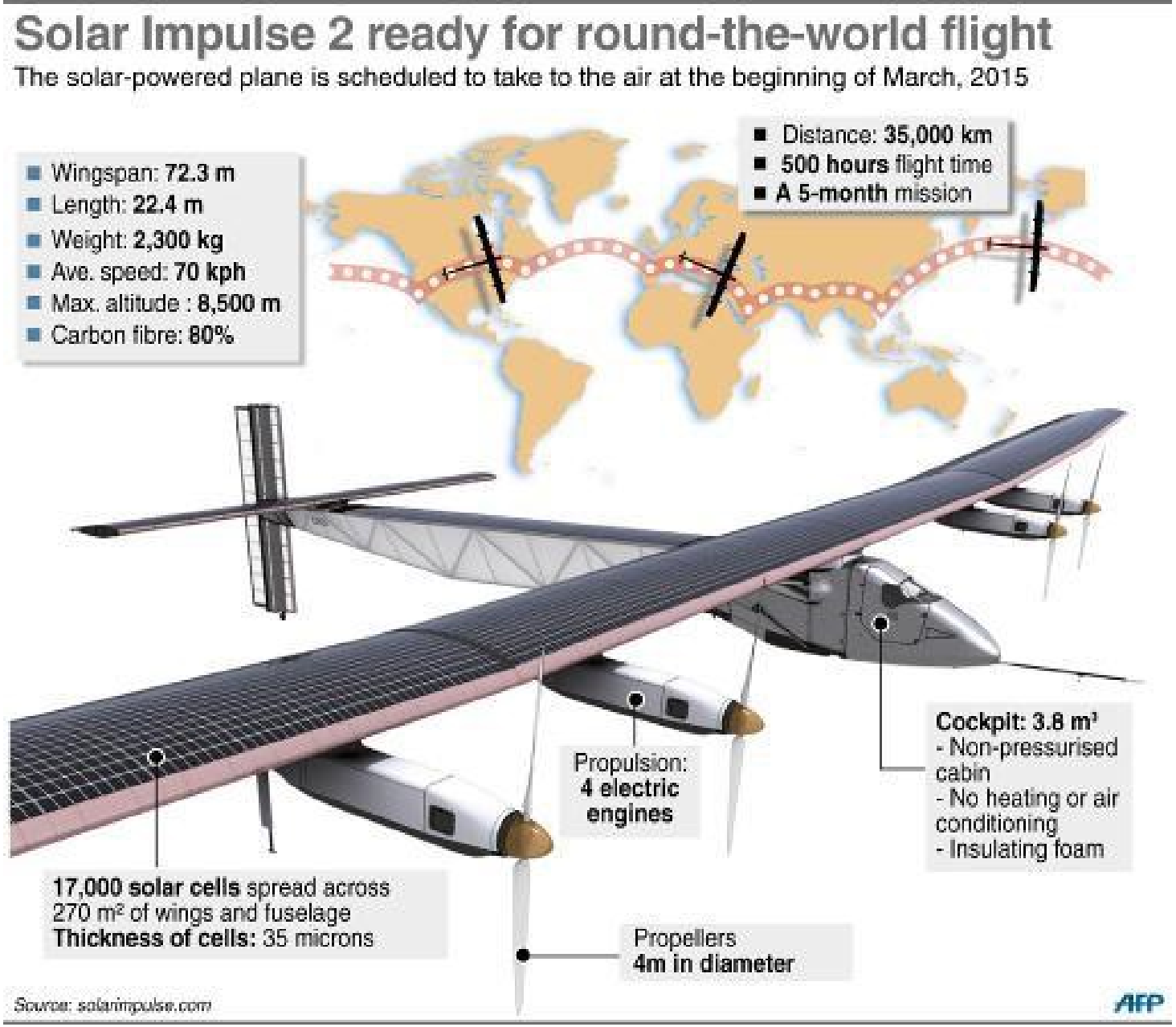
Ultra-light aircrafts



Material	Modulus E (GPa)	Density ρ (Mg/m^3)	Index* $E^{1/2}/\rho$	Shape Factor ϕ_B^e	Index* M_1 $(\phi_B^e E)^{1/2}/\rho$
Balsa	4.2–5.2	0.17–0.24	10	2	15
Spruce	9.8–11.9	0.36–0.44	8	2	12
Steel	200–210	7.82–7.84	1.8	25	9
Al 7075 T6	71–73	2.8–2.82	3	20	14
CFRP	100–160	1.5–1.6	7	10	23

With no shape, wood is dominant (see first aircrafts)

With shape, CFRP is largely dominant



Index* M_1 $(\phi_B^e E)^{1/2}/\rho$
15
12
9
14
23

With no shape, wood is dominant (see first aircrafts)

With shape, CFRP is largely dominant

Updated graphical selection: «virtual» coordinates

$$I_1 = \frac{(E \cdot \Phi_B^e)^{\frac{1}{2}}}{\rho}$$

Index for a SHAPED material

$$E^* = \frac{E}{\Phi_B^e}$$

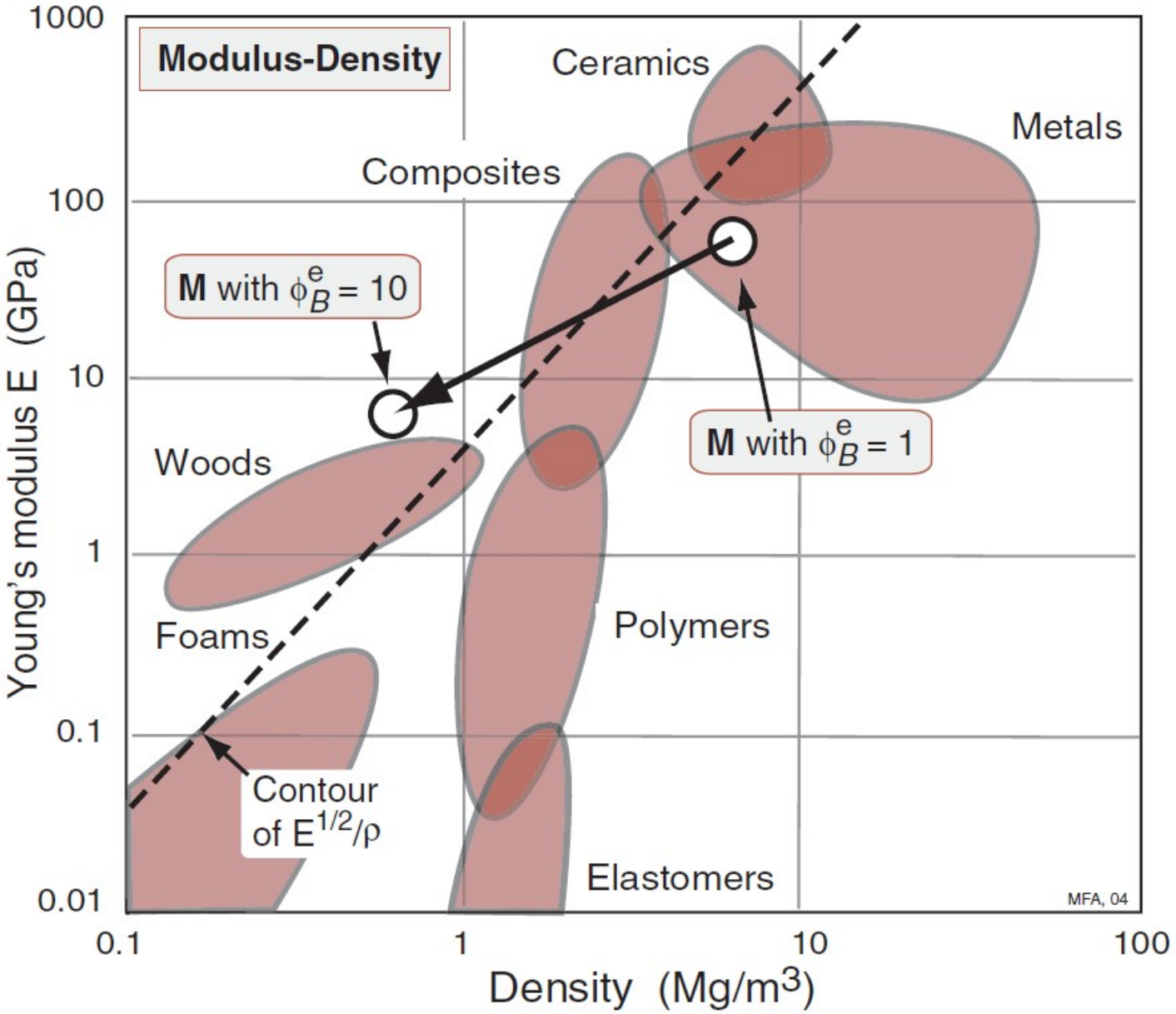
Let's take a second material, un-shaped

$$\rho^* = \frac{\rho}{\Phi_B^e}$$

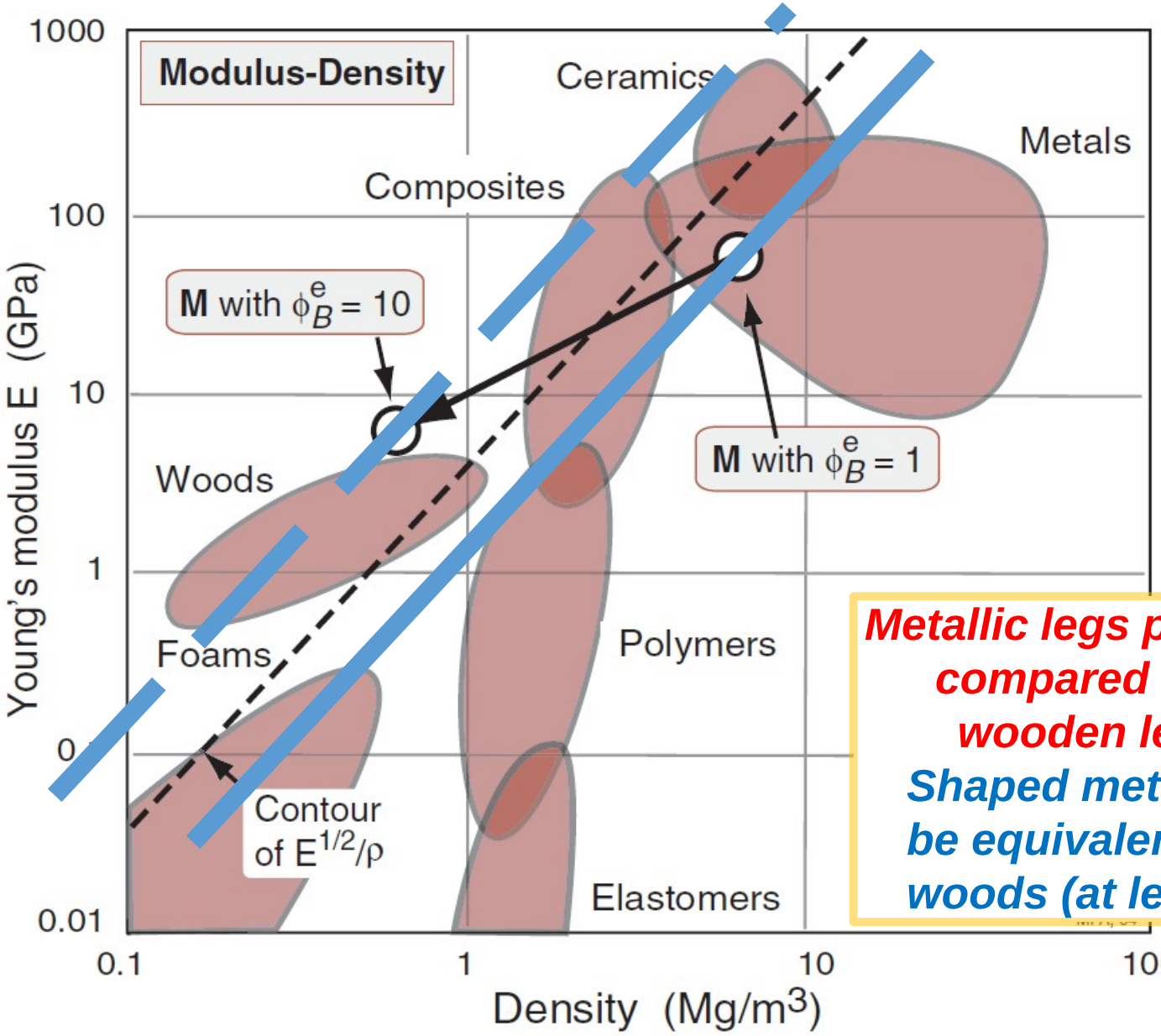
$$I_2 = \frac{\left(\frac{E}{\Phi_B^e}\right)^{\frac{1}{2}}}{\left(\frac{\rho}{\Phi_B^e}\right)} = \frac{E^{\frac{1}{2}}}{\Phi_B^{e\,\frac{1}{2}}} \cdot \frac{\Phi_B^e}{\rho} = E^{\frac{1}{2}} \cdot \frac{\Phi_B^{e\,\frac{1}{2}}}{\rho} = \frac{(E \cdot \Phi_B^e)^{\frac{1}{2}}}{\rho} = I_1$$

- **The second, un-shaped material, is equivalent to the shaped material**
- **A shaped material can still be represented in a material property graph** if the actual coordinates (E, ρ), are **replaced by those of the equivalent un-shaped material [virtual coordinates: E*,ρ*]**

Updated graphical selection: «virtual» coordinates



Updated graphical selection: «virtual» coordinates



Metallic legs properly compared with wooden legs

Shaped metals may be equivalent to woods (at least)

Shape factor for strength problems

Key point: Z/A correlation

$$Z = \frac{J}{y_{max}}$$

Square cross-section

$$Z_0 = \frac{J_0}{y_{max}} = \frac{\frac{1}{12} \cdot A^2}{\frac{1}{2} \cdot A^{\frac{1}{2}}} = \frac{A^{\frac{3}{2}}}{6}$$

$$\Phi_B^f = \frac{Z}{Z_0} = \frac{Z}{\frac{A^{\frac{3}{2}}}{6}} = 6 \cdot \frac{Z}{A^{\frac{3}{2}}}$$

Second shape factor

$$Z = \Phi_B^f \cdot \frac{A^{\frac{3}{2}}}{6}$$

Strength condition

$$\sigma_{max} = \frac{M_f}{J} \cdot y_{max} = \frac{M_f}{Z} \leq \sigma_f$$

$$\frac{M_f}{Z} \leq \sigma_f \quad \rightarrow \quad \frac{M_f}{\Phi_B^f \cdot \frac{A^{\frac{3}{2}}}{6}} \leq \sigma_f$$

Shape factor for strength problems (BARS)

Key point: Z/A correlation

$$A^{\frac{3}{2}} \geq \frac{6 \cdot M_f}{\Phi_B^f \cdot \sigma_f} \rightarrow A \geq \left(6 \cdot M_f\right)^{\frac{2}{3}} \cdot \frac{1}{\left(\Phi_B^f \cdot \sigma_f\right)^{\frac{2}{3}}}$$

The shape supports the elastic limit in reducing the area

The shape factor helps the elastic limit against ρ, in order to reduce m

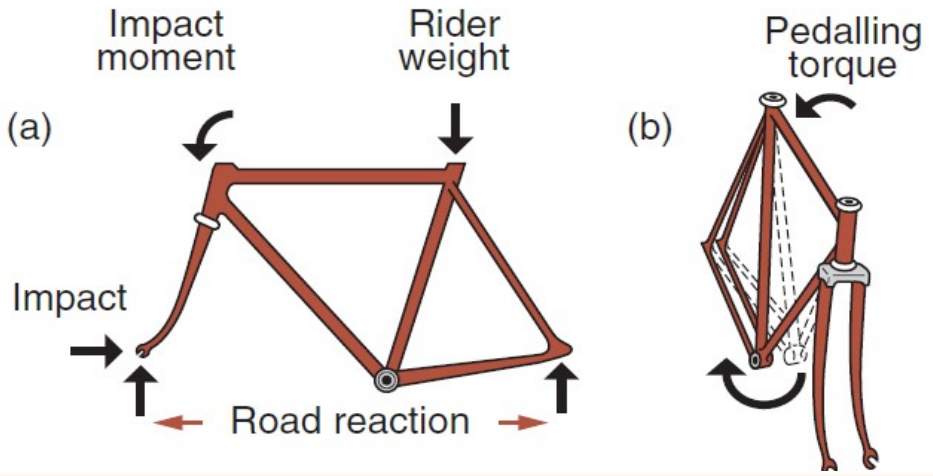
$$m \geq \left(6 \cdot M_f\right)^{\frac{2}{3}} \cdot L \cdot \frac{\rho}{\left(\Phi_B^f \cdot \sigma_f\right)^{\frac{2}{3}}}$$

New index (for the minimization of m)

$$I = \frac{\left(\Phi_B^f \cdot \sigma_f\right)^{\frac{2}{3}}}{\rho}$$

Materials & shape selection for bike forks





Material	Strength, σ_f (MPa)	Density, ρ (Mg/m^3)	Shape factor, ϕ_B^f	Index*, $\sigma_f^{2/3}/\rho$	Index, $M_3^*\left(\phi_B^f \sigma_f\right)^{2/3}/\rho$
Spruce (Norwegian)	70–80	0.46–0.56	1	36	36
Bamboo	80–160	0.6–0.8	2.2	34	59
Steel (Reynolds 531)	770–990	7.82–7.83	7.5	12	48
Alu (6061–T6)	240–260	2.69–2.71	5.9	15	[illegible]
Titanium 6–4	930–980	4.42–4.43	5.9	22	72
Magnesium AZ 61	160–170	1.80–1.81	4.25	17	[illegible]
CFRP	300–450	1.5–1.6	4.25	33	88

Materials & shape selection for bike forks

Attention to industrial sustainability: CFRP confirmed, Ti more difficult to be adopted (welding problems)



Full carbon fork Very common for racinf bikes (CFRP)



Ti fork (quite rare)



Steel fork

Aluminum fork



Attention to AERO sections

The shape factor is maximized in one direction, minimized in the other…

Updated graphical selection: «virtual» coordinates

$$\sigma_f^{\#} = \frac{\sigma_f}{\left(\Phi_B^f\right)^2} \qquad \rho^{\#} = \frac{\rho}{\left(\Phi_B^f\right)^2}$$

New normalization Attention to the exponent

$$I_2 = \frac{\sigma^{f\#\frac{2}{3}}}{\rho^{\#}} = \frac{\left(\frac{\sigma_f}{\left(\Phi_B^f\right)^2}\right)^{\frac{2}{3}}}{\left(\frac{\rho}{\left(\Phi_B^f\right)^2}\right)} = \frac{\sigma_f^{\frac{2}{3}}}{\left(\Phi_B^f\right)^{\frac{4}{3}}} \cdot \frac{\left(\Phi_B^f\right)^2}{\rho}$$

$$= \sigma_f^{\frac{2}{3}} \cdot \frac{\left(\Phi_B^f\right)^{\frac{2}{3}}}{\rho} = \frac{\left(\sigma_f \cdot \Phi_B^f\right)^{\frac{2}{3}}}{\rho}$$

Torsion to be treated in analogy with bending

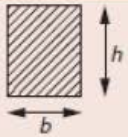
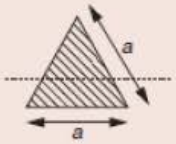
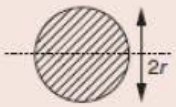
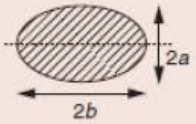
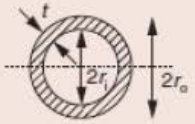
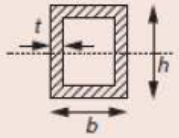
Shape factors for stiffness

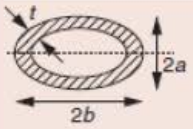
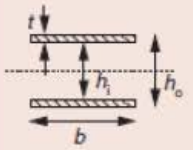
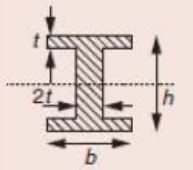
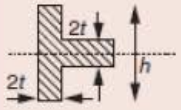
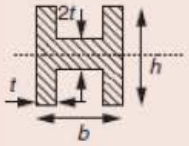
Material	$(\phi_B^e)_{max}$	$(\phi_T^e)_{max}$
Structural steel	65	25
6061 aluminum alloy	44	31
GFRP and CFRP	39	26
Polymers (e.g. nylons)	12	8
Woods (solid sections)	5	1
Elastomers	<6	3

Torsion to be treated in analogy with bending

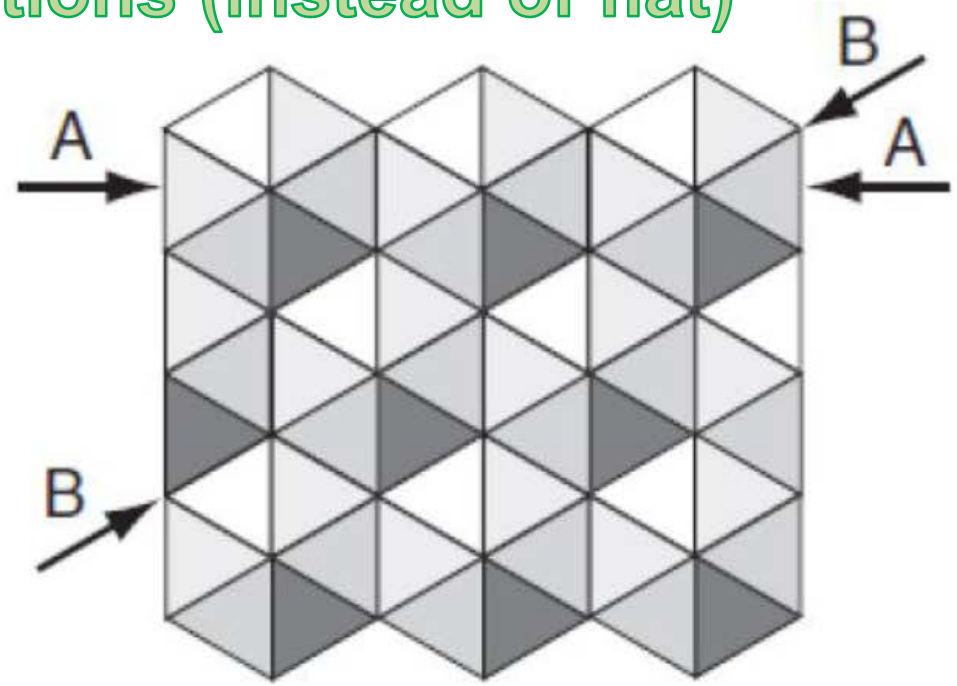
Shape factors for strength

Material	$(\phi_B^f)_{max}$	$(\phi_T^f)_{max}$
Structural steel	13	7
6061 aluminum alloy	10	8
GFRP and CFRP	9	7
Polymers (e.g. nylons)	5	4
Woods (solid sections)	3	1
Elastomers	–	–

Section shape	Bending factor, φ_B^e	Torsional factor, φ_T^e	Bending factor, φ_B^f	Torsional factor, φ_T^f	Bending factor, φ_B^{pl}
	$\frac{h}{b}$	$2.38\frac{h}{b}\left(1-0.58\frac{b}{h}\right)$ $(h>b)$	$\left(\frac{h}{b}\right)^{0.5}$	$1.6\sqrt{\frac{b}{h}}\frac{1}{(1+0.6b/h)}$ $(h>b)$	$\left(\frac{h}{b}\right)^{0.5}$
	$\frac{2}{\sqrt{3}}=1.15$	0.832	$\frac{3^{1/4}}{2}=0.658$	0.83	$\frac{3^{1/4}}{2}=0.658$
	$\frac{3}{\pi}=0.955$	1.14	$\frac{3}{2\sqrt{\pi}}=0.846$	1.35	$\frac{4}{3\sqrt{\pi}}=0.752$
	$\frac{3}{\pi}\frac{a}{b}$	$\frac{2.28ab}{(a^2+b^2)}$	$\frac{3}{2\sqrt{\pi}}\sqrt{\frac{a}{b}}$	$1.35\sqrt{\frac{a}{b}}$ $(a<b)$	$\frac{4}{3\sqrt{\pi}}\sqrt{\frac{a}{b}}=0.752\sqrt{\frac{a}{b}}$
	$\frac{3}{\pi}\left(\frac{r}{t}\right)$ $(r\gg t)$	$1.14\left(\frac{r}{t}\right)$	$\frac{3}{\sqrt{2\pi}}\sqrt{\frac{r}{t}}$	$1.91\sqrt{\frac{r}{t}}$	$\sqrt{\frac{2}{\pi}}\sqrt{\frac{r}{t}}$
	$\frac{1}{2}\frac{h}{t}\frac{(1+3b/h)}{(1+b/h)^2}$ $(h,\ b\gg t)$	$\frac{3.57b^2(1-t/h)^4}{th(1+b/h)^3}$	$\frac{1}{\sqrt{2}}\sqrt{\frac{h}{t}}\frac{(1+3b/h)}{(1+b/h)^{3/2}}$	$3.39\sqrt{\frac{h^2}{bt}}\frac{1}{(1+h/b)^{3/2}}$	$\sqrt{2}\sqrt{\frac{h^2}{bt}}\frac{(1+h/2b)}{(1+h/b)^{3/2}}$

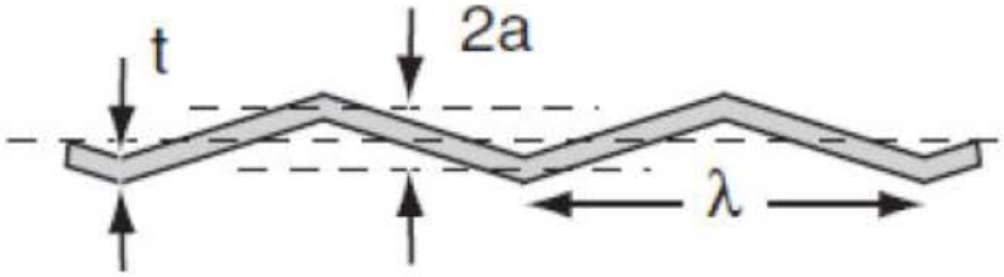
Section shape	Bending factor, φ_B^e	Torsional factor, φ_T^e	Bending factor, φ_B^f	Torsional factor, φ_T^f	Bending factor, φ_B^{pl}
	$\frac{3}{\pi}\frac{a}{t}\frac{(1+3b/a)}{(1+b/a)^2}$ $(a,b \gg t)$	$\frac{9.12(ab)^{5/2}}{t(a^2+b^2)(a+b)^2}$	$\frac{3}{2\sqrt{\pi}}\sqrt{\frac{a}{t}}\frac{(1+3b/a)}{(1+b/a)^{3/2}}$	$5.41\sqrt{\frac{a}{t}}\frac{1}{(1+a/b)^{3/2}}$	$\frac{4}{\sqrt{\pi}}\sqrt{\frac{a^2}{bt}}\frac{(2+a/b)}{(1+a/b)^{3/2}}$
	$\frac{3}{2}\frac{h_o^2}{bt}$ $(h, b \gg t)$	—	$\frac{3}{\sqrt{2}}\frac{h_o}{\sqrt{bt}}$	—	$\sqrt{2}\frac{h_o}{\sqrt{bt}}$
	$\frac{1}{2}\frac{h}{t}\frac{(1+3b/h)}{(1+b/h)^2}$ $(h, b \gg t)$	$1.19\left(\frac{t}{b}\right)\frac{(1+4h/b)}{(1+h/b)^2}$	$\frac{1}{\sqrt{2}}\sqrt{\frac{h}{t}}\frac{(1+3b/h)}{(1+b/h)^{3/2}}$	$1.13\sqrt{\frac{t}{b}}\frac{(1+4h/b)}{(1+h/b)^{3/2}}$	$\sqrt{2}\sqrt{\frac{h^2}{bt}}\frac{(1+h/2b)}{(1+h/b)^{3/2}}$
	$\frac{1}{2}\frac{h}{t}\frac{(1+4bt^2/h^3)}{(1+b/h)^2}$ $(h, b \gg t)$	$0.595\left(\frac{t}{h}\right)\frac{(1+8b/h)}{(1+b/h)^2}$	$\frac{3}{4}\sqrt{\frac{h}{t}}\frac{(1+4bt^2/h^3)}{(1+b/h)^{3/2}}$	$0.565\sqrt{\frac{t}{h}}\frac{(1+8b/h)}{(1+b/h)^{3/2}}$	$\frac{1}{\sqrt{2}}\sqrt{\frac{h}{t}}\left(\frac{h}{(h+b)}\right)^{3/2}\left[1+\frac{2t(b-2t)}{h^2}\right]$
	$\frac{1}{2}\frac{h}{t}\frac{(1+4bt^2/h^3)}{(1+b/h)^2}$ $(h, b \gg t)$	$1.19\left(\frac{t}{h}\right)\frac{(1+4b/h)}{(1+b/h)^2}$	$\frac{3}{4}\sqrt{\frac{h}{t}}\frac{(1+4bt^2/h^3)}{(1+b/h)^{3/2}}$	$1.13\sqrt{\frac{t}{h}}\frac{(1+4b/h)}{(1+b/h)^{3/2}}$	$\frac{1}{\sqrt{2}}\sqrt{\frac{h}{t}}\left(\frac{h}{(h+b)}\right)^{3/2}\left[1+\frac{2t(b-2t)}{h^2}\right]$

Shape factors for panels
The great impact of 'wavy' cross-sections (instead of flat)



$$J_b = \frac{(2a+t)^2 \cdot t}{12}$$

$$J_{bo} = \frac{t^3}{12}$$



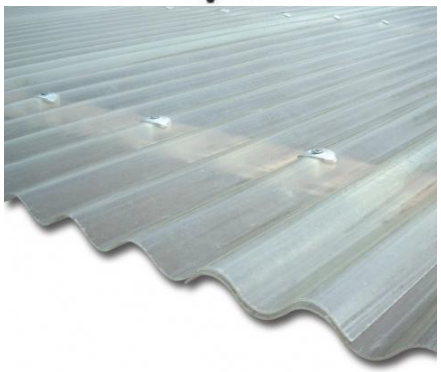
$$\Phi_B^e = \frac{J_b}{J_{bo}} = \frac{(2a+t)^2}{t^2}$$

$$\Phi_B^f = \frac{Z_b}{Z_{bo}} = \frac{(2a+t)}{t}$$

Applications (so many…)

















Focus on bike components





Circa 2015



Modern racing bike crankset

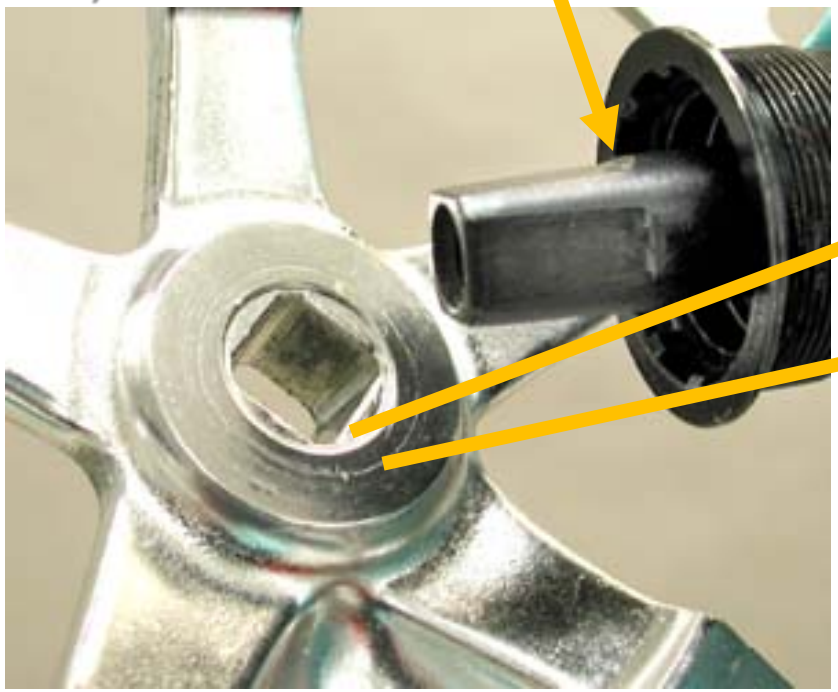
Wavy external chainring

Hollow cranks

Hollow ‘spindle’ instead of traditional square spindle



Traditional square spindle (cylindrical spindle with prismatic ends)



Flat chainring





Traditional square spindle (cylindrical spindle with prismatic ends)

Hollow spindle (TORSION)

Hollow cranks (BENDING)





Modern cranksets are lighter…and much more efficient in terms of stiffness

Advanced shapes by control of manufacturing techniques

Excellent results even with «old» Al alloy instead of CFRP

Wavy chainring







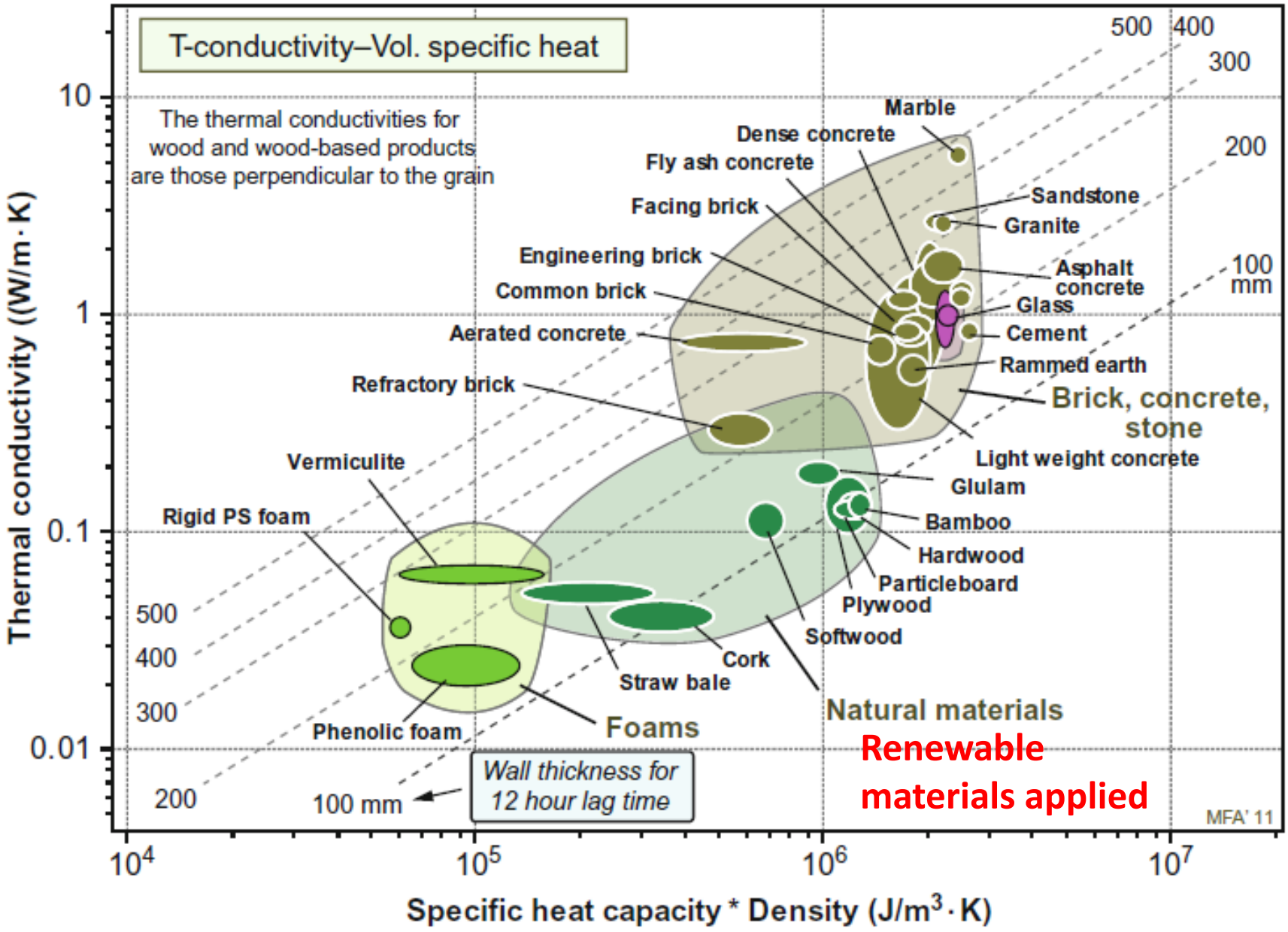
More...with less
Less material, more sustainability

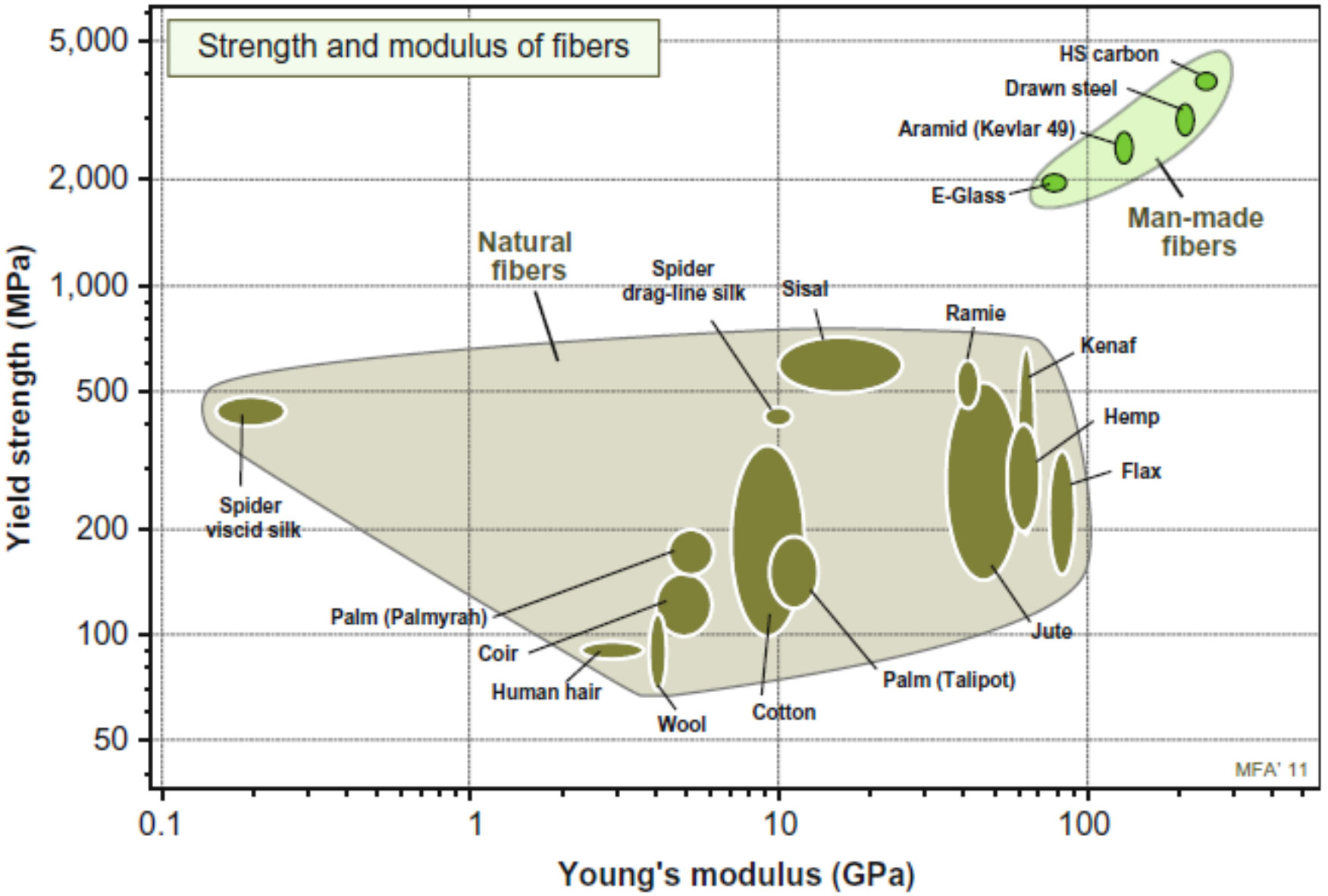
Lightness by smart construction with **AI** instead of applying **CFRP**: easier **recycling** (enhanced end-of-life)

Renewable materials

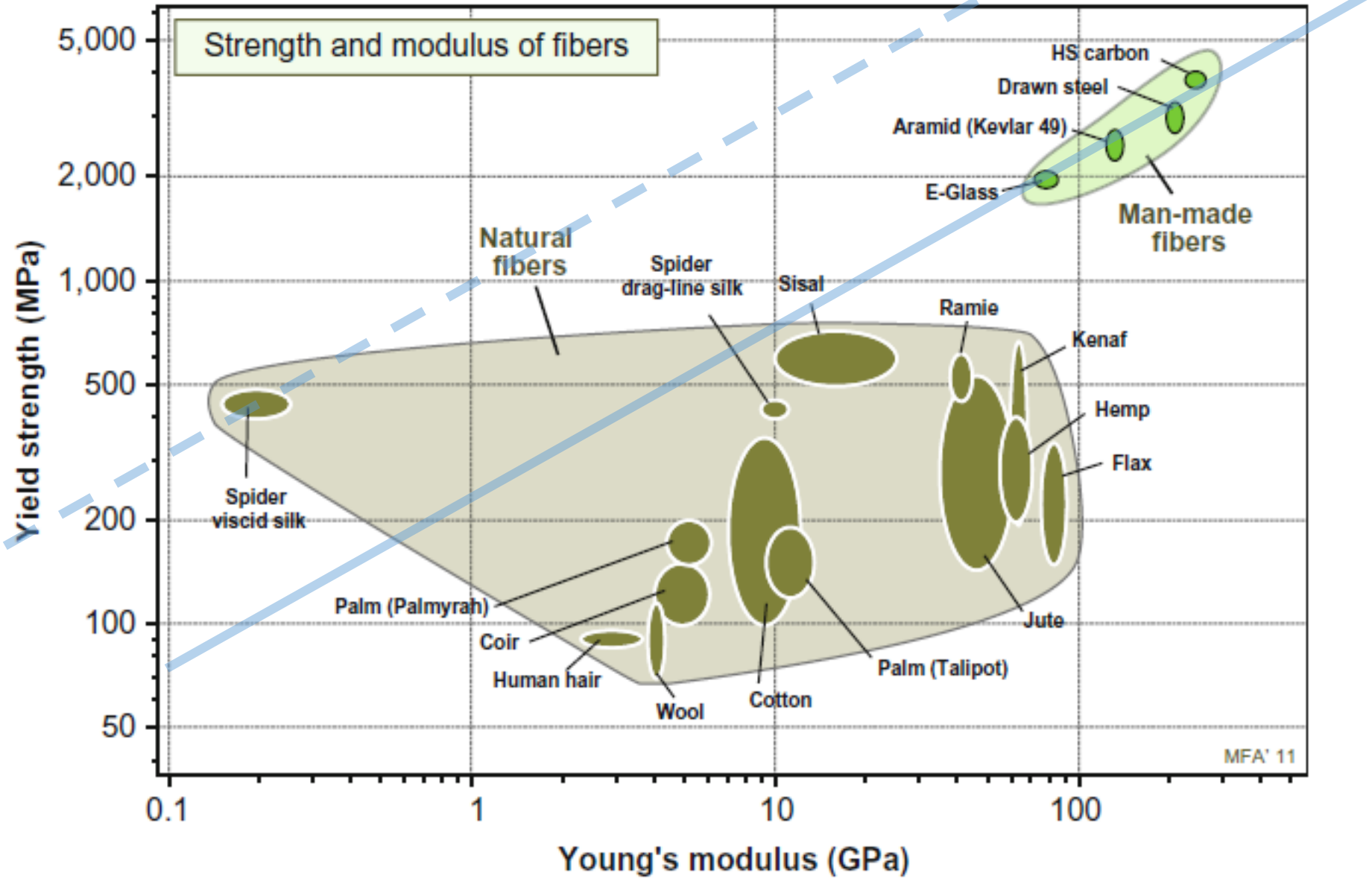
- be drawn from a resource so vast that its use by man has no effect on supply (like sea water);
- be re-created in perfect form after use (like ice in the arctic); or
- regrow as fast as it is used (the biosphere, if properly managed).

and...**engineered by nature** (=evolution)

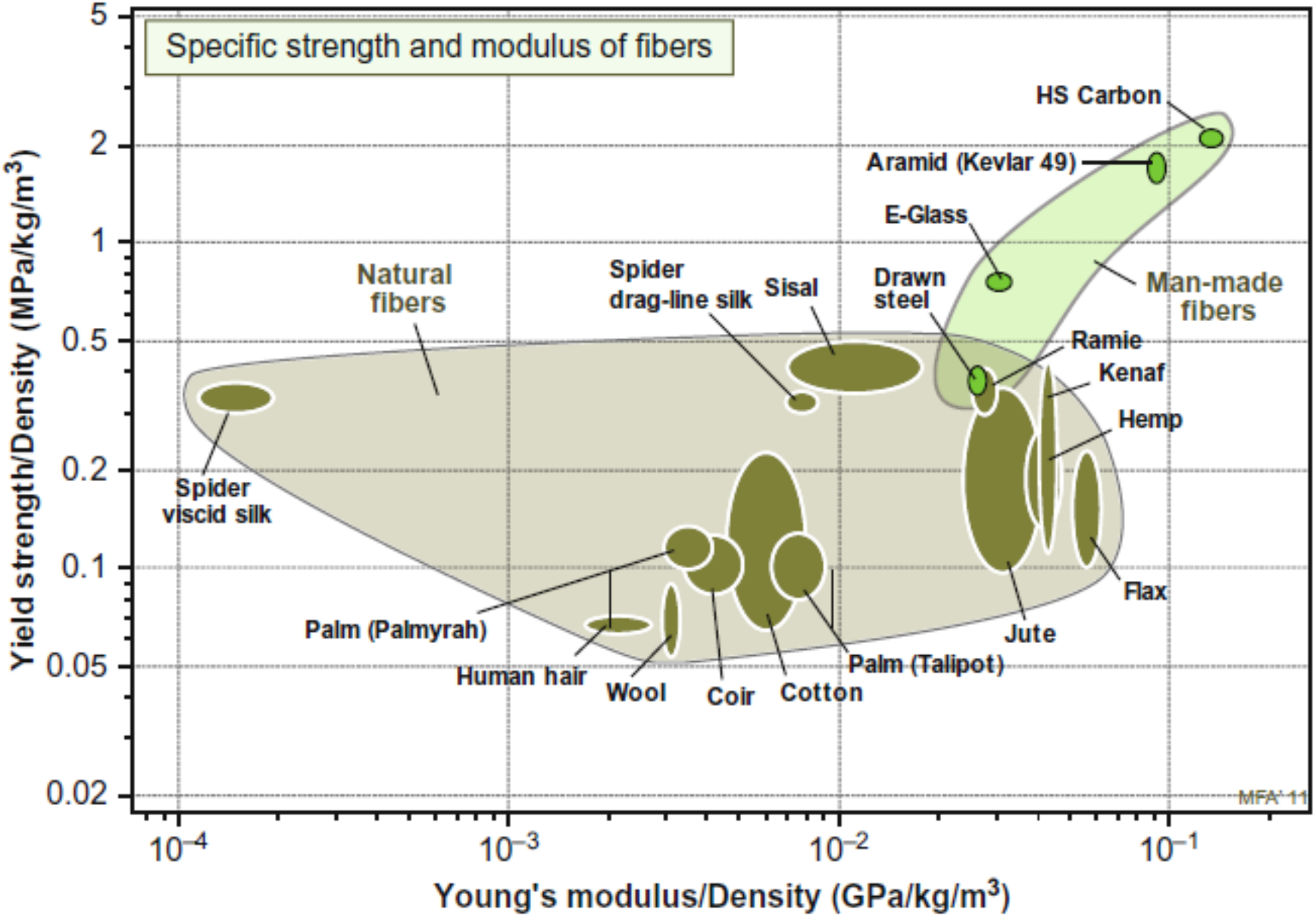

T-conductivity–Vol. specific heat
The thermal conductivities for wood and wood-based products are those perpendicular to the grain
Thermal conductivity ((W/m·K)
Specific heat capacity * Density (J/m³·K)
10
1
0.1
0.01
10⁴
10⁵
10⁶
10⁷
500
400
300
200
100 mm
Marble
Dense concrete
Fly ash concrete
Facing brick
Engineering brick
Common brick
Aerated concrete
Refractory brick
Sandstone
Granite
Asphalt concrete
Glass
Cement
Rammed earth
Brick, concrete, stone
Light weight concrete
Glulam
Bamboo
Hardwood
Particleboard
Plywood
Softwood
Cork
Straw bale
Natural materials
Vermiculite
Rigid PS foam
Phenolic foam
Foams
Wall thickness for 12 hour lag time
Renewable materials applied
MFA' 11


Strength and modulus of fibers
Yield strength (MPa)
5,000
2,000
1,000
500
200
100
50
0.1
1
10
100
Young's modulus (GPa)
HS carbon
Drawn steel
Aramid (Kevlar 49)
E-Glass
Man-made fibers
Natural fibers
Spider drag-line silk
Sisal
Ramie
Kenaf
Hemp
Flax
Jute
Palm (Talipot)
Cotton
Wool
Human hair
Coir
Palm (Palmyrah)
Spider viscid silk
MFA' 11

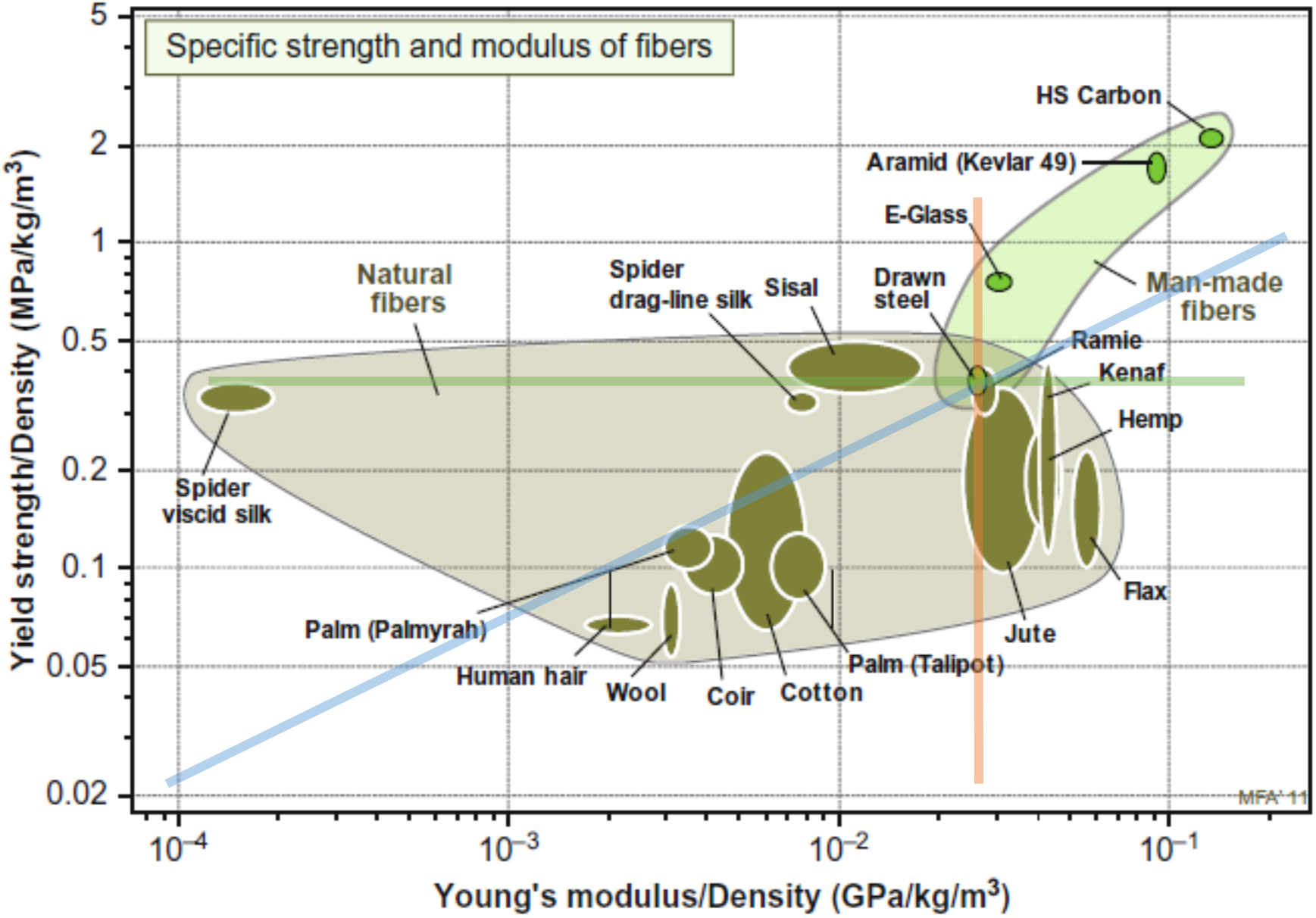
Elastic energy per volume



Index of elasticity: most natural fibres less performing than artificial ones

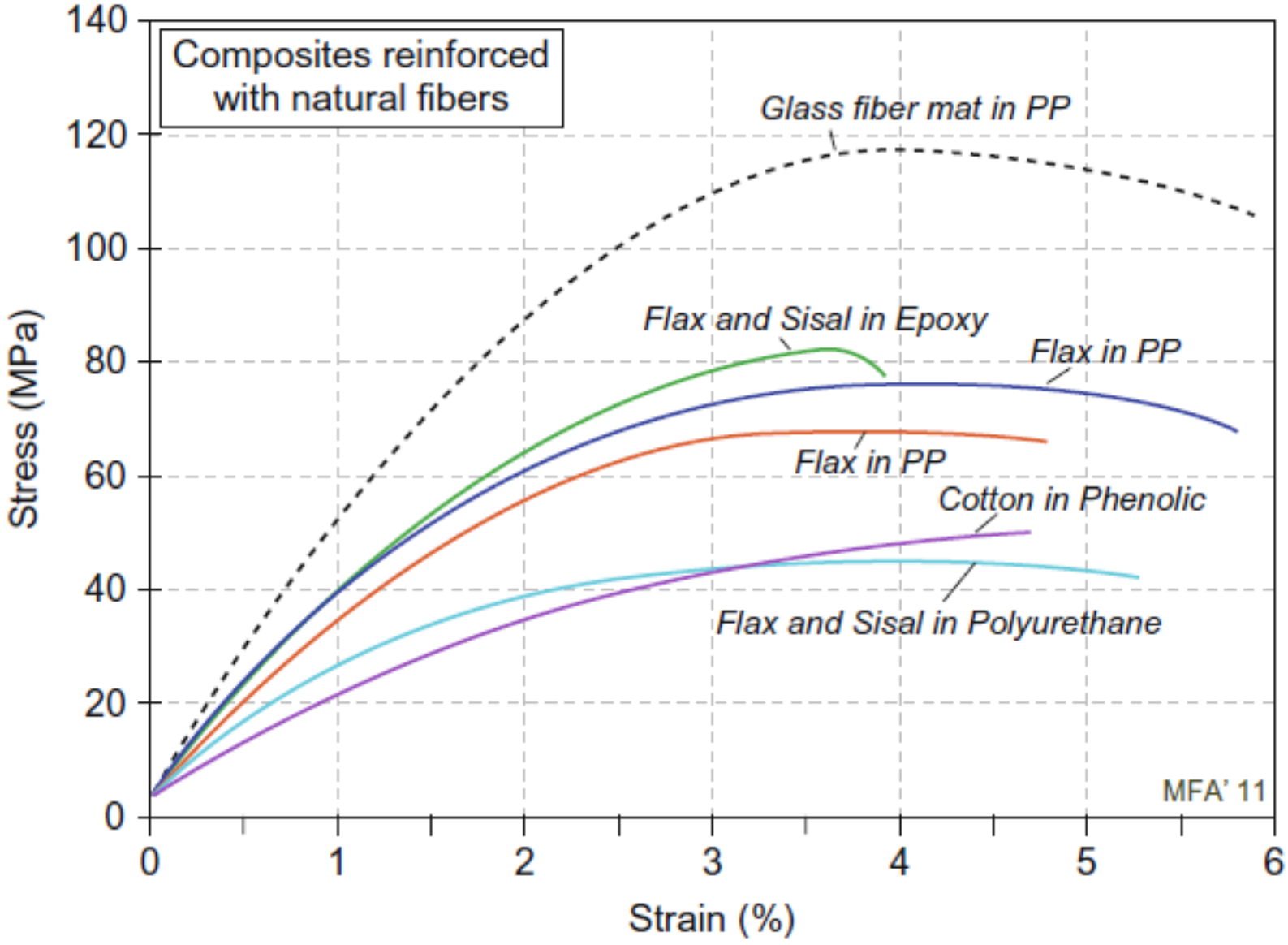

Specific strength and modulus of fibers
HS Carbon
Aramid (Kevlar 49)
E-Glass
Drawn steel
Man-made fibers
Natural fibers
Spider drag-line silk
Sisal
Ramie
Kenaf
Hemp
Spider viscid silk
Flax
Jute
Palm (Palmyrah)
Palm (Talipot)
Human hair
Wool
Coir
Cotton
MFA' 11
Yield strength/Density (MPa/kg/m³)
Young's modulus/Density (GPa/kg/m³)
5
2
1
0.5
0.2
0.1
0.05
0.02
10⁻⁴
10⁻³
10⁻²
10⁻¹

Elastic energy per mass: natural fibres become more attractive





http://www.naturalfibersforautomotive.com/?cat=3



A win-win situation: natural fibres for reinforcing recycled polymers