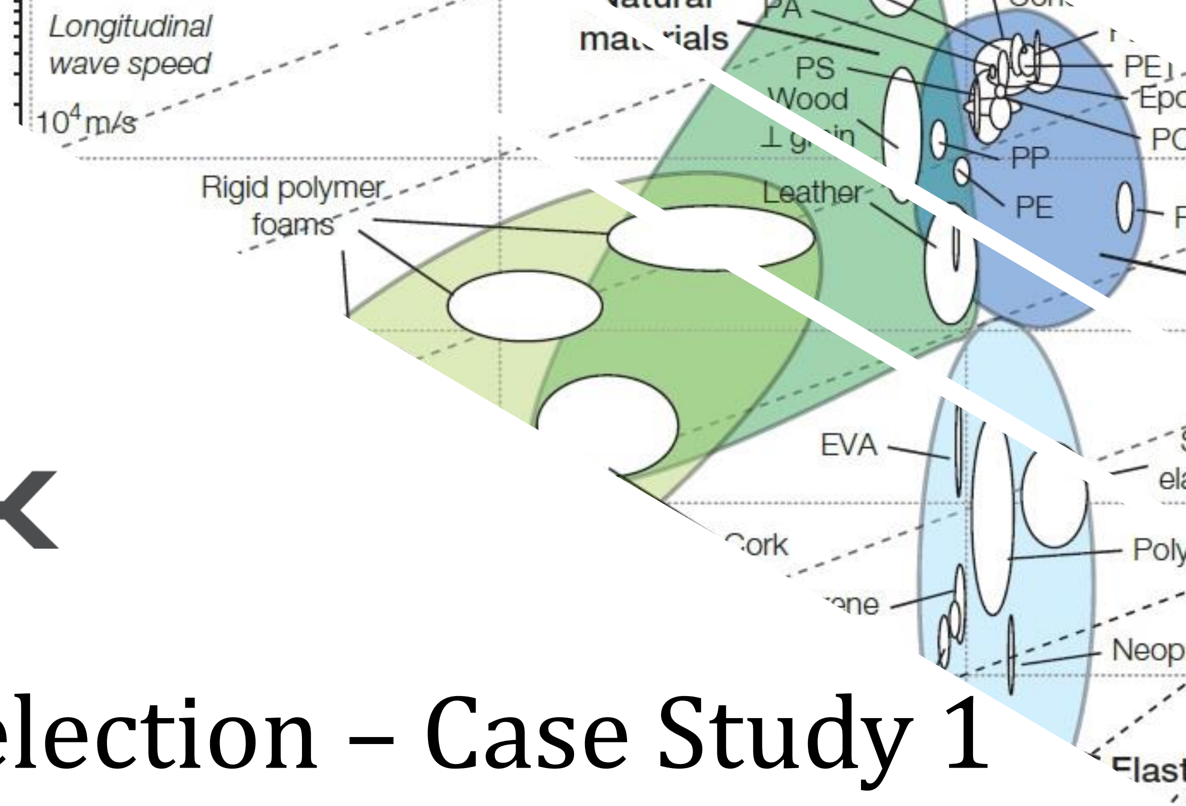


Materials Selection – Case Study 1
Bases and Mechanical Properties

Professors:
Anne Mertens and Davide Ruffoni
Assistant:
Tommaso Maurizi Enrici

Mechanical Properties Case Studies

- *Case Study 1: The Lightest STIFF <u>Beam</u>*
- *Case Study 2: The Lightest STIFF <u>Tie-Rod</u>*
- *Case Study 3: The Lightest STIFF <u>Panel</u>*
- *Case Study 4: Materials for Oars*
- *Case Study 5: Materials for CHEAP and Slender Oars*
- *Case Study 6: The Lightest STRONG <u>Tie-Rod</u>*
- *Case Study 7: The Lightest STRONG <u>Beam</u>*
- *Case Study 8: The Lightest STRONG <u>Panel</u>*
- *Case Study 9: Materials for Constructions*
- *Case Study 10: Materials for Small Springs*
- *Case Study 11: Materials for Light Springs*
- *Case Study 12: Materials for Car Body*

CES 2009 (Case Studies 1–8)

CES 2016 (Case Studies 9–12)

Materials selection

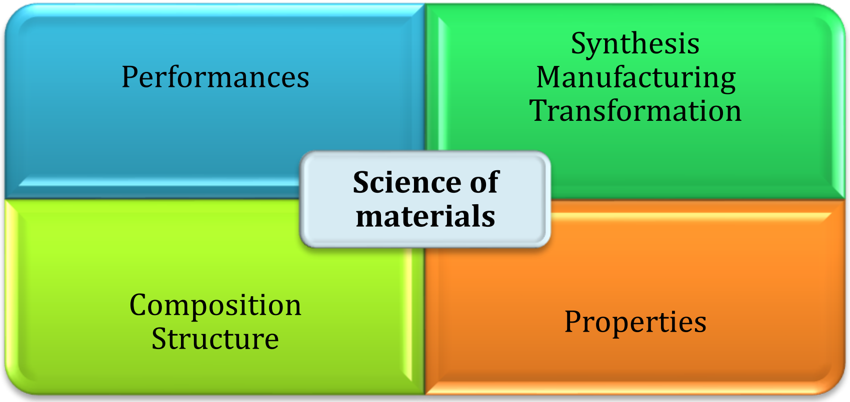
- **Mechanical properties**: tensile test, fatigue, hardness, toughness, creep…
- **Physical properties**: density, conductivity, coefficient of thermal expansion
- **Chemical properties** : corrosion
- **Microscopic characteristics**: anisotropy of properties, hardening, microstructure, grain size, segregation, inclusions…

Materials selection

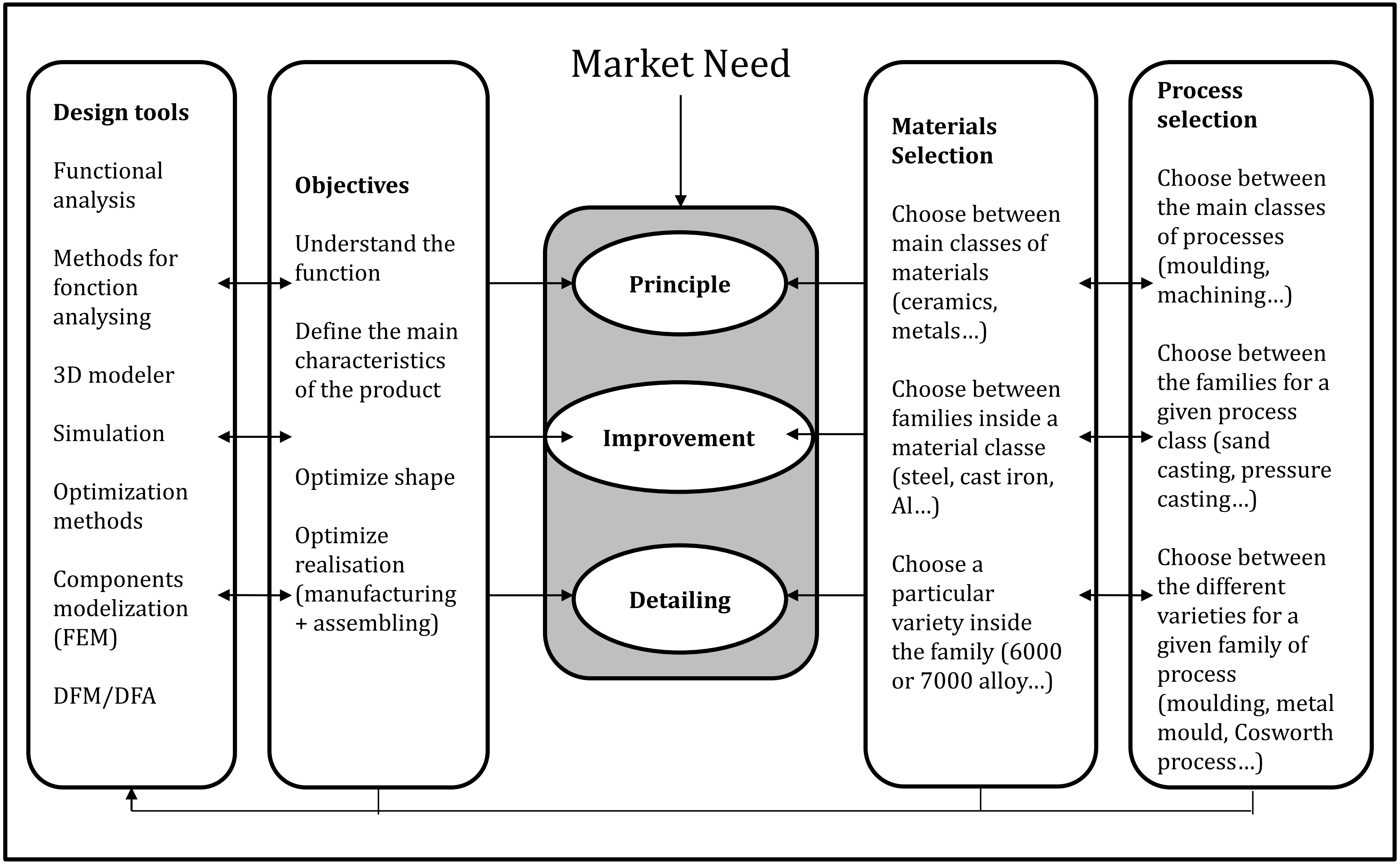
- **Process linked aspects**: formability, machinability, weldability, stampability
- **Aestethic aspects**: colour and surface roughness

Notice: surface properties ≠ volume properties

4 poles for engineering and material science →



Design steps



Forecasts

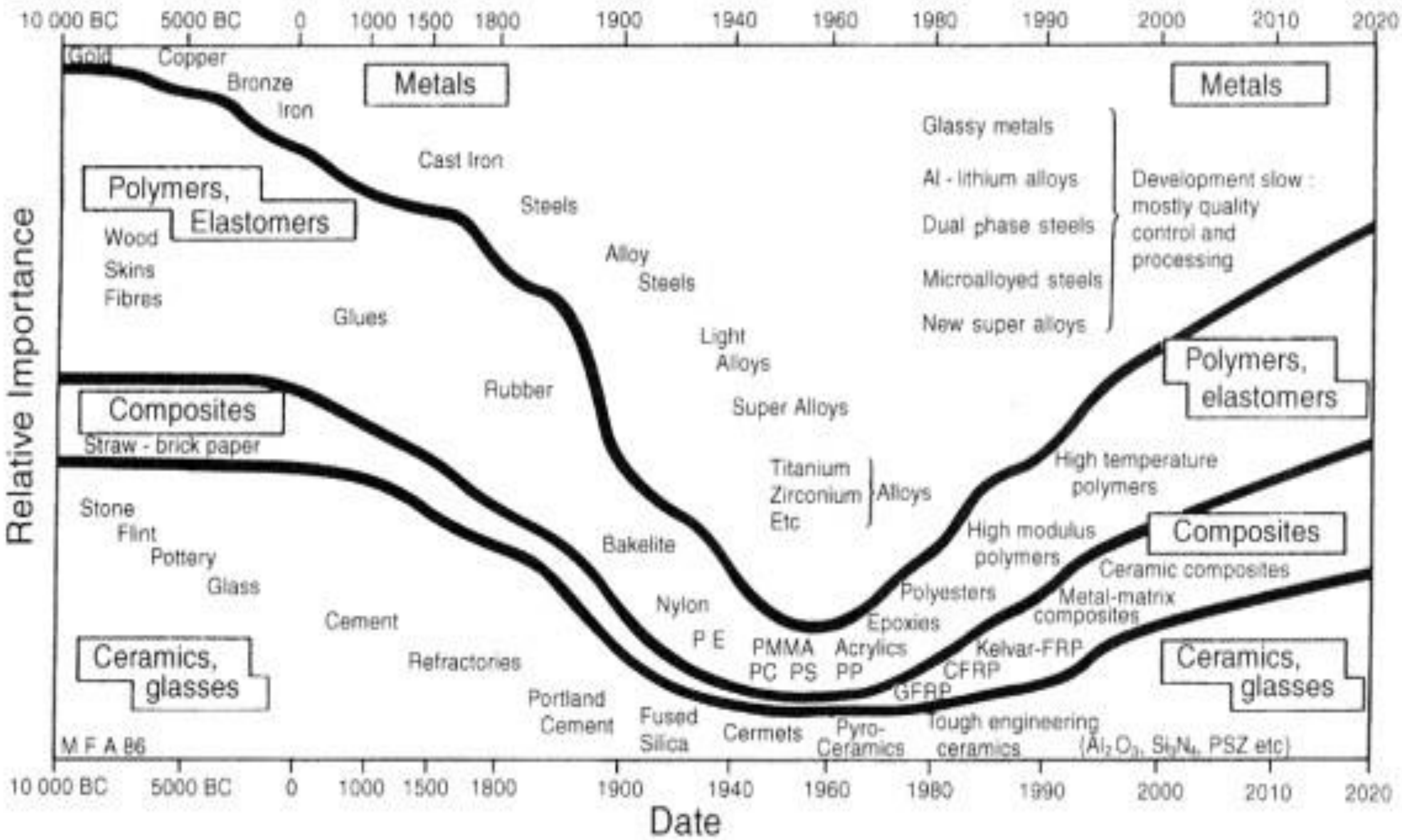
Evolution of materials is challenged by:

- ↗ mechanical properties
- ↗ physical and chemical properties
- ↘ environmental problems (manufacturing)
- ↘ materials ressource

<u>Key Domains</u> : energy (nuclear, solar cells, …)

transport

A bit of History



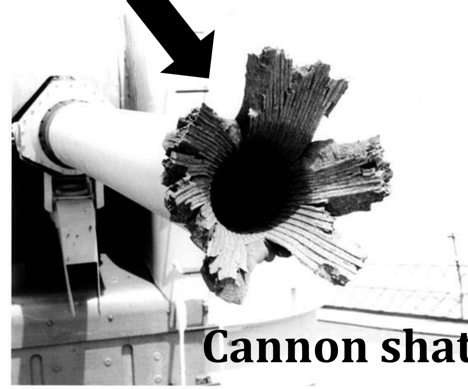
A bit of History

1850s, time of the Crimean War

Napoleon III

French military engineers had found they could control the trajectory applying a rifling or "spinning" in the barrels of guns (cannon)

The spiraling motion added extra stresses
Consequence?

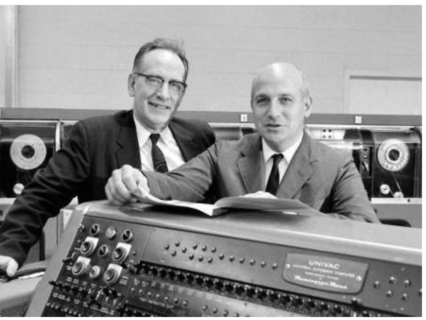


Cannon shatter

Need a higher-strength material
→ **Steel**

A bit of History

1946, University of Pennsylvania
Moore School of Electrical Engineering



Electronic Numerical Integrator Analyser and Computer (**Eniac**) by **John Mauchly and J. Presper Eckert**

The first general-purpose electronic computer

17468 thermionic valves
70,000 resistors
....
Covered 167 square metres of floor space
Weighed 30 tonnes
Consumed 160 kW of electricity

1947,
Discovery of the Transistor (Semiconductors)

Built from materials such as **Silicon and Germanium** which can either behave as an electrical insulator or conductor

Companies spent tens of billion of dollars to squeeze more circuits on to a small 'chip' of material

2010, an Intel X3370 microprocessor – 820 million transistors
Your computer could handle 3 billion instructions /s
600000 more than Eniac

A bit of History

2012, low cost airlines company

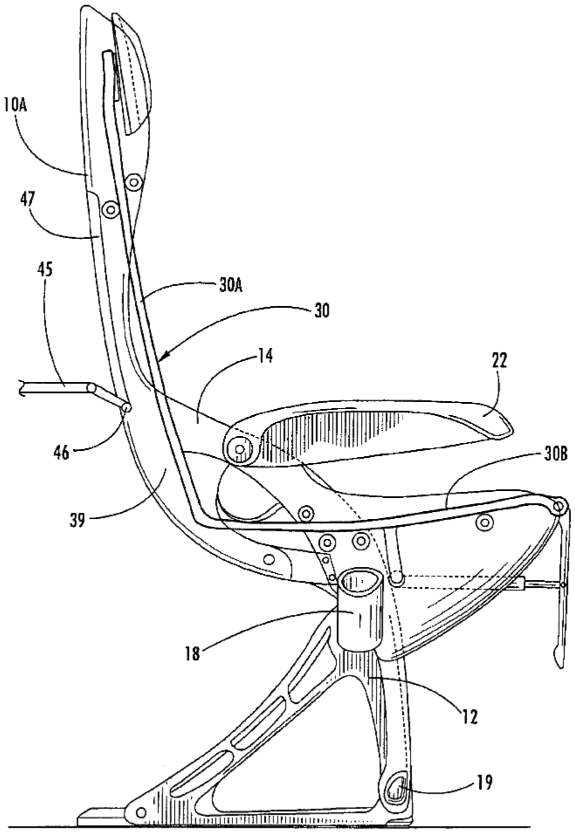
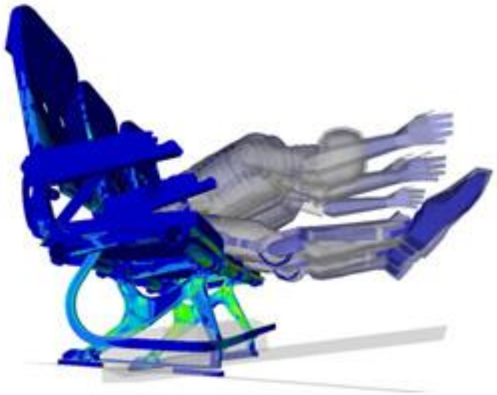


FIG. 2

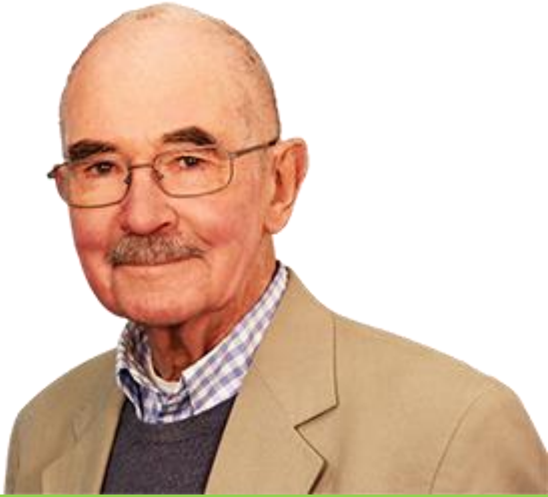


Change the material of a small pivot (46) for each seat

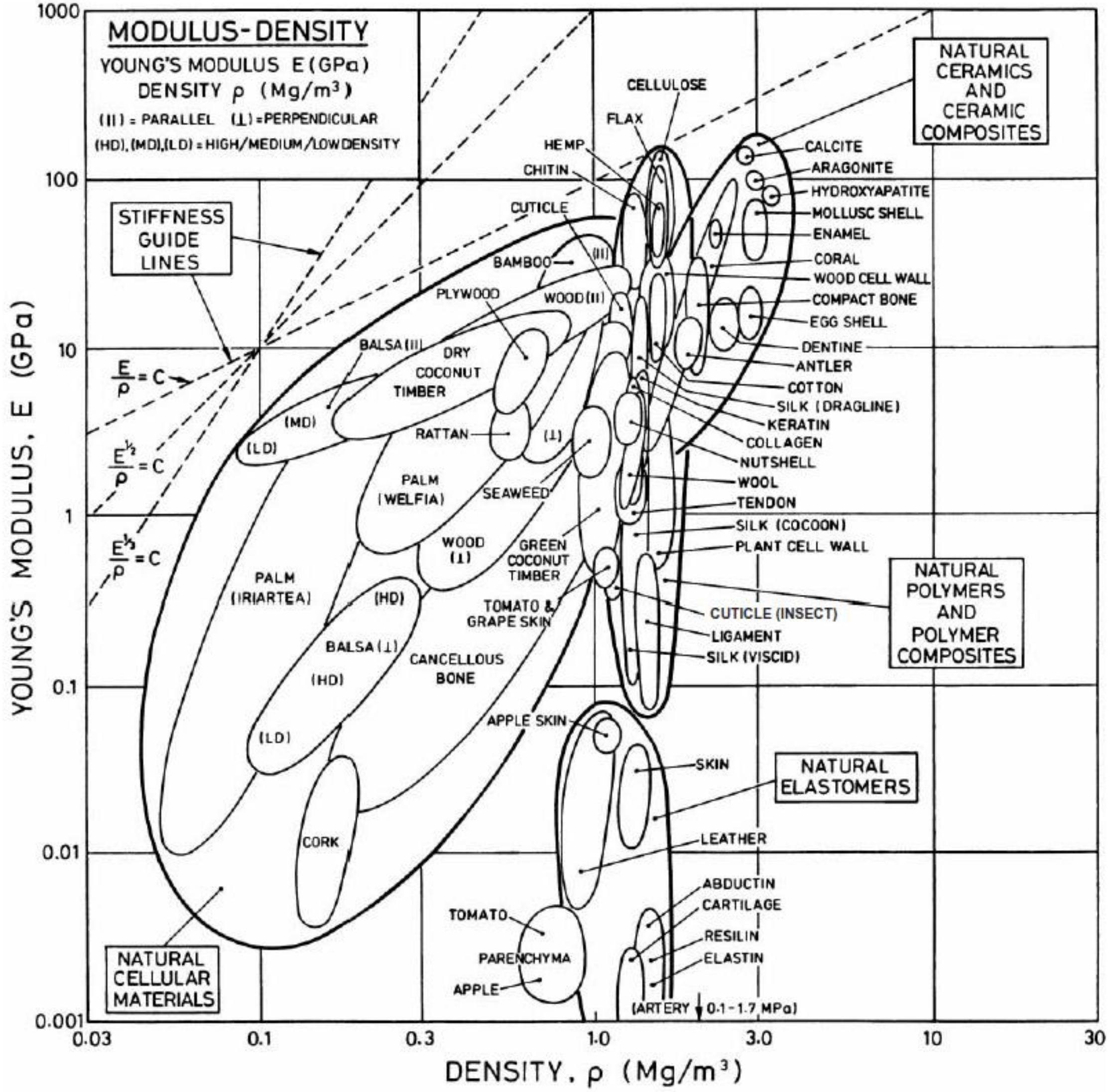
In the air transports
Weight = Costs

Aluminum → PE+ Glass fibers Composite → 10,000,000 dollars saved each year

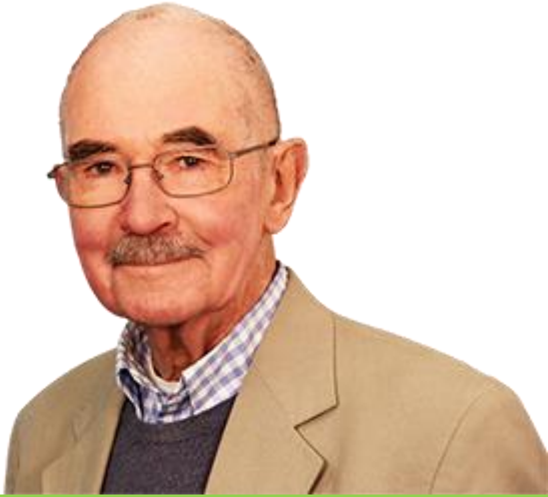
Mike Ashby from Univesity of Cambridge



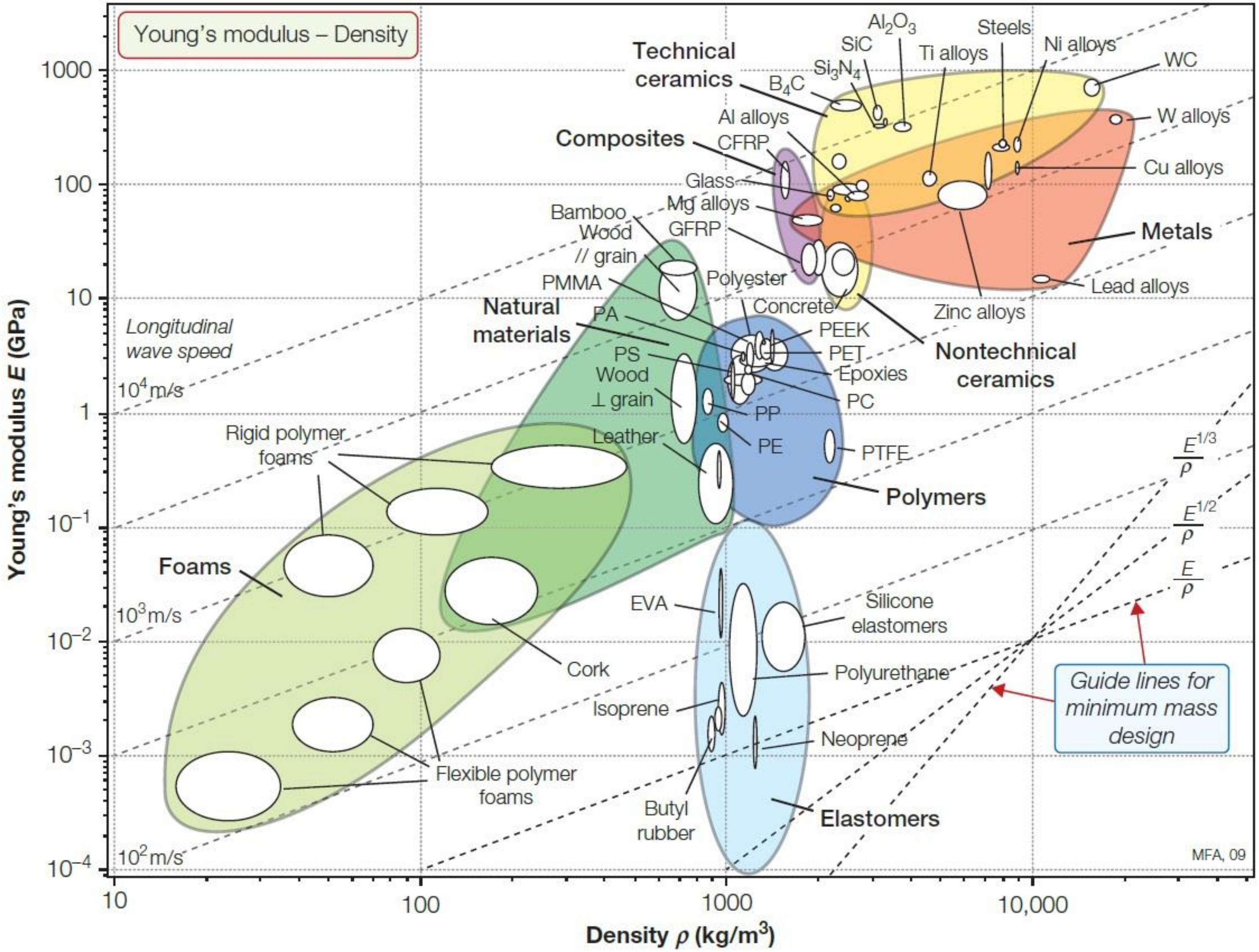
Ashby Diagrams



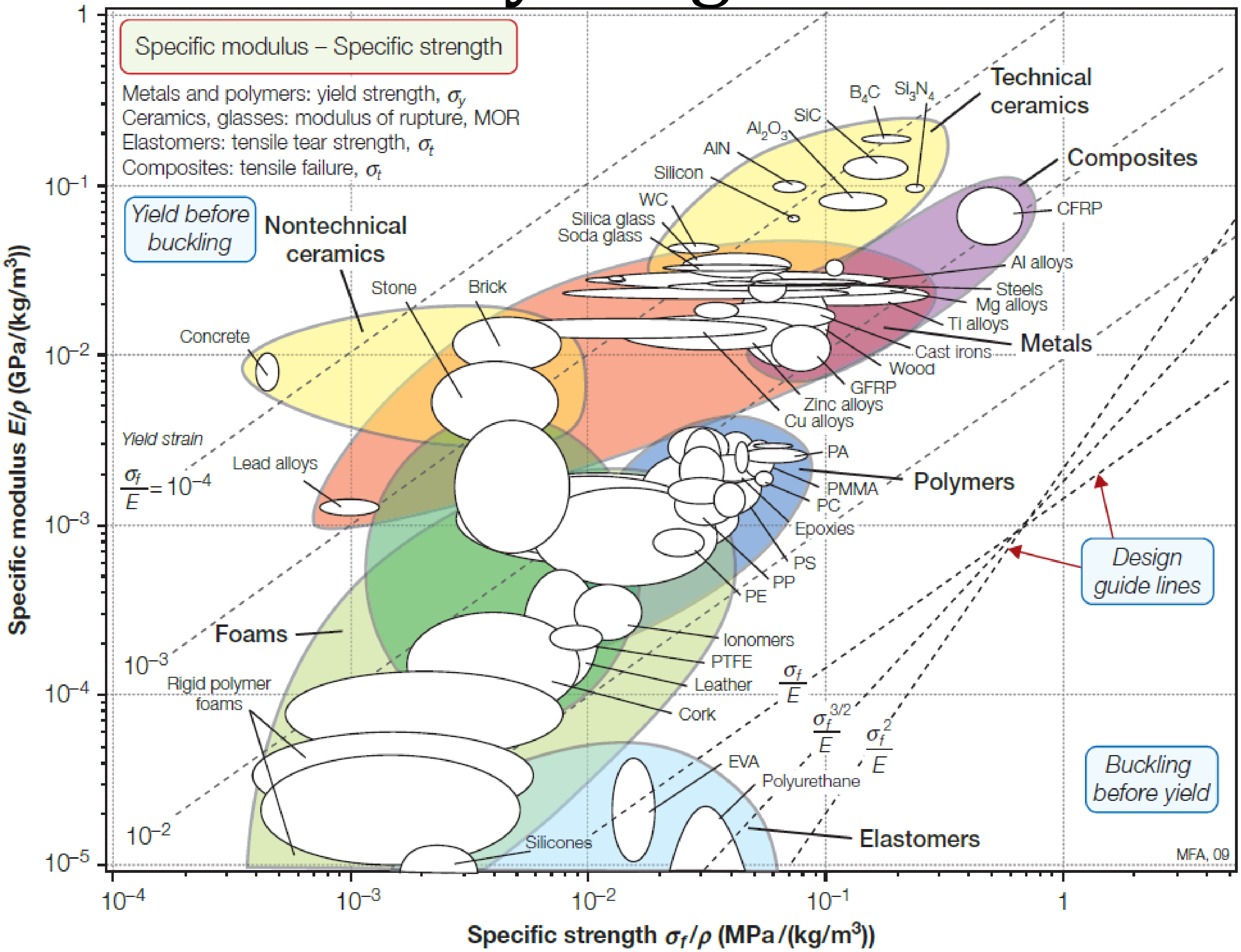
[The mechanical efficiency of natural materials, Mike Ashby, 2003]



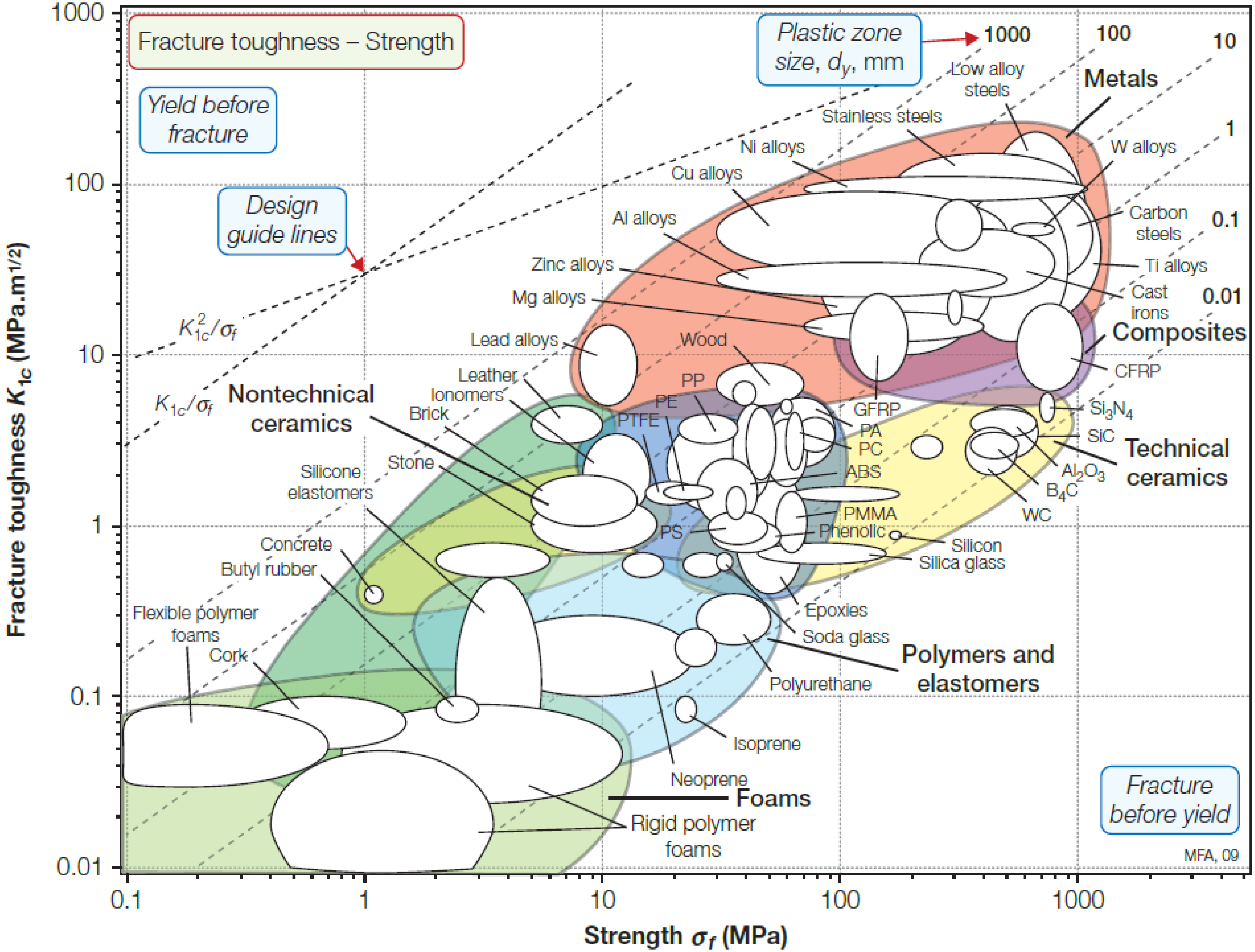
Ashby Diagrams



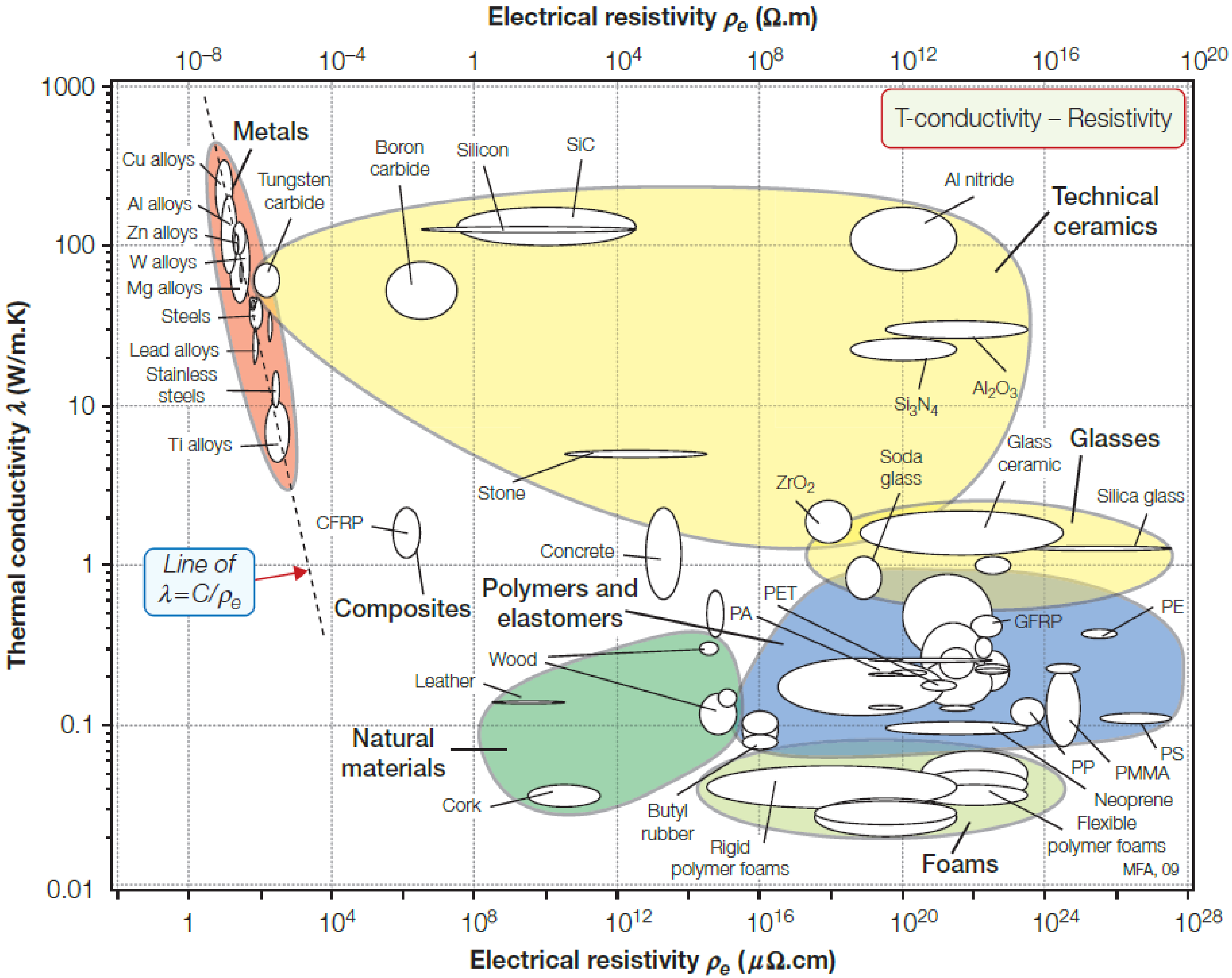
Ashby Diagrams



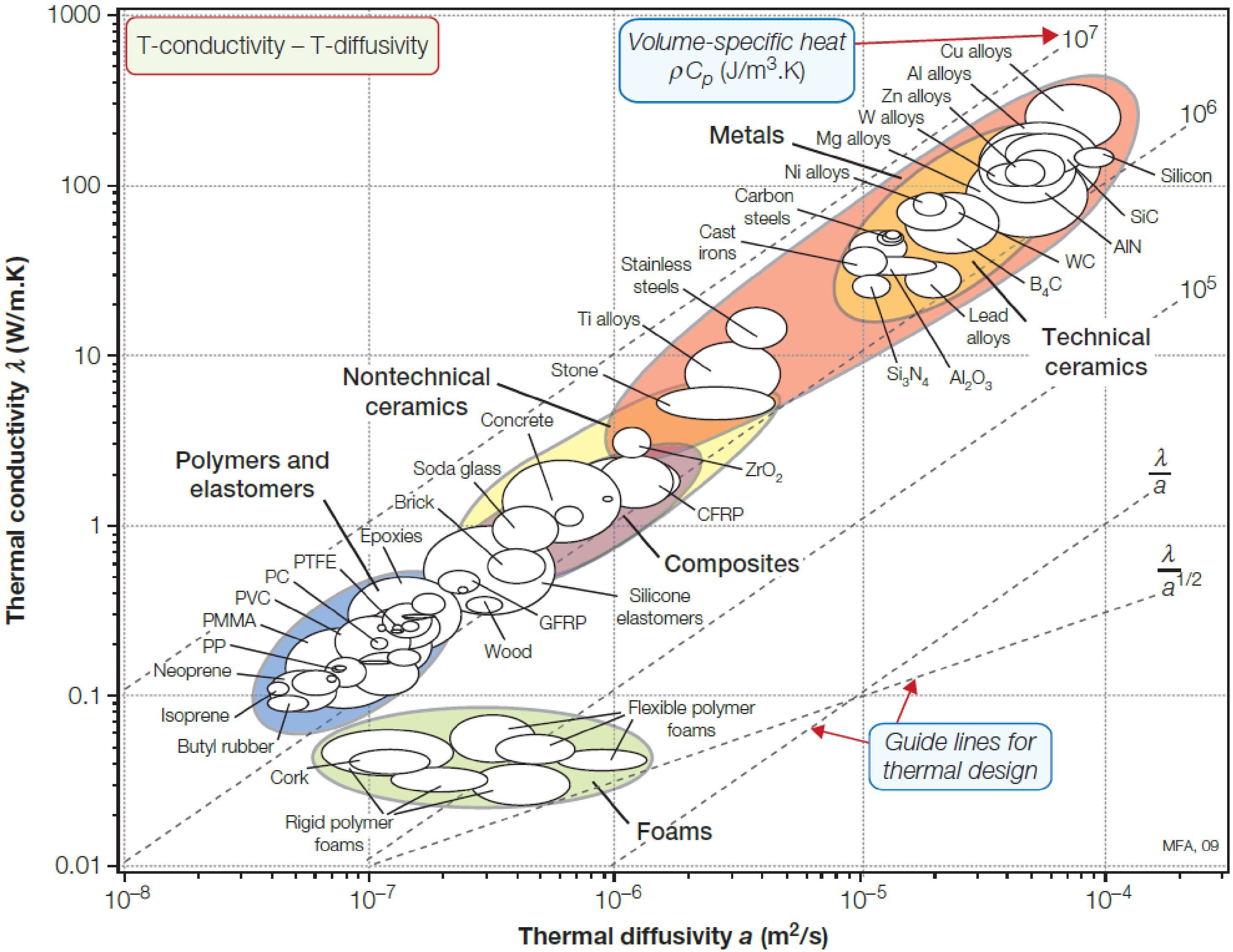
Ashby Diagrams



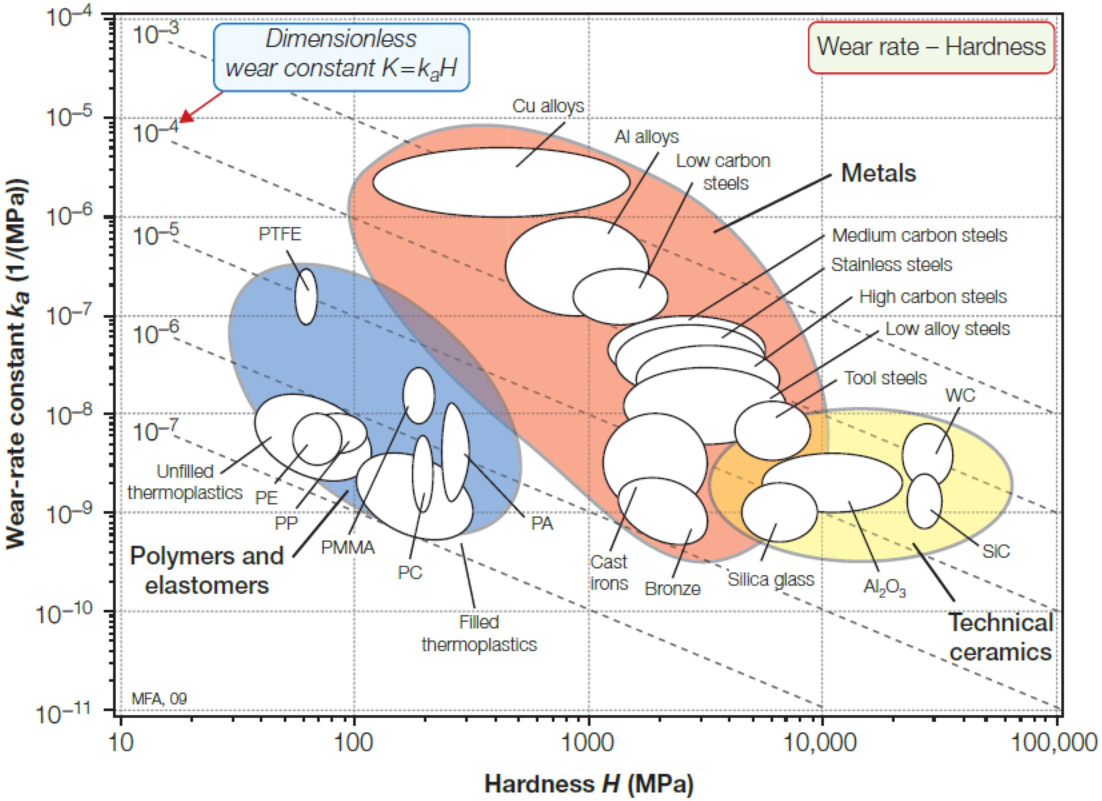
Ashby Diagrams

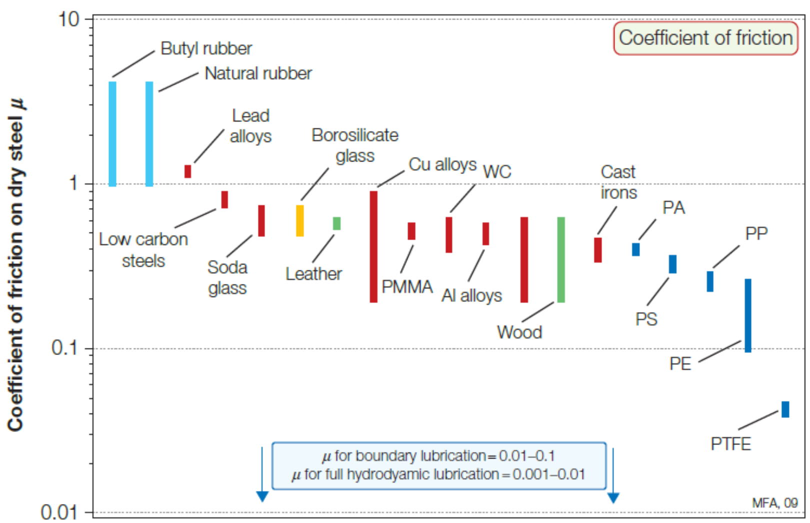


Ashby Diagrams

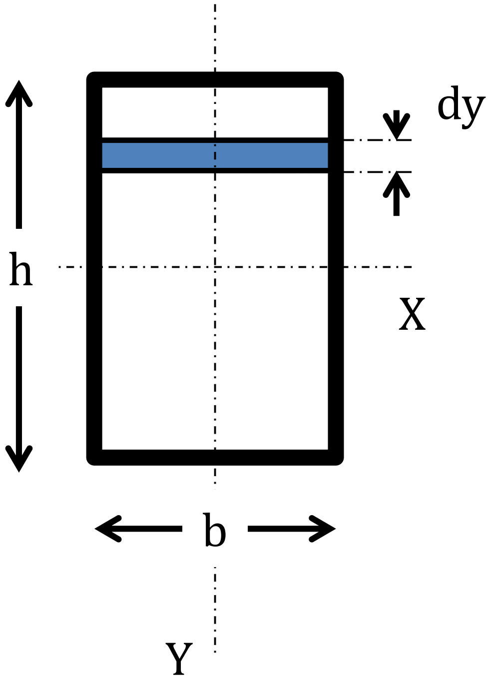


Ashby Diagrams





Simplification: Where is the problem?



For a beam under flexion, the moment of inertia : $I_{XX} = \frac{bh^3}{12}$

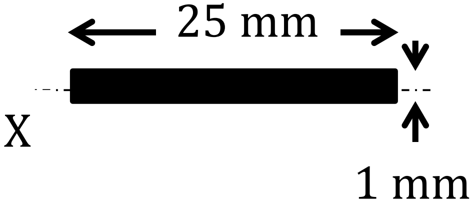
Length (L): 300 mm

Thickness (h) = 1 mm

Width (b) = 25 mm

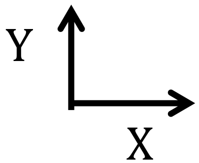
$$I_{XX} = \frac{25 \cdot 1^3}{12} = 2{,}1\ mm^4$$

$$I_{YY} = \frac{1 \cdot 25^3}{12} = 1300\ mm^4$$

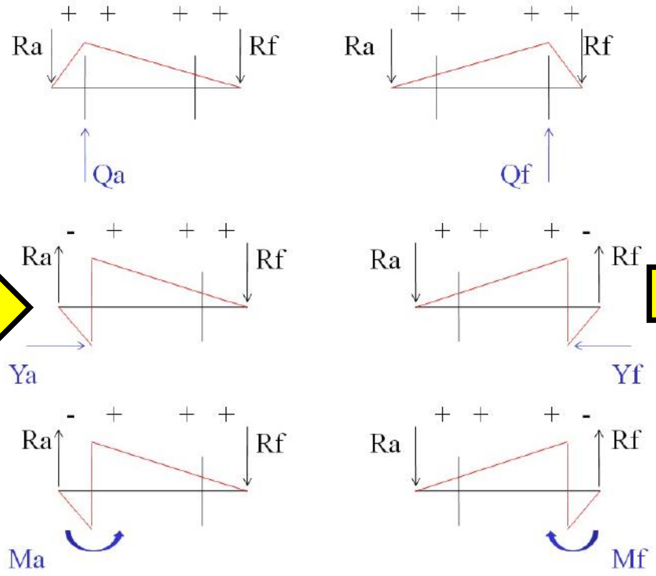


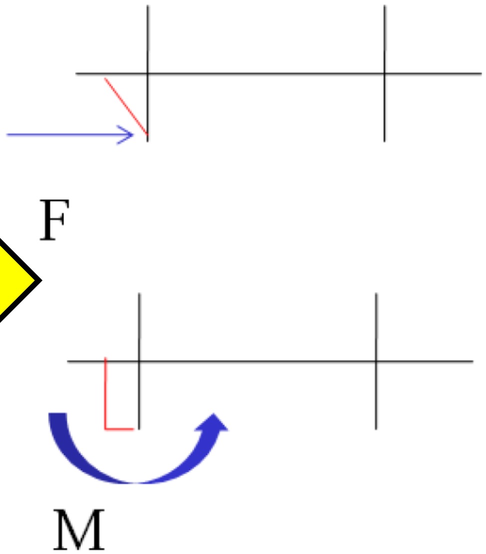
In the case of the mechanical properties, it is important to consider the forces applied, but it is the weakest point that determine the selection.

It is possible to change the geometry, but if you cannot
What can we do?

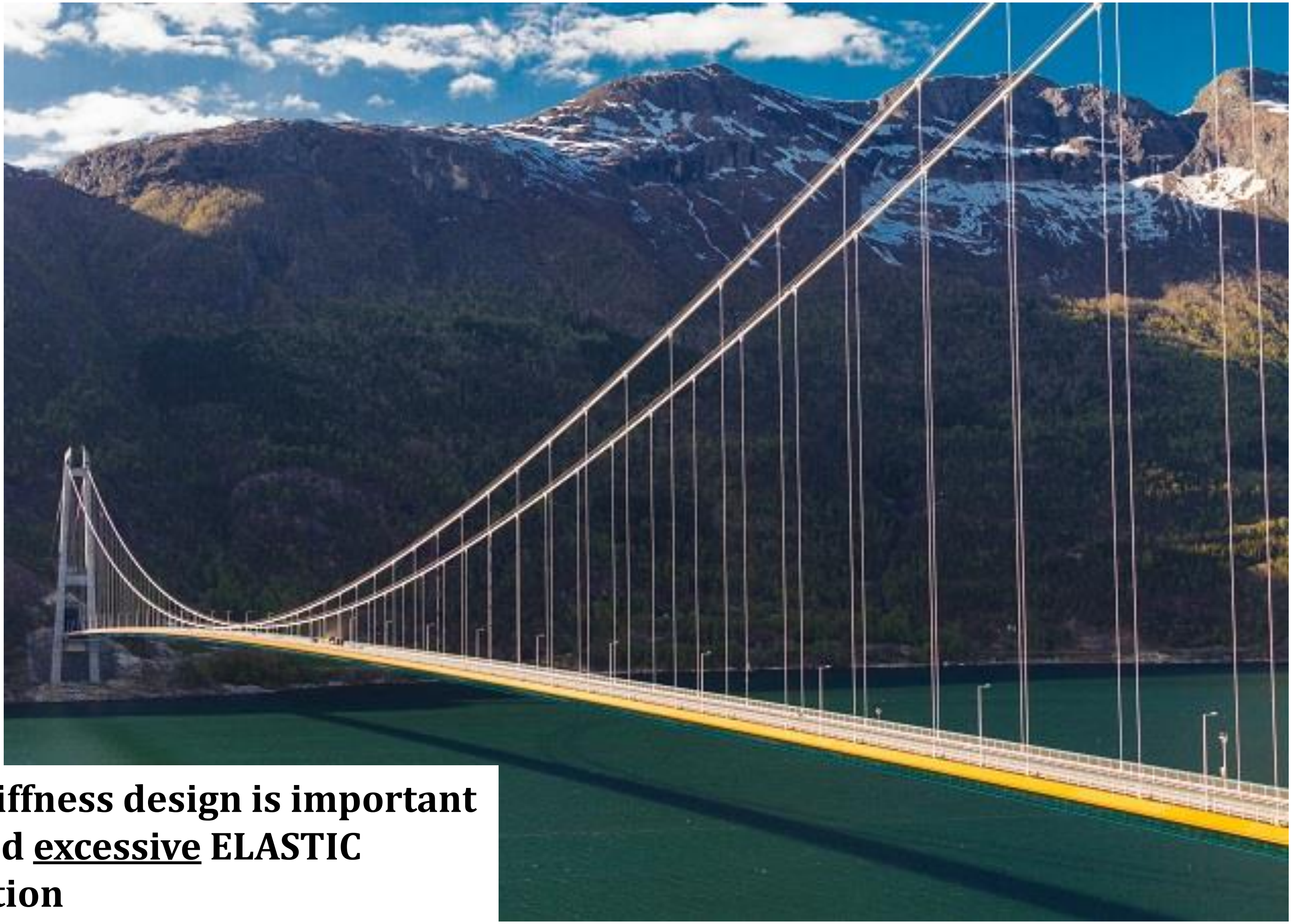


Simplification: Train Wheel (Fast Example)





The Stiffness design

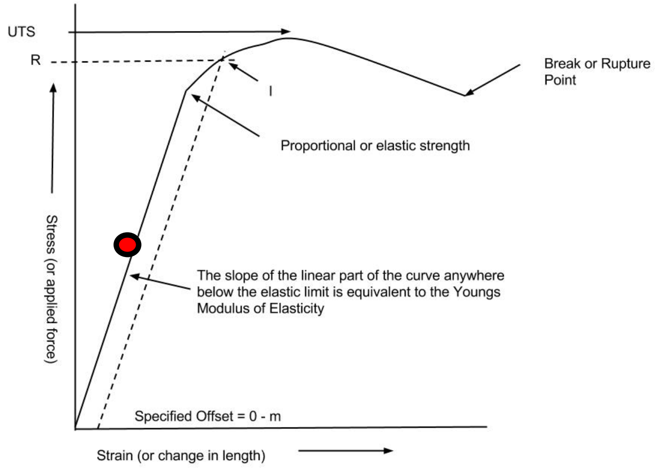


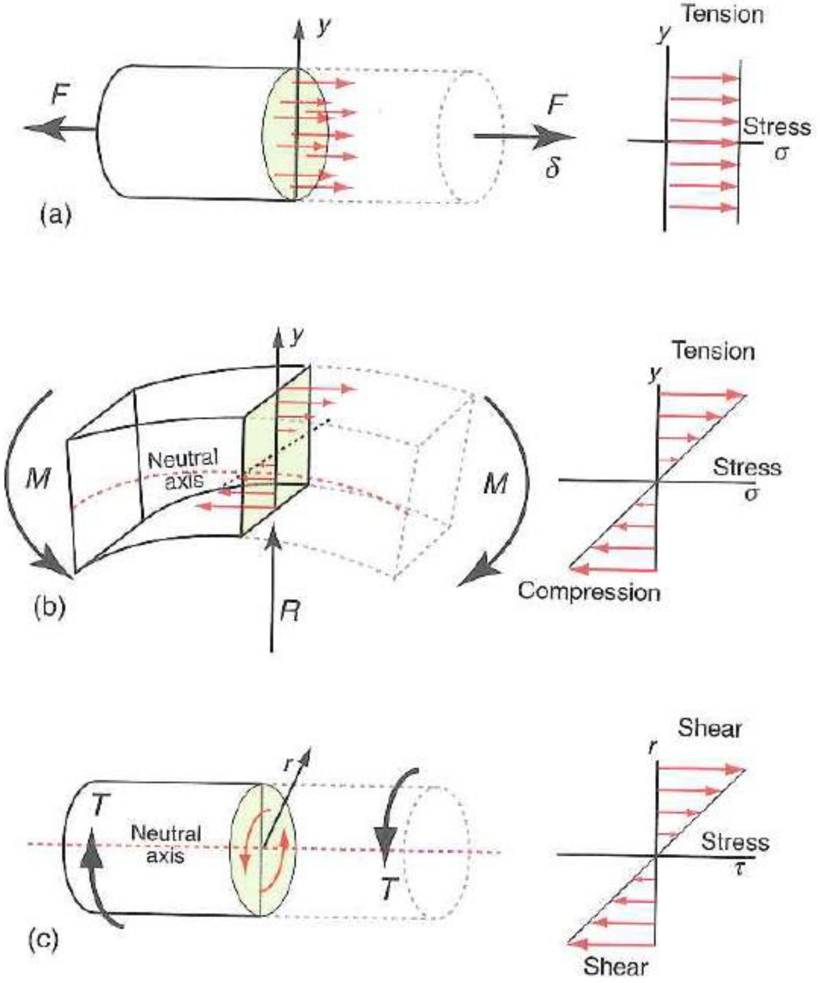
The Stiffness design is important to avoid <u>excessive</u> ELASTIC deflection

The Stiffness design

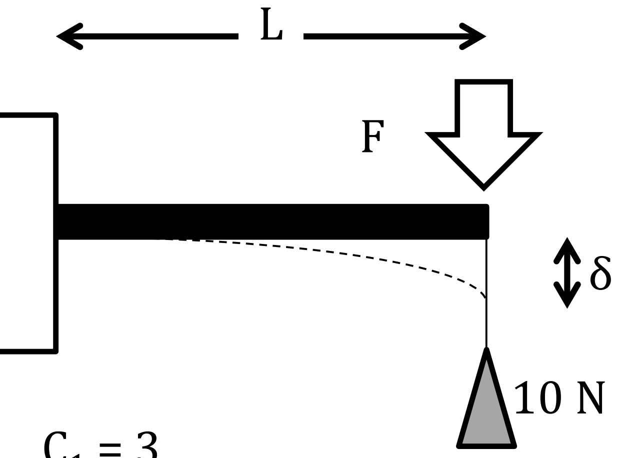
The Stiffness design is important to avoid excessive ELASTIC deflection

Your are here





The Stiffness



$C_1 = 3$

$$S = \frac{F}{\delta} = \frac{C_1 EI}{L^3}$$

$$\delta = \varepsilon \cdot L$$

EI = Flexural rigidity
I = Second Moment of inertia
E = Young's Modulus
δ = Deflexion

Length (L): 300 mm
Thickness (h)= 1 mm
Width (b)= 25 mm

$$I_{XX} = \frac{25 \cdot 1^3}{12} = 2{,}1\ mm^4$$

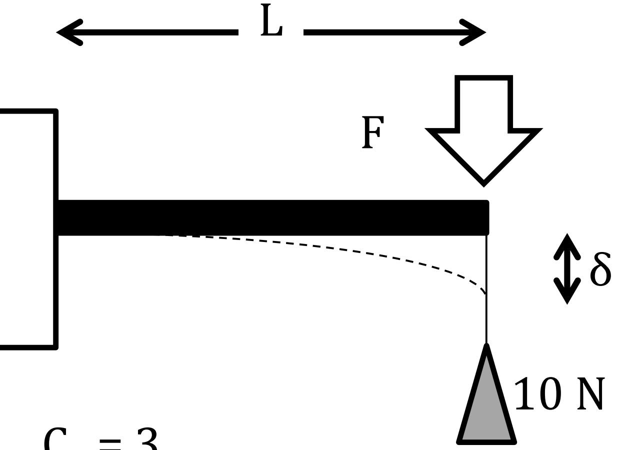
$$I_{YY} = \frac{1 \cdot 25^3}{12} = 1300\ mm^4$$

Problem :

δ??
IF we consider that the beam is made of Stainless Steel (E = 200 GPa)

Which are the consequences if I want to use Polystyrene (E = 2 GPa)?
IF I can change the thickness and hold the same deflection.

The Stiffness



$C_1 = 3$

$$S = \frac{F}{\delta} = \frac{C_1 EI}{L^3}$$

EI = Flexural rigidity
I = Second Moment of inertia
E = Young's Modulus

Stainless Steel (E = 200 GPa; ρ = 7800 kg/m^3)
Polystyrene (E = 2 GPa; ρ = 1040 kg/m^3)

Steel

$$I_{YY} = \frac{1 \cdot 25^3}{12} = 1300\ mm^4 \longrightarrow \delta = \frac{10 \cdot (0{,}25)^3}{3 \cdot (200 \cdot 10^9) \cdot (1300 \cdot 10^{-12})} = 0{,}02\ mm$$

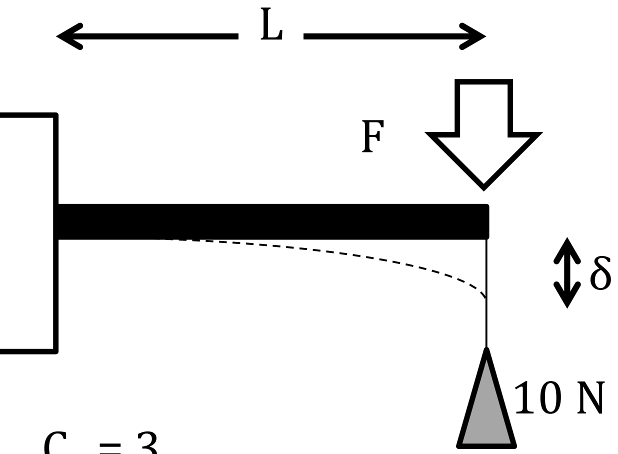
$$I_{XX} = \frac{25 \cdot 1^3}{12} = 2{,}1\ mm^4 \longrightarrow \delta = \frac{FL^3}{C_1 E Y_{XX}} = 124\ mm$$

PS

$$With\ \delta = 124\ mm \qquad I_{XX} = \frac{10 \cdot (0{,}25)^3}{3 \cdot (2 \cdot 10^9) \cdot (0{,}124)} = 210\ mm^4$$

$$h = \left(\frac{12 I_{XX}}{w}\right)^{1/3} = \left(\frac{12 \cdot 210}{25}\right)^{1/3} = 4{,}6\ mm \qquad When\ h(Steel) = 1\ mm$$

The Stiffness



$C_1 = 3$

$$S = \frac{F}{\delta} = \frac{C_1 EI}{L^3}$$

Length: 300 mm

Width = 25 mm

EI = Flexural rigidity

I = Second Moment of inertia

E = Young's Modulus

δ = Deflexion

Stainless Steel (E = 200 GPa; ρ = 7800 kg/m^3)

Polystyrene (E = 2 GPa; ρ = 1040 kg/m^3)

Thickness = 1 mm

Thickness = 4,6 mm

About the weight?

$$m_{SS} = 7800 \cdot 0{,}3 \cdot 0{,}025 \cdot 0{,}001 = 59\ gr$$

$$m_{PS} = 1040 \cdot 0{,}3 \cdot 0{,}025 \cdot 0{,}046 = 36\ gr$$

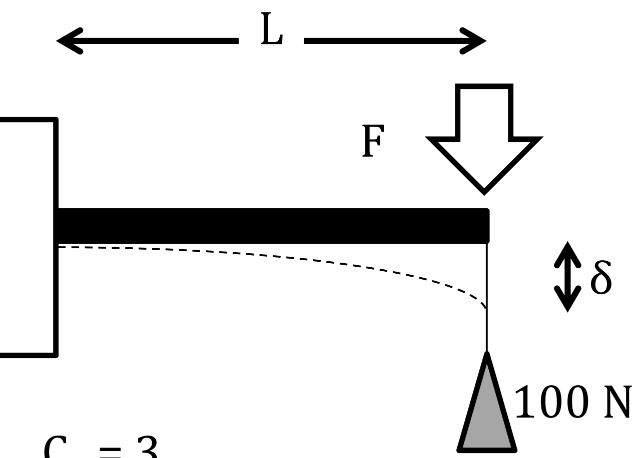
BIGGER Section
BUT LIGHTER

Depends on what you need and the conditions

The Materials Selection approach

Case Study 1:
Find the Lightest STIFF Beam

Objective	• Minimize the mass
Constraints	• Stiffness specified • Length L • Square shape
Free Variables	• Area (A) of the cross-section • Choice of the material



$C_1 = 3$

Length: 300 mm

EI = Flexural rigidity
I = Second Moment of inertia
E = Young's Modulus
δ = Deflexion

Hypothesis:

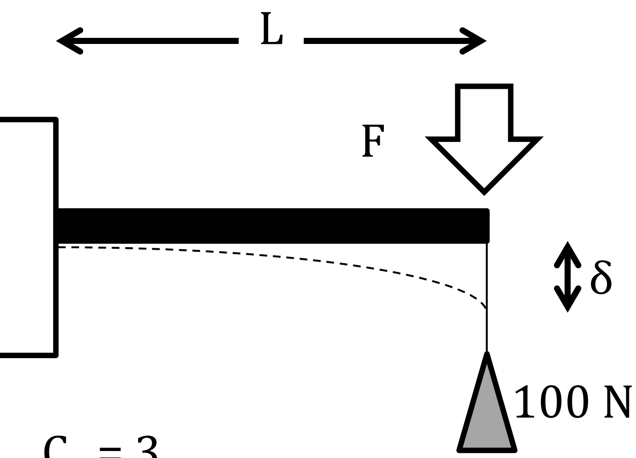
- $\frac{F}{\delta} = S \geq S_{min}$

$$\begin{cases} \frac{F}{\delta} \geq S_{min} = \frac{C_1 EI}{L^3} \\ m = A \cdot L \cdot \rho \longrightarrow A = \frac{m}{L \cdot \rho} \end{cases}$$

m = mass
A = area of the section
L = Length
ρ = Density

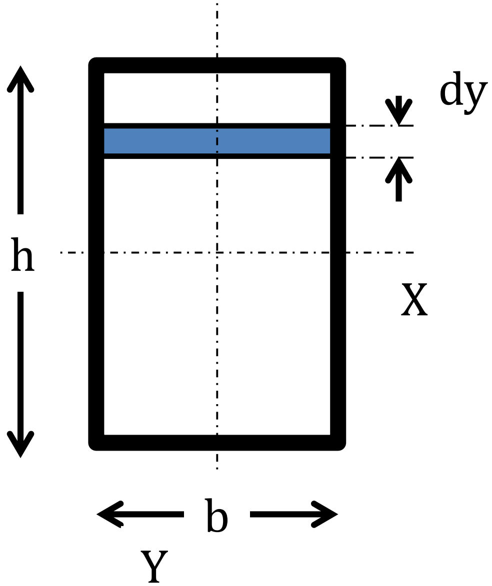
The Materials Selection approach

Case Study 1:
Find the Lightest STIFF <u>Beam</u>



$C_1 = 3$

<u>Beam: Square Section</u>
b=h



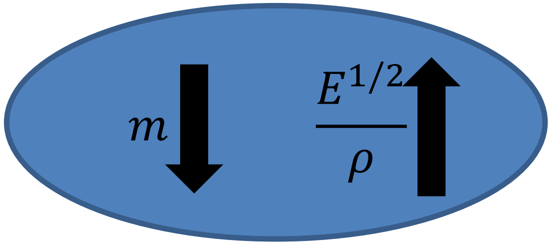
$$\begin{cases} \dfrac{F}{\delta} = \dfrac{C_1 E I}{L^3} \geq S_{min} \\ A = \dfrac{m}{L \cdot \rho} \end{cases}$$

Since $A = b^2$

$$I = \frac{bh^3}{12} = \frac{A^2}{12}$$

$$\begin{cases} A = \dfrac{m}{L \cdot \rho} \\ m \geq \left(\dfrac{12 \cdot S}{C_1 \cdot L}\right)^{1/2} \cdot L^3 \cdot \dfrac{\rho}{E^{1/2}} \end{cases}$$

The Area will be the Free Variable



Just remember:

Constraints	• Stiffness specified • Length L • Square shape

The Material Index (M)

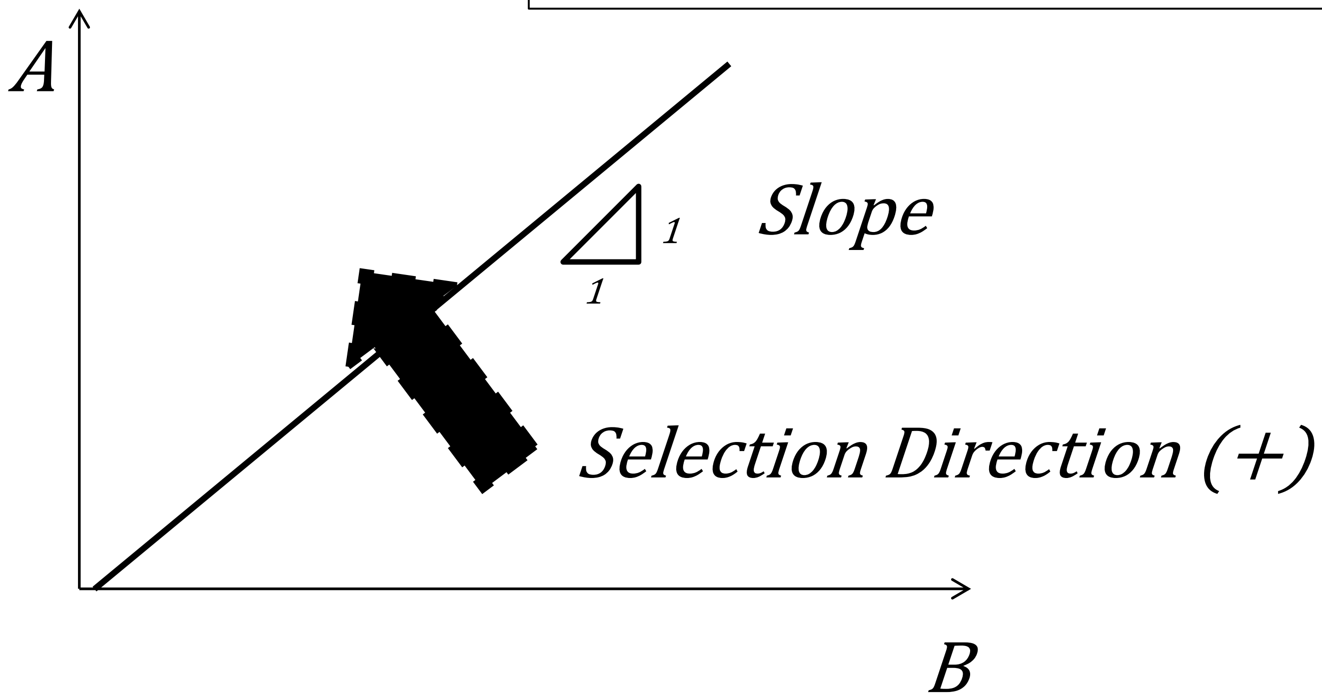
Case Study 1:
Find the Lightest STIFF <u>Beam</u>

$$M = \frac{A}{B}$$

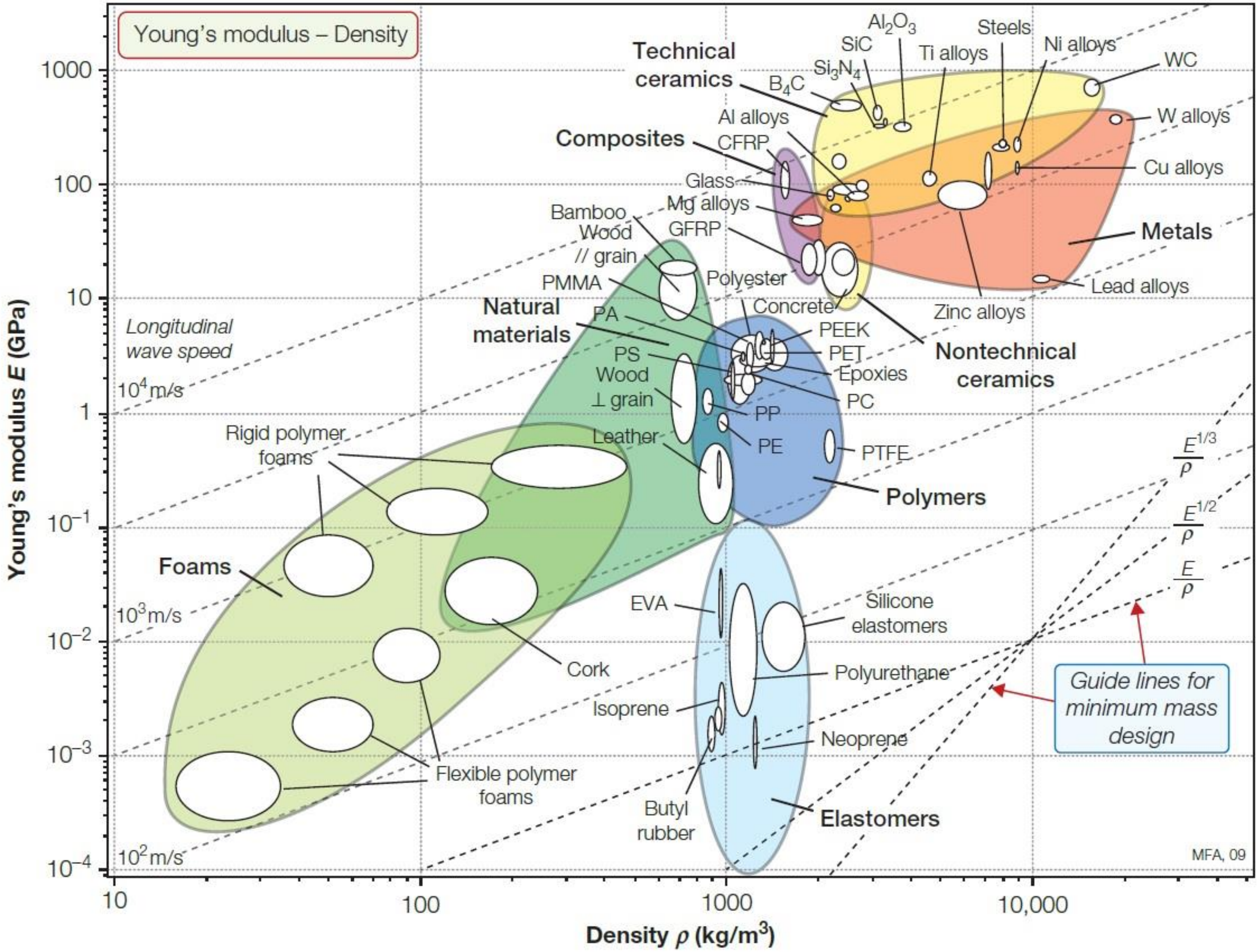
$$Log(M) = Log\,(A) - Log(B)$$

$$Log(A) = Log(B) + Log\,(M)$$

For instance $\frac{E^{1/2}}{\rho}$



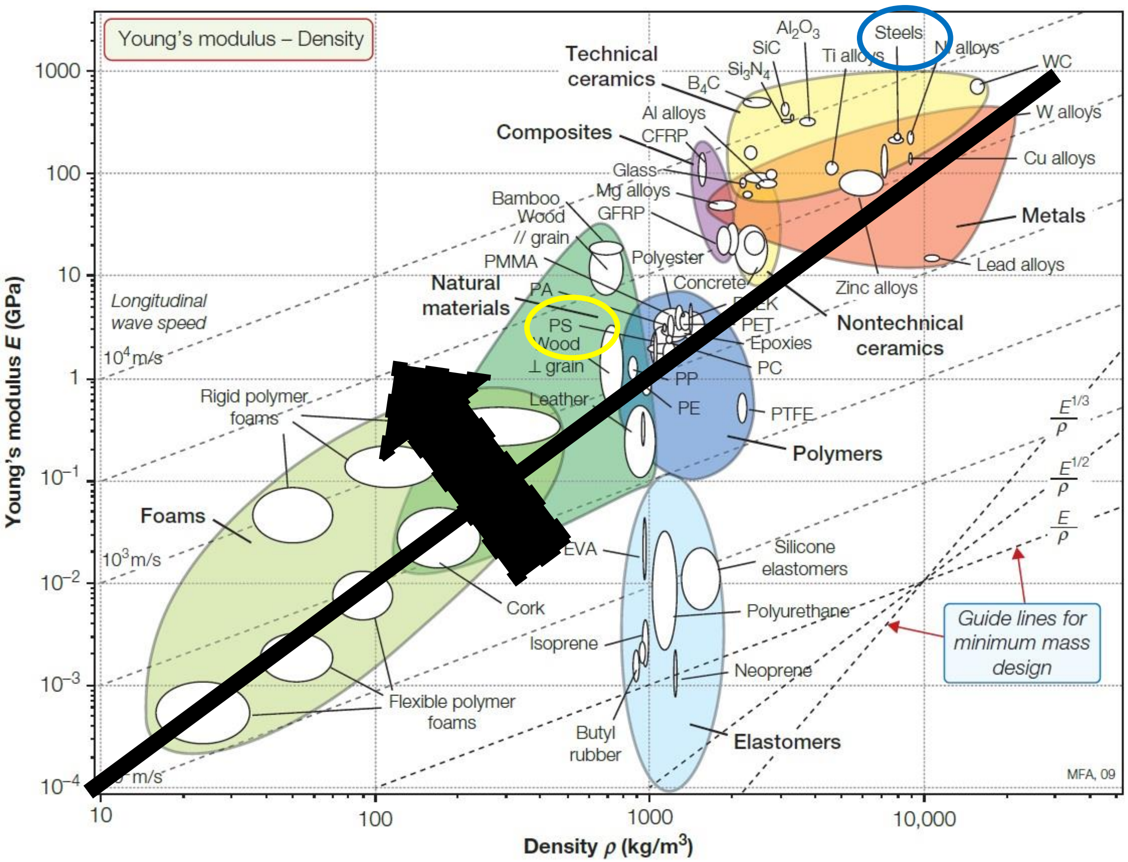
Ashby Diagrams

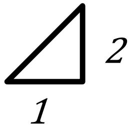


The Material Index (M)

Case Study 1:
Find the Lightest STIFF <u>Beam</u>

$m \downarrow \quad \frac{E^{1/2}}{\rho} \uparrow$





Slope

Stainless Steel
(E = 200 GPa; ρ = 7800 kg/m^3)
Polystyrene
(E = 2 GPa; ρ = 1040 kg/m^3)

Lightest Beam (Bending conditions)

Case Study 1:
Find the Lightest STIFF <u>Beam</u>

Length: 300 mm

Thickness = 1 mm

Width = 25 mm

Width and thickness ?

F = 100 N

δ = 0,34 mm

$S_{min} = 296 \cdot 10^3$ N/m

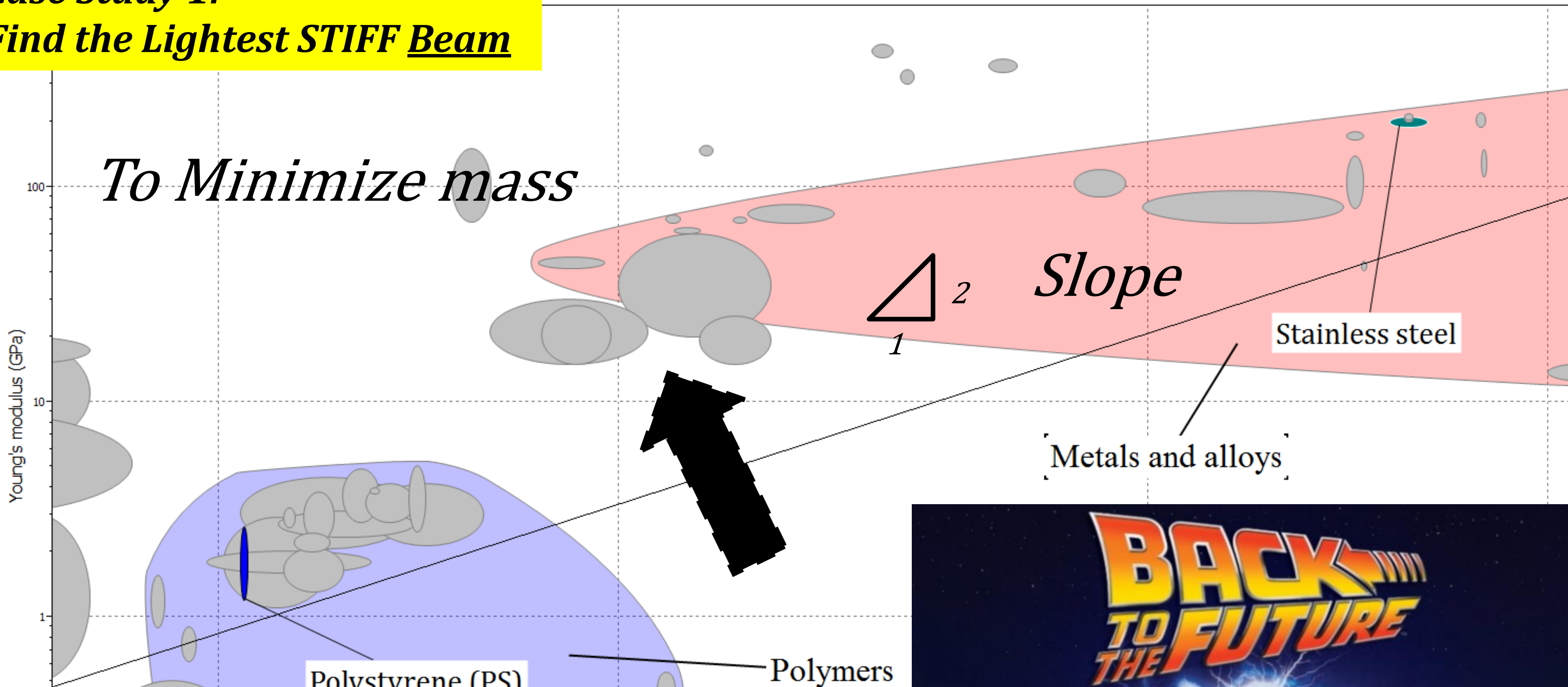
Stainless Steel (E = 200 GPa; ρ = 7800 kg/m^3)
Polystyrene (E = 2 GPa; ρ = 1040 kg/m^3)

$$\begin{cases} m \geq \left(\frac{12 \cdot S}{C_1 \cdot L}\right)^{1/2} \cdot L^3 \cdot \frac{\rho}{E^{1/2}} \\ A = \frac{m}{L \cdot \rho} \end{cases}$$

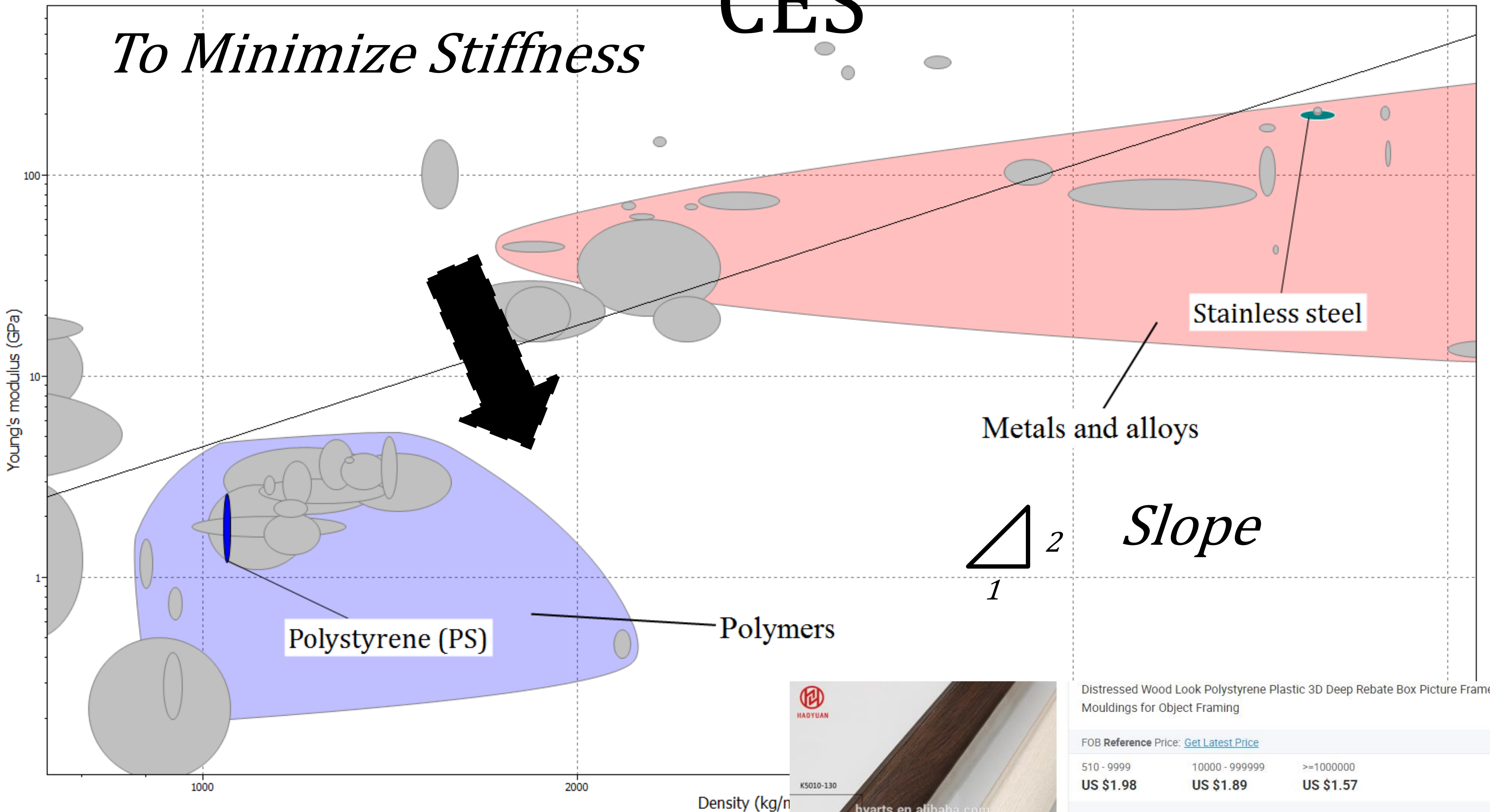
Material	**Weight (kg)**	**A (mm^2)**	**Width and Thickness (mm)**
Stainless Steel	0,935	400	20
Polystyrene	1,25	4000	63

CES

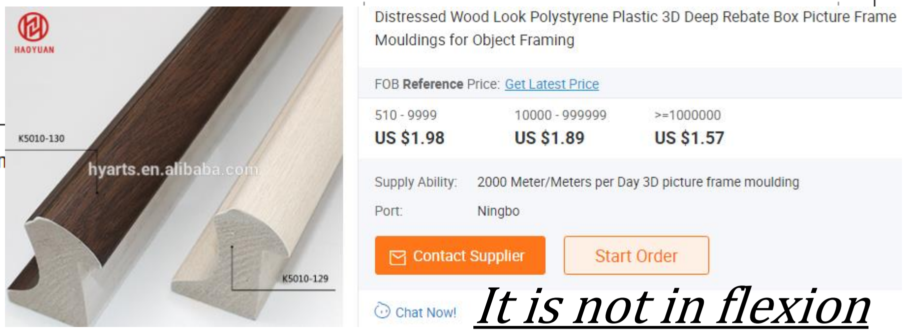
Case Study 1:
Find the Lightest STIFF <u>Beam</u>



CES



Depends on what you need→



It is not in flexion

Ok, slow down..

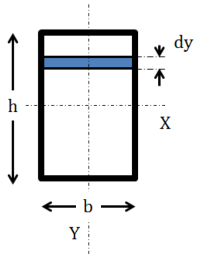
Case Study 2:
Find the Lightest STIFF <u>Tie-Rod</u>

Objective	• Minimize the mass
Constraints	• Stiffness specified • Length L
Free Variables	• Area (A) of the cross-section • Choice of the material

Tie-Rod =
TRACTION CONDITIONS

DATA
F =1000 N

Dimensions:
Length: 300 mm
Thickness = 1 mm
Width = 25 mm



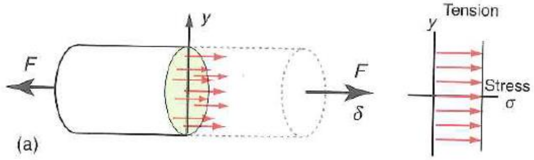
In Traction,
the shape of the cross-section is not important

$$m = A \cdot L \cdot \rho \longrightarrow A = \frac{m}{L \cdot \rho}$$

$$From\ material: \frac{\sigma}{\varepsilon} = E$$

$$From\ definition: \delta = \varepsilon \cdot L$$

$$F = \sigma \cdot A$$



$$\frac{F}{\delta} \geq S_{min} = S$$

Lightest Tie-Rod (Traction conditions)

Case Study 2:
Find the Lightest STIFF <u>Tie-Rod</u>

$$\frac{F}{\delta} \geq S_{min} = S$$

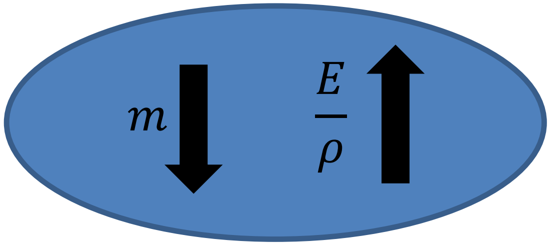
$$\frac{\sigma \cdot A}{\varepsilon \cdot L} \geq S_{min}$$

$$\left.\begin{aligned} \frac{E \cdot A}{L} &\geq S_{min} \\ A &= \frac{m}{L \cdot \rho} \end{aligned}\right\} \quad m \geq S \cdot L^2 \cdot \frac{\rho}{E}$$

F = 1000 N
$\delta = 3{,}78 \cdot 10^{-3}$ mm
$S_{min} = 264{,}5 \cdot 10^{6}$ N/m
Dimensions:
Length: 300 mm
Thickness = 1 mm
Width = 25 mm

$$m \geq (264{,}5 \cdot 10^{6}) \cdot (300 \cdot 10^{-3})^{2} \cdot \frac{\rho}{E}$$

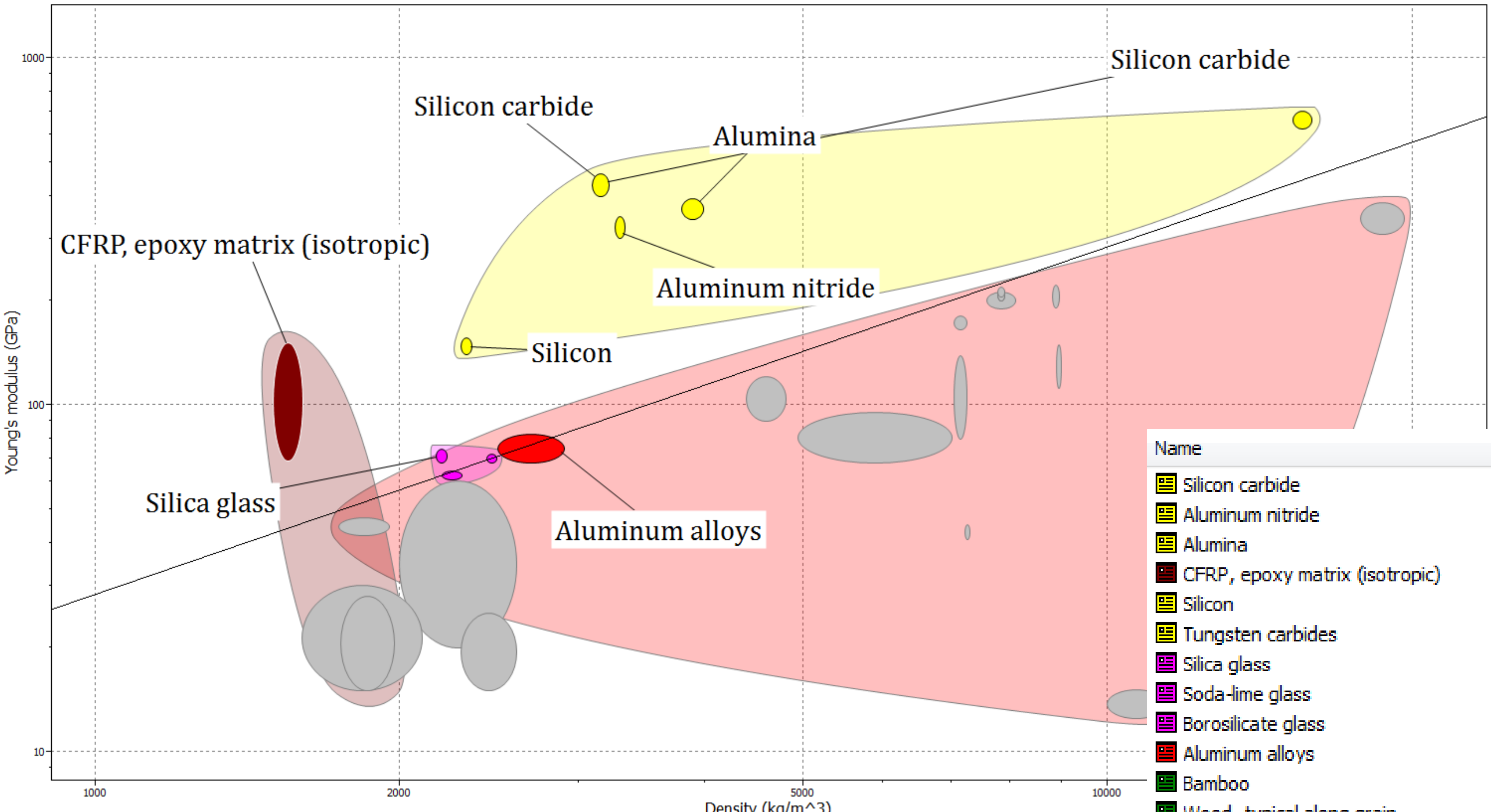
$$\geq \; \ldots \cdot \frac{\rho}{E}$$



CES

$m \downarrow$ $\quad \frac{E}{\rho} \uparrow$

Case Study 2:
Find the Lightest STIFF <u>Tie-Rod</u>



Name	Stage 1: Index
Silicon carbide	0.136
Aluminum nitride	0.0984
Alumina	0.094
CFRP, epoxy matrix (isotropic)	0.0657
Silicon	0.0634
Tungsten carbides	0.0425
Silica glass	0.0323
Soda-lime glass	0.0284
Borosilicate glass	0.0278
Aluminum alloys	0.0277
Bamboo	0.025
Wood, typical along grain	0.0158

Lightest Tie-Rod (Traction conditions)

Case Study 2:
Find the Lightest STIFF Tie-Rod

$$\left.\begin{array}{l} \frac{E \cdot A}{L} \geq S_{min} \\ A = \frac{m}{L \cdot \rho} \end{array}\right\} m \geq S \cdot L^2 \cdot \frac{\rho}{E}$$

$m \downarrow \quad \frac{E}{\rho} \uparrow$

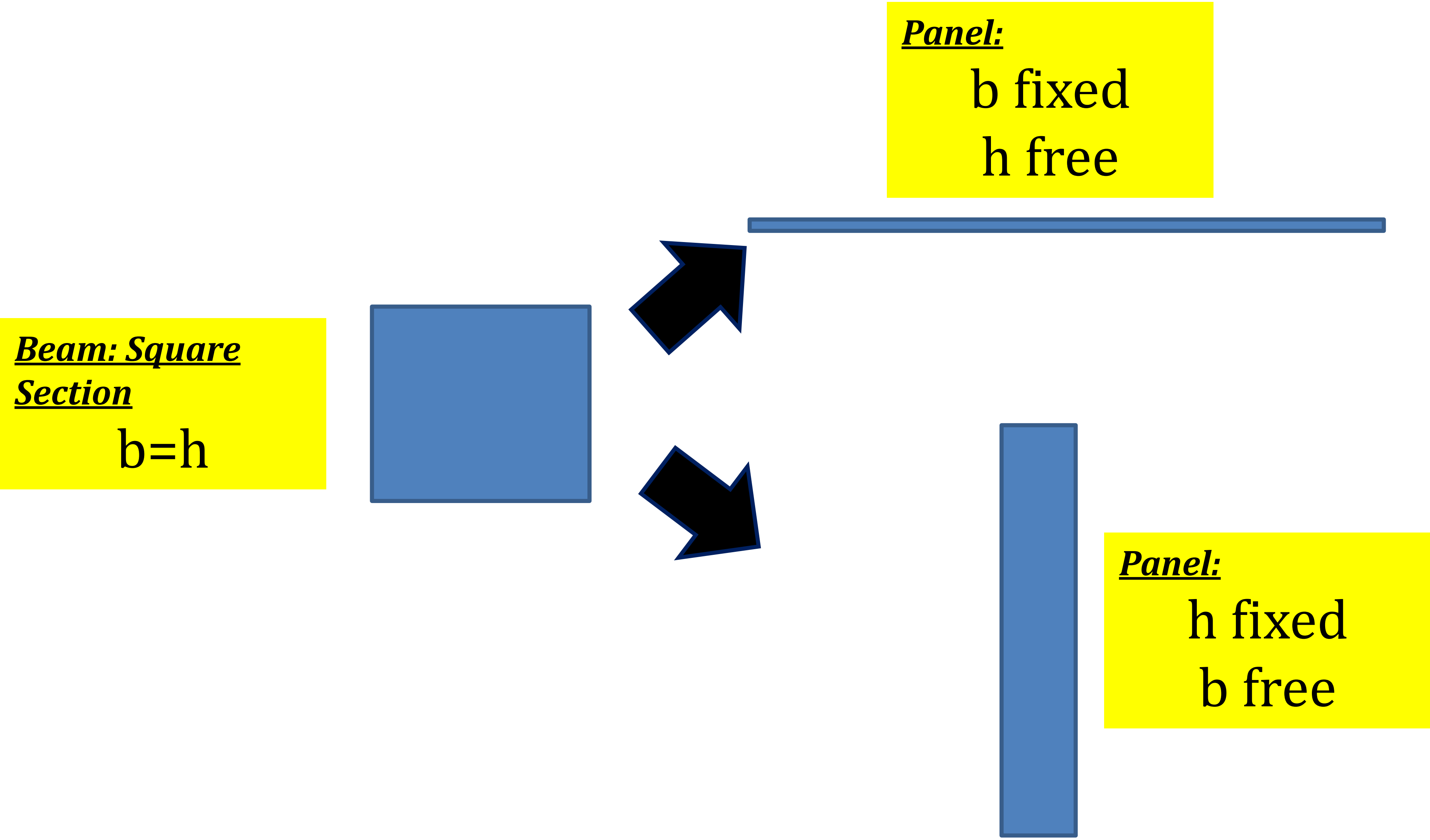
F = 1000 N
$\delta = 3{,}78 \cdot 10^{-3}$ mm
$S_{min} = 264{,}5 \cdot 10^6$ N/m

Dimensions:
Length: 300 mm
Thickness = 1 mm
Width = 25 mm

Stainless Steel (E = 200 GPa; ρ = 7800 kg/m^3)
Silicon carbide (E = 430 GPa; ρ = 3150 kg/m^3)
Al Alloys (E = 75 Gpa; ρ = 2700 kg/m^3)

Material	Weight (kg)	A (mm^2)	Width and Thickness (mm)
Silicon Carbide	0,174	179,8	13,4
Al Alloys	0,856	1050	32,4

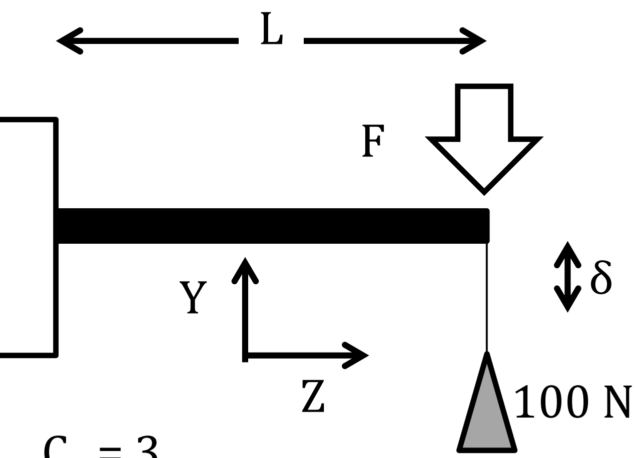
Change of the section



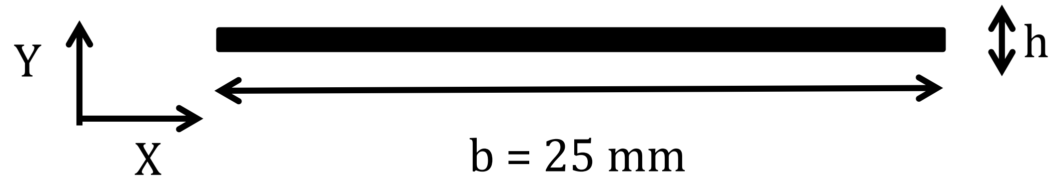
Lightest Panel (Bending conditions)

Case Study 3:
Find the Lightest STIFF <u>Panel</u>

Objective	• Minimize the mass
Constraints	• Stiffness specified • Length L and b specified
Free Variables	• h (thickness) of the cross-section • Choice of the material



$C_1 = 3$



Hypothesis:

- $\frac{F}{\delta} \geq S = S_{min}$

Length: 300 mm
Width: 25 mm

$$\left\{ \begin{array}{l} \frac{F}{\delta} \geq \frac{C_1 EI}{L^3} = S_{min} \\ m = A \cdot L \cdot \rho \longrightarrow A = \frac{m}{L \cdot \rho} \end{array} \right.$$

m = mass
A = area of the section
L = Length
ρ = Density

Lightest Panel (Bending conditions)

Case Study 3:
Find the Lightest STIFF <u>Panel</u>

<u>Panel:</u>

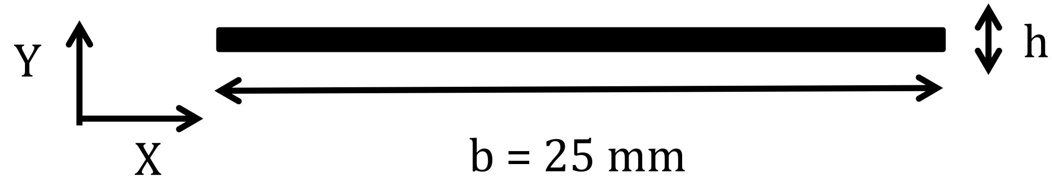
b fixed
h free

Since A = bh

$$h = \frac{A}{b}$$

$$I = \frac{b \cdot \left(\frac{A}{b}\right)^3}{12} = \frac{A^3}{12 \cdot b^2}$$

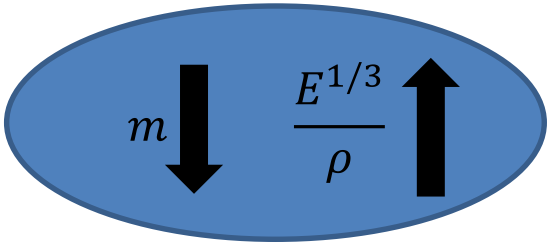
$$\begin{cases} S_{min} \leq \dfrac{C_1 E I}{L^3} \\ A = \dfrac{m}{L \cdot \rho} \end{cases}$$



$$\begin{cases} A = \dfrac{m}{L \cdot \rho} \\ m \geq \left(\dfrac{12 \cdot S \cdot b^2}{C_1}\right)^{1/3} \cdot L^2 \cdot \dfrac{\rho}{E^{1/3}} \end{cases}$$

The Area will be the Free Variable, but all the consequences of the selection are on the thickness

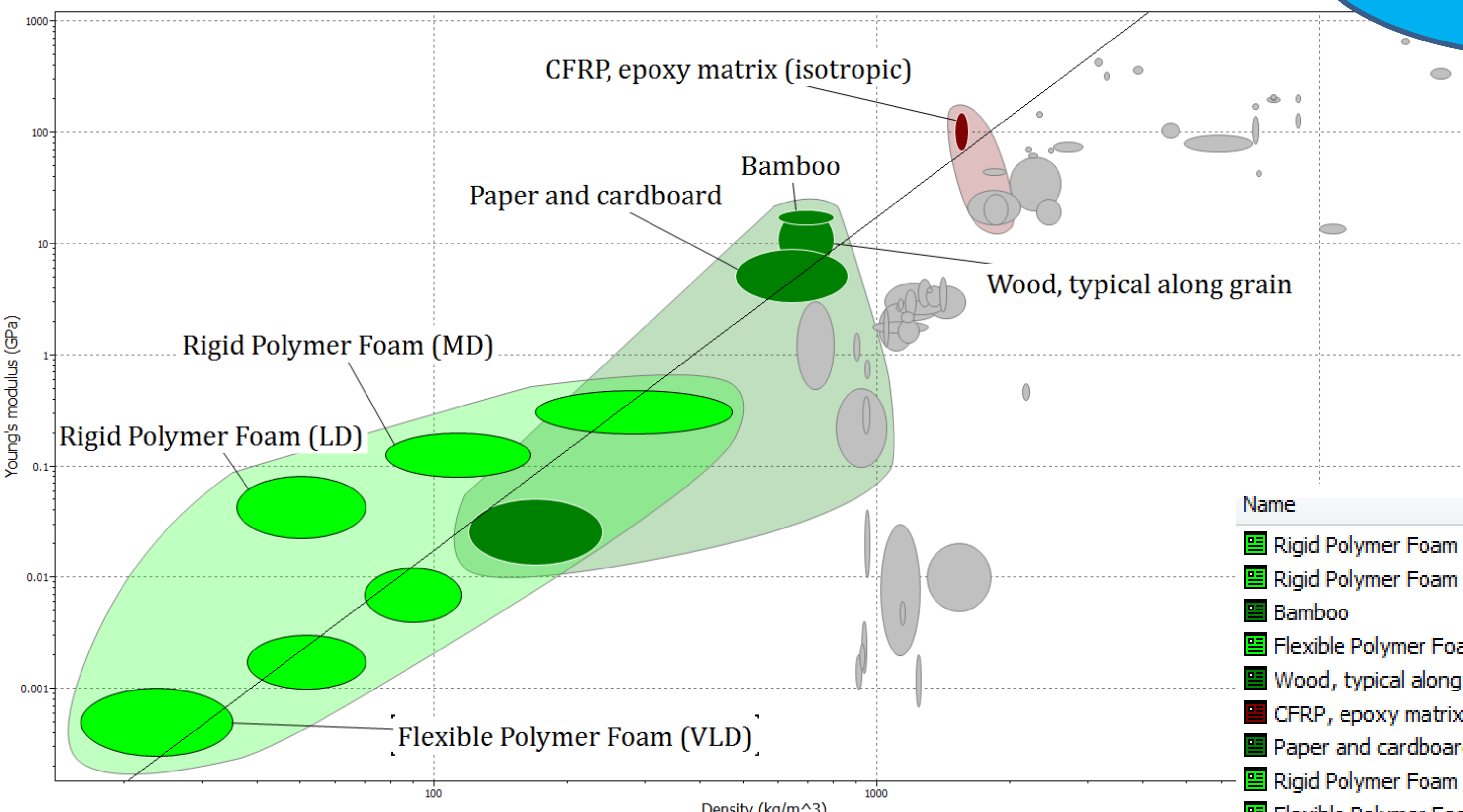
$$h = \frac{A}{b}$$



CES

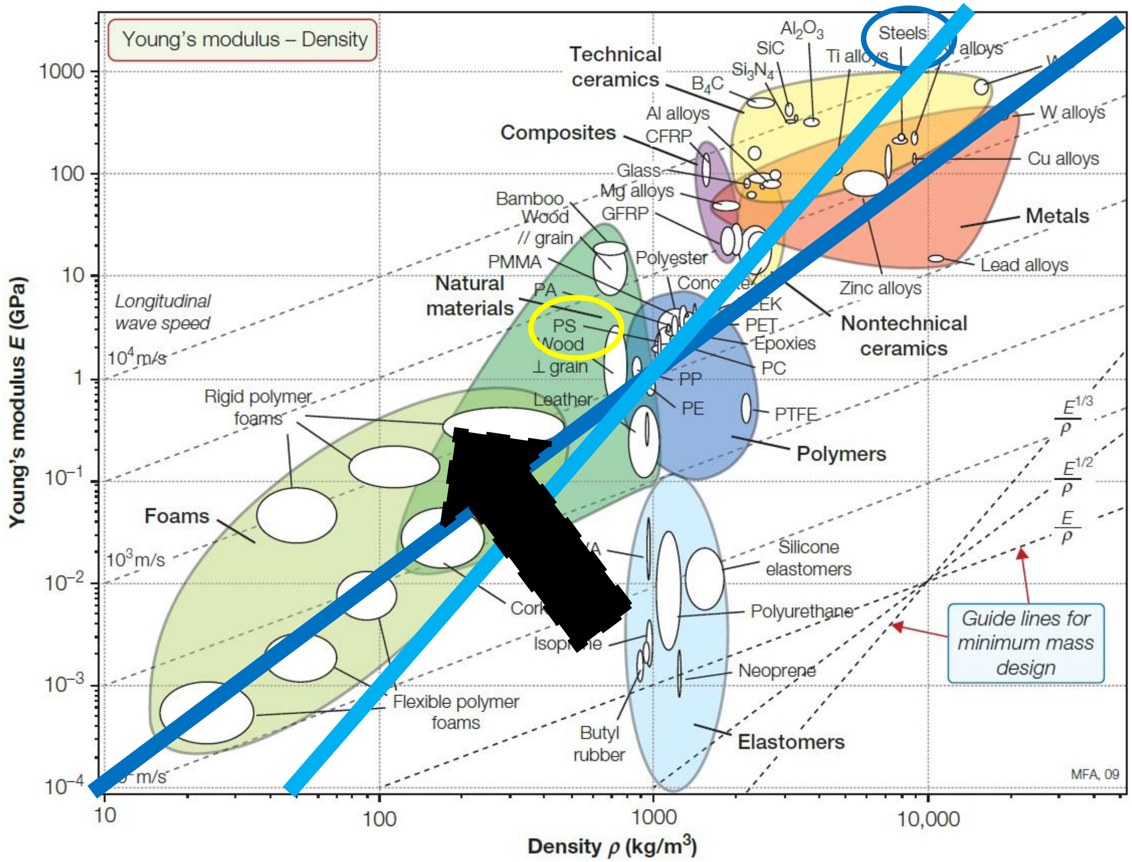
Case Study 3:
Find the Lightest STIFF <u>Panel</u>

$m \downarrow \quad \frac{E^{1/3}}{\rho} \uparrow$



Name	Stage 1: Index
Rigid Polymer Foam (LD)	0.00697
Rigid Polymer Foam (MD)	0.00442
Bamboo	0.00373
Flexible Polymer Foam (VLD)	0.00335
Wood, typical along grain	0.00321
CFRP, epoxy matrix (isotropic)	0.00301
Paper and cardboard	0.00269
Rigid Polymer Foam (HD)	0.00239
Flexible Polymer Foam (LD)	0.00233
Flexible Polymer Foam (MD)	0.00212
Cork	0.00173

Bending conditions



$m \downarrow \quad \frac{E^{1/2}}{\rho} \uparrow$

$m \downarrow \quad \frac{E^{1/3}}{\rho} \uparrow$

Stainless Steel
(E = 200 GPa; ρ = 7800 kg/m^3)
Polystyrene
(E = 2 GPa; ρ = 1040 kg/m^3)

Bending conditions

F = 100 N
δ = 0,34 mm
S_{min}= 296 · 10^3 N/m

Stainless Steel (E = 200 GPa; ρ = 7800 kg/m^3)
Polystyrene (E = 2 GPa; ρ = 1040 kg/m^3)

	Material	Weight (kg)	A (mm^2)	Thickness h (mm)
Beam	Stainless Steel	0,935	400	20
	Polystyrene	1,25	4000	63
Panel (b= 25 mm)	Stainless Steel	1,09	466	21,59
	Polystyrene	0,67	2147	46,34

Stiffness Summary

↑	$\frac{E}{\rho}$	$\frac{E^{1/2}}{\rho}$	$\frac{E^{1/3}}{\rho}$

To

m ↓ $At\ fixed\ S_{min}$

S_{min} ↑

δ_{max} ↓ $At\ fixed\ m$

Stiffness – Traction :

Name	Stage 1: Index
Silicon carbide	0.136
Aluminum nitride	0.0984
Alumina	0.094
CFRP, epoxy matrix (isotropic)	0.0657
Silicon	0.0634
Tungsten carbides	0.0425
Silica glass	0.0323
Soda-lime glass	0.0284
Borosilicate glass	0.0278
Aluminum alloys	0.0277
Bamboo	0.025
Wood, typical along grain	0.0158

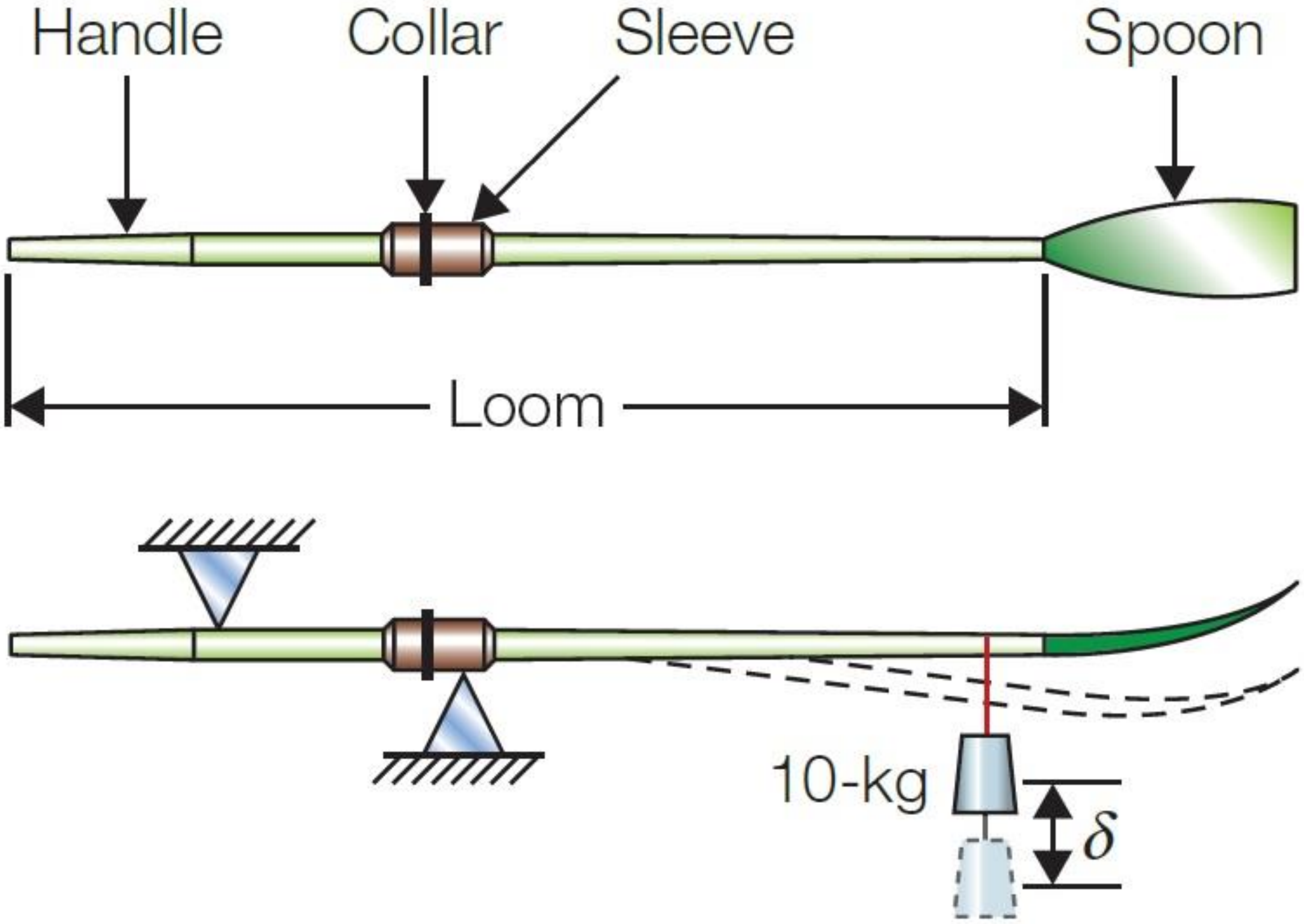
Stiffness – Bending :

Name	Stage 1: Index
Silicon carbide	0.00657
CFRP, epoxy matrix (isotropic)	0.00651
Bamboo	0.00601
Aluminum nitride	0.00546
Silicon	0.00522
Alumina	0.00492
Wood, typical along grain	0.00478
Rigid Polymer Foam (LD)	0.00413
Silica glass	0.00384
Magnesium alloys	0.00362
Paper and cardboard	0.00354
Rigid Polymer Foam (MD)	0.00314

Stiffness – Bending :

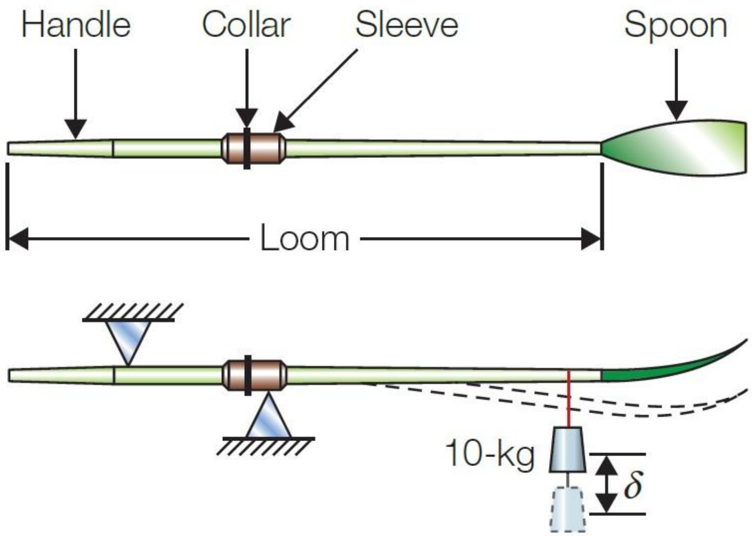
Name	Stage 1: Index
Rigid Polymer Foam (LD)	0.00697
Rigid Polymer Foam (MD)	0.00442
Bamboo	0.00373
Flexible Polymer Foam (VLD)	0.00335
Wood, typical along grain	0.00321
CFRP, epoxy matrix (isotropic)	0.00301
Paper and cardboard	0.00269
Rigid Polymer Foam (HD)	0.00239
Flexible Polymer Foam (LD)	0.00233
Flexible Polymer Foam (MD)	0.00212
Cork	0.00173

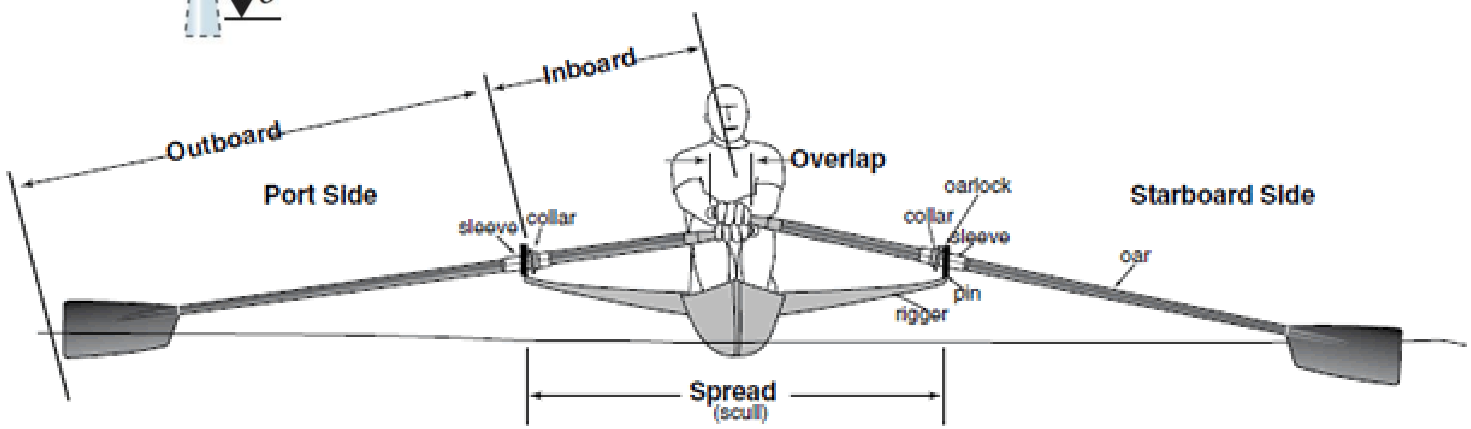
Case Study 4: Materials for Oars



Case Study 4:
Materials for Oars

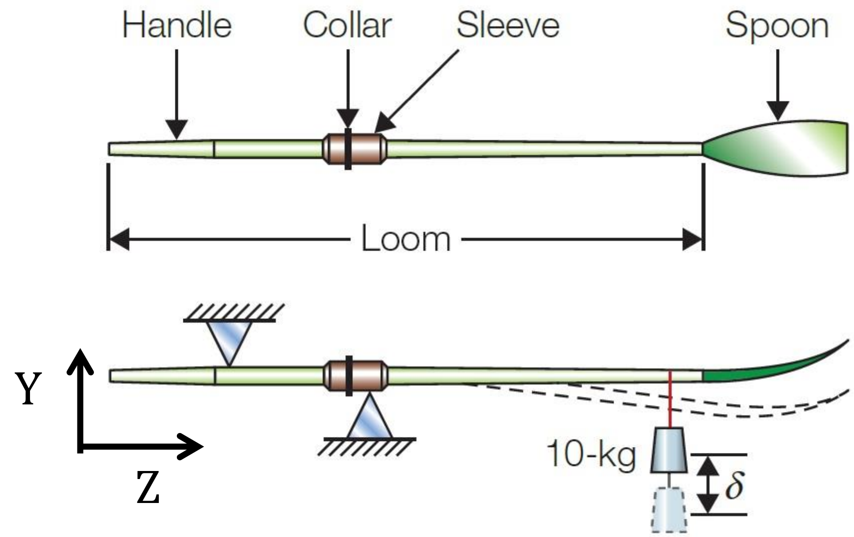
Objective	• Minimize the mass
Constraints	• Stiffness specified • Length L • Circular shape (beam)
Free Variables	• Area (A) of the cross-section • Choice of the material





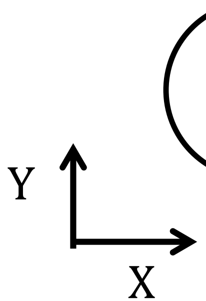
L (Outboard) = 2 m

Case Study 4: Materials for Light Oars



We assume solid section

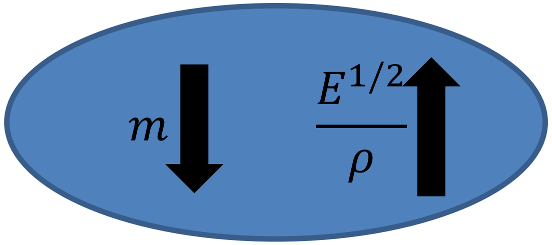
$$A = \pi \cdot r^2$$



$$I = \frac{\pi r^4}{4} = \frac{A^2}{4\pi}$$

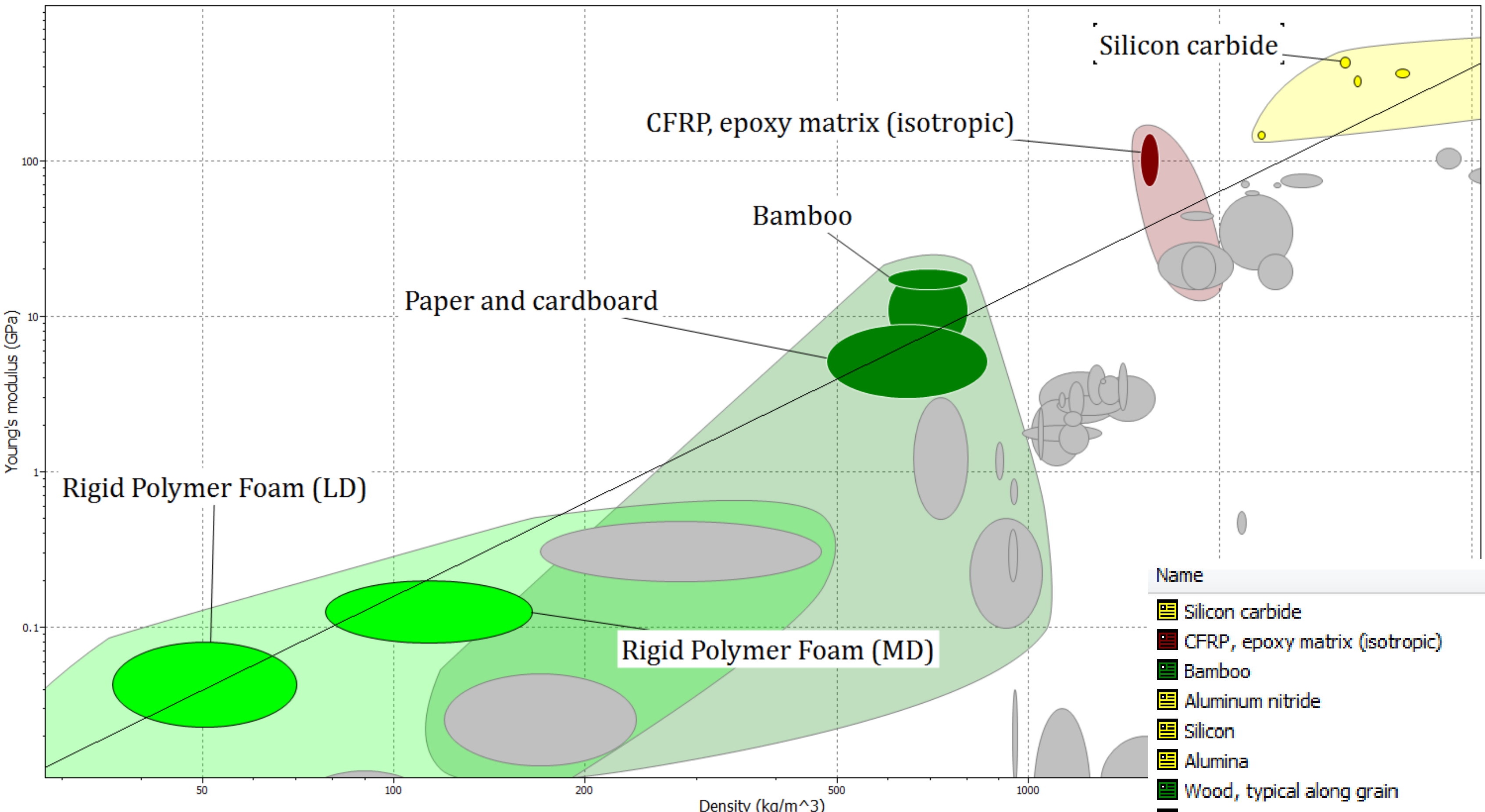
$$\begin{cases} \frac{F}{\delta} \geq S_{min} = \frac{C_1 EI}{L^3} \\ A = \frac{m}{L \cdot \rho} \end{cases}$$

$$\begin{cases} A = \frac{m}{L \cdot \rho} \\ m \geq \left(\frac{4 \cdot \pi \cdot S \cdot L^5}{3}\right)^{1/2} \cdot \frac{\rho}{E^{1/2}} \end{cases}$$



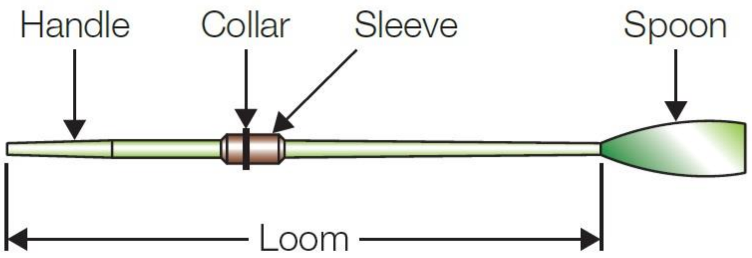
Case Study 4:
Materials for Light Oars

$m \downarrow$ $\quad \dfrac{E^{1/2}}{\rho} \uparrow$



Name	Stage 1: Index
Silicon carbide	0.00657
CFRP, epoxy matrix (isotropic)	0.00651
Bamboo	0.00601
Aluminum nitride	0.00546
Silicon	0.00522
Alumina	0.00492
Wood, typical along grain	0.00478
Rigid Polymer Foam (LD)	0.00413
Paper and cardboard	0.00354
Rigid Polymer Foam (MD)	0.00314

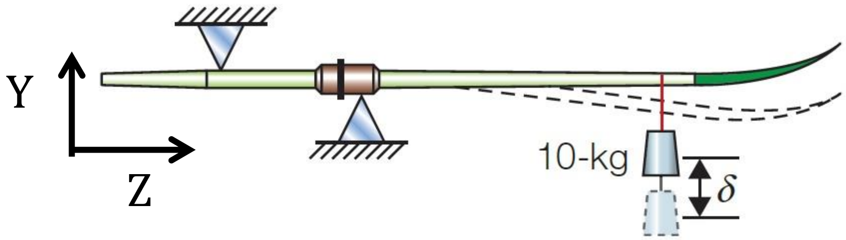
Case Study 4:
Materials for Light and Slender Oars

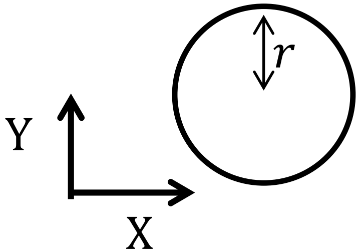


We assume solid section

$$A = \pi \cdot r^2$$

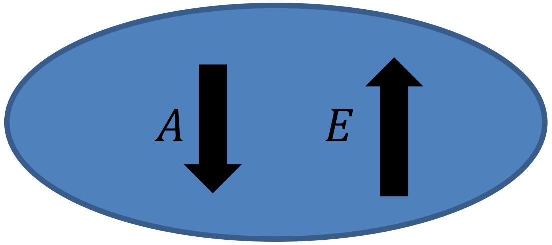
$$I = \frac{\pi r^4}{4} = \frac{A^2}{4\pi}$$





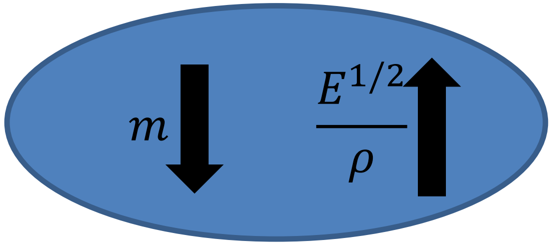
$$\begin{cases} \frac{F}{\delta} \geq S_{min} = \frac{C_1 E I}{L^3} \\ I = \frac{\pi r^4}{4} = \frac{A^2}{4\pi} \end{cases}$$

$$A \leq \left(\frac{4 \cdot \pi \cdot S \cdot L^3}{3}\right)^{1/2} \cdot \frac{1}{E^{1/2}}$$



Place LIMITS to a single Property
Evaluating the Properties Chart ➡ 10 Gpa < E < <u>200 GPa</u>

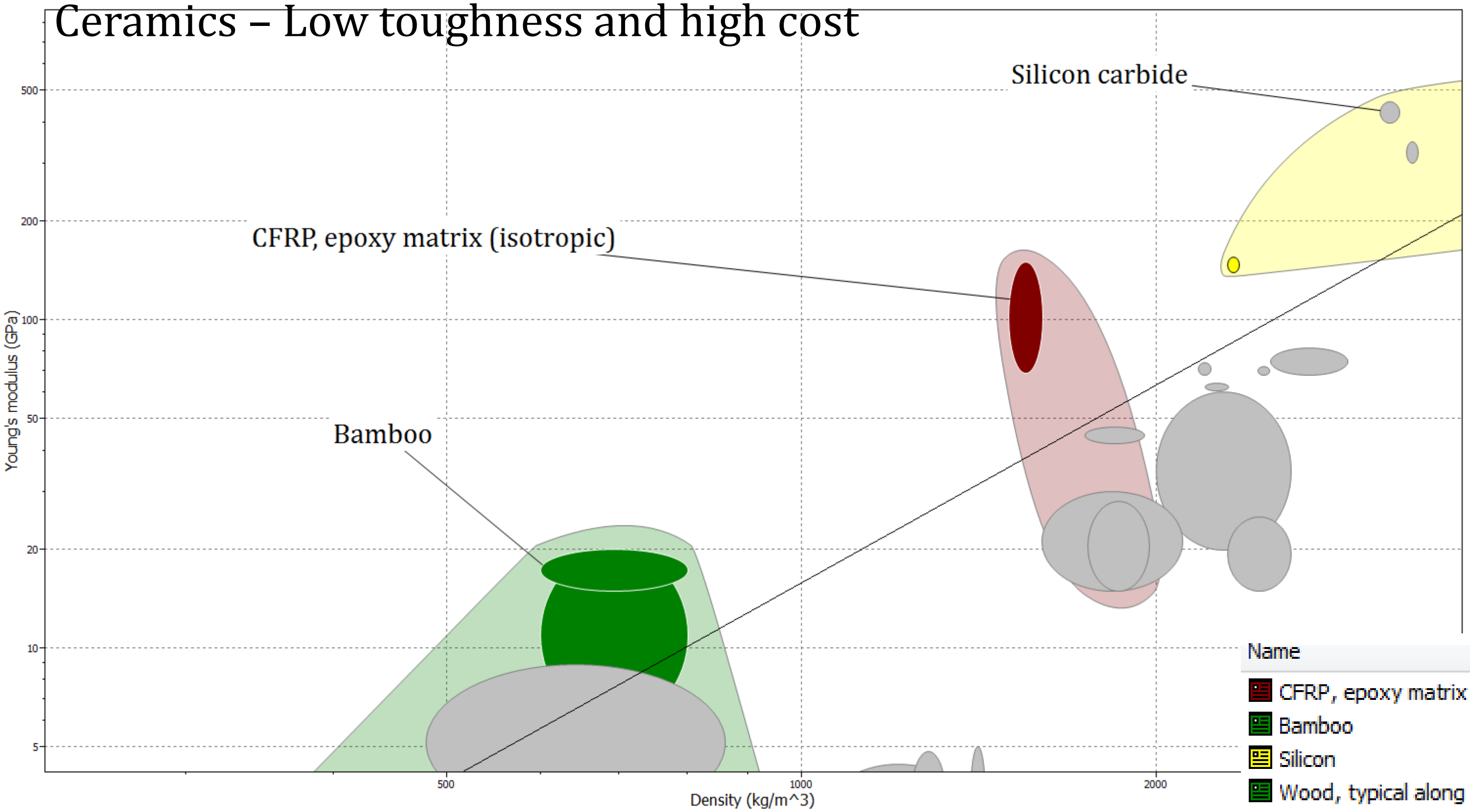
Case Study 4: Materials for Light and Slender Oars



\+

10 Gpa < E < 200 GPa

CFRP - best material with more control of the properties
Bamboo – Traditional material for oars for canoes
Woods – Traditional, but with natural variabilities
Ceramics – Low toughness and high cost

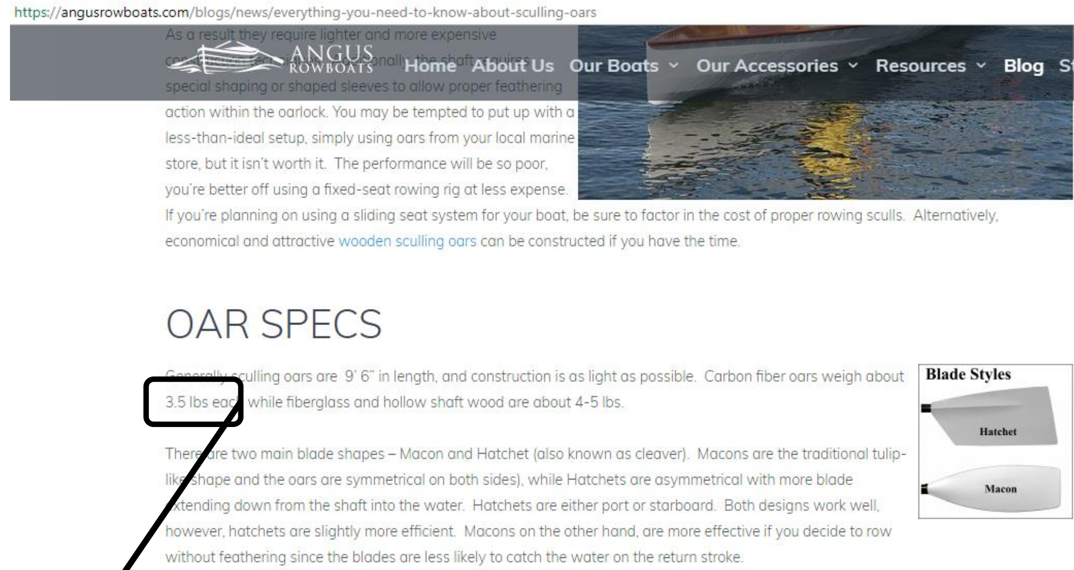


Name	Stage 1: Index
CFRP, epoxy matrix (isotropic)	0.00651
Bamboo	0.00601
Silicon	0.00522
Wood, typical along grain	0.00478

Case Study 4:
Materials for Light and Slender Oars

$$Solid\ I = \frac{\pi r^4}{4} = \frac{A^2}{4\pi}$$

$$Tube\ I = \pi r^3 t$$



1,58 kg
Probably Tube shape
Assume 2,5 kg for a Solid Oar (exagerated)

$$S \geq \frac{3 \cdot m^2}{4 \cdot \pi \cdot L^5} \cdot \frac{E}{\rho^2}$$

CFRP (E = 110 GPa; ρ = 1550 kg/m^3)
Bamboo (E = 17,5 GPa; ρ = 700 kg/m^3)

S_{CFRP} = 853,94 N/m
S_{Bamboo} = 666,1 N/m

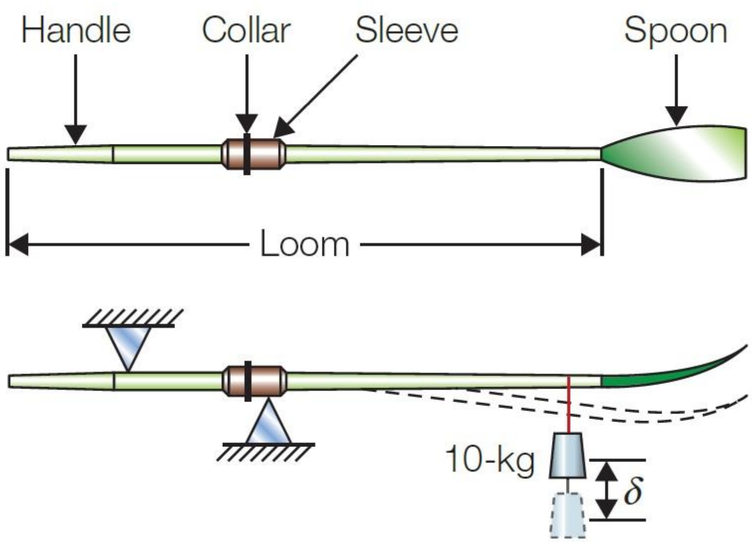
m ⬇ *At fixed* S_{min}

S_{min} ⬆
δ_{max} ⬇ *At fixed* m

CFRP good for Competition Oar

Case Study 5: Materials for CHEAP and Slender Oars

Objective	• Minimize the cost
Constraints	• Stiffness specified • Length L • Circular shape (beam)
Free Variables	• Area (A) of the cross-section • Choice of the material



L (Outboard) = 2 m

Case Study 5:
Materials for CHEAP and Slender Oars

$$\begin{cases} m \geq \left(\dfrac{4 \cdot \pi \cdot S \cdot L^5}{3}\right)^{1/2} \cdot \dfrac{\rho}{E^{1/2}} \\ C = m \cdot C_m \end{cases}$$

$$C = m \cdot C_m \longrightarrow m = \frac{C}{C_m}$$

$$C \geq \left(\frac{4 \cdot \pi \cdot S \cdot L^5}{3}\right)^{1/2} \cdot \frac{\rho \cdot C_m}{E^{1/2}}$$

$C \downarrow \quad \dfrac{E^{1/2}}{\rho \cdot C_m} \uparrow$

$\boldsymbol{C}$ *Cost*

$\boldsymbol{C_m}$ Cost per unit of mass

↓

Better to consider cost always as a function of mass

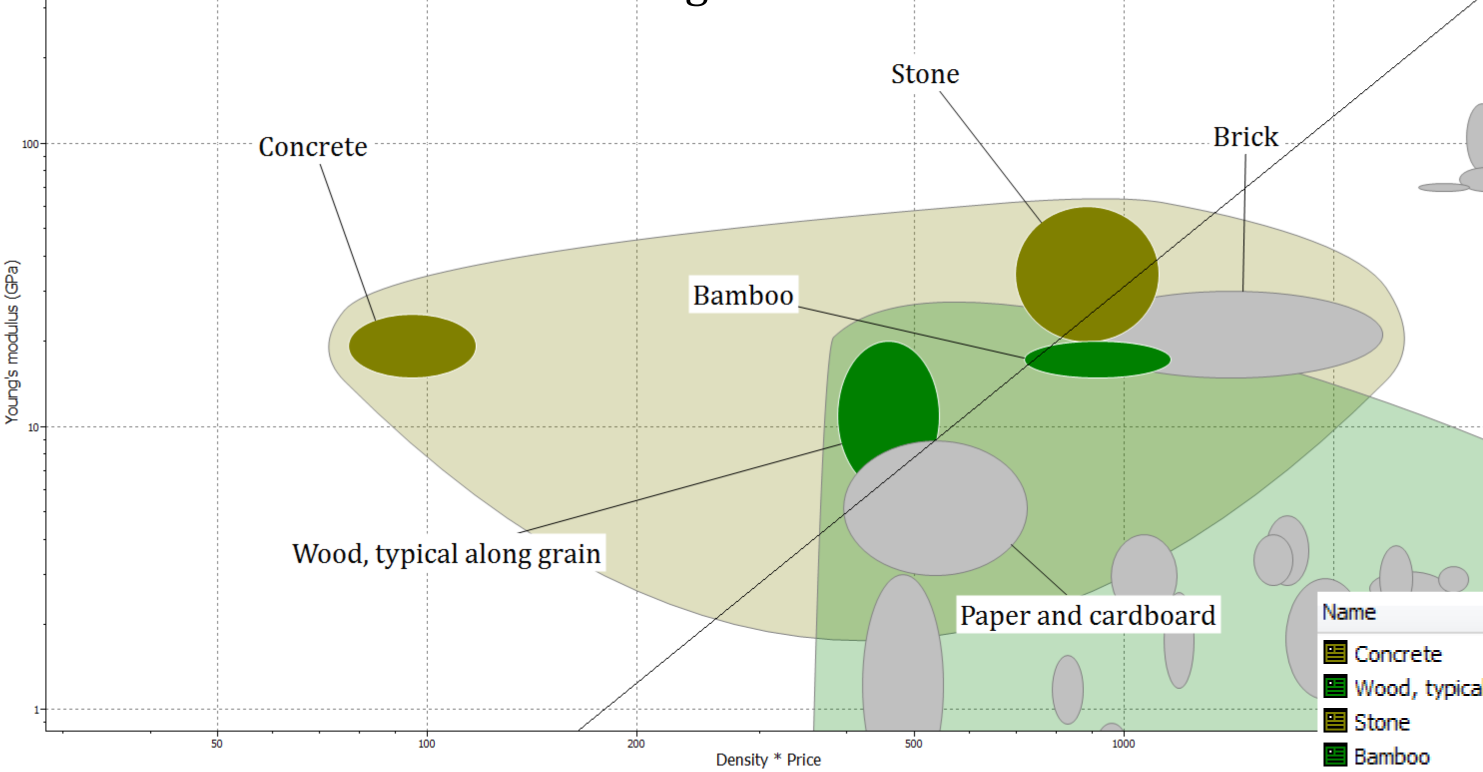
Case Study 5:
Materials for CHEAP and Slender Oars

$$C \downarrow \quad \frac{E^{1/2}}{\rho \cdot C_m} \uparrow$$

$+$

10 Gpa < E < 200 GPa

Bamboo – Traditional material for oars for canoes
Woods – Traditional, but with natural variabilities
Stone and Concrete – Low toughness and difficult to manufacture



Name	Stage 1: Index
Concrete	0.0464
Wood, typical along grain	0.00722
Stone	0.00665
Bamboo	0.00455

Case Study 5:
Materials for CHEAP and Slender Oars

$$\begin{cases} m \geq \left(\frac{4 \cdot \pi \cdot S \cdot L^5}{3}\right)^{1/2} \cdot \frac{\rho}{E^{1/2}} \\ C = m \cdot C_m \end{cases}$$

$C = m \cdot C_m \longrightarrow m = \frac{C}{C_m}$

$$C \geq \left(\frac{4 \cdot \pi \cdot S \cdot L^5}{3}\right)^{1/2} \cdot \frac{\rho \cdot C_m}{E^{1/2}}$$

$\boldsymbol{C}$ *Cost*

$\boldsymbol{C_m}$ Cost per unit of mass

↓

Better to consider cost always as a function of mass

$C \downarrow \quad \frac{E^{1/2}}{\rho \cdot C_m} \uparrow$

Woods good for Commercial Oar

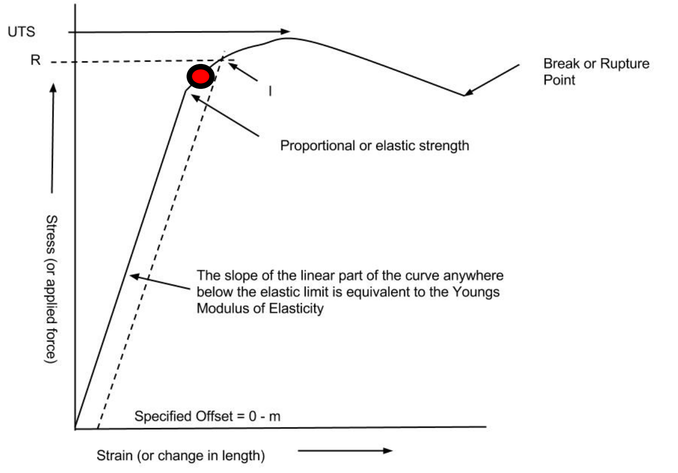
The Strength design

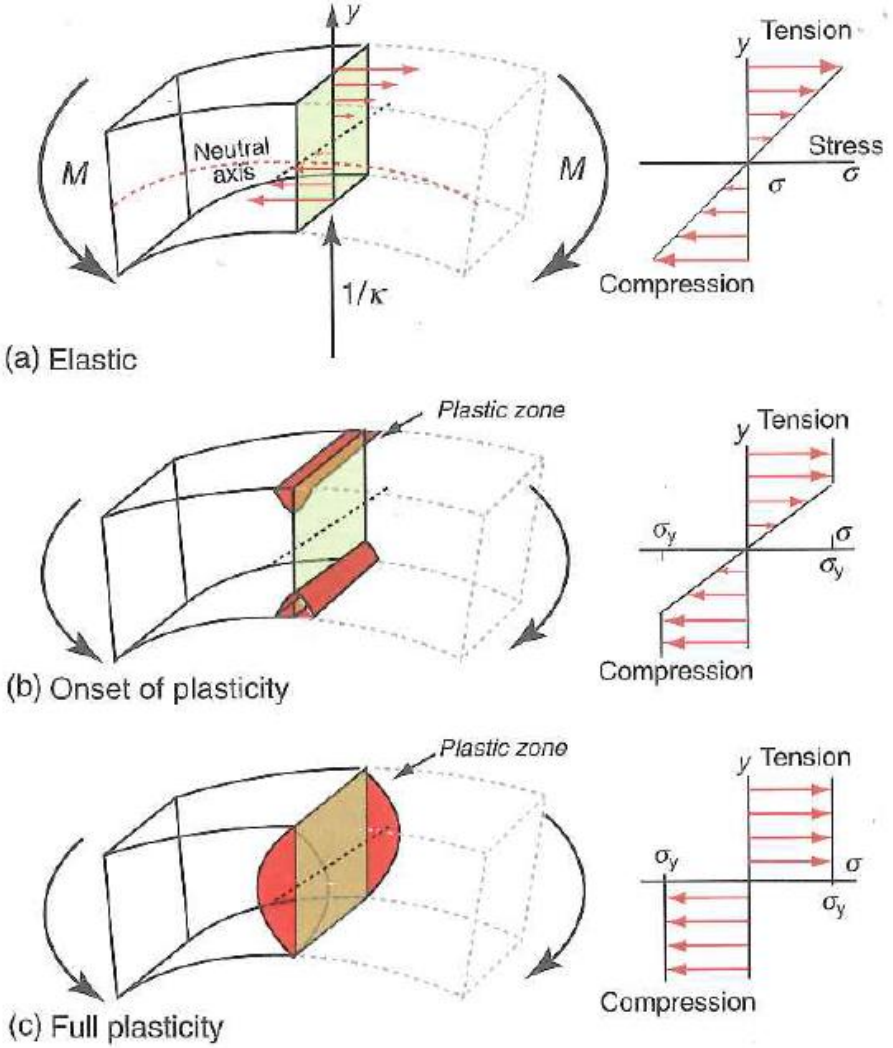
The Strength design is important to avoid plastic collapse… or maybe not

The Strength design

The Strength design is important to avoid plastic collapse

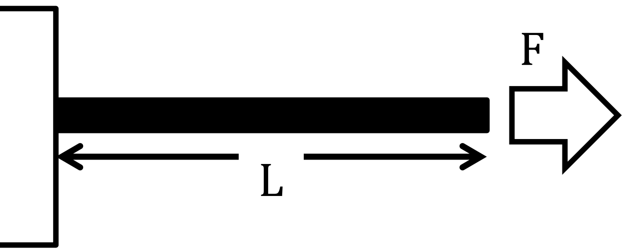
Your are here





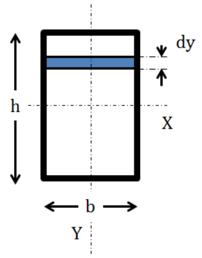
Lightest Tie-Rod (Traction conditions)

Case Study 6:
Find the Lightest STRONG <u>Tie-Rod</u>



Objective	• Minimize the mass
Constraints	• Support tensile load F without yielding • Length L
Free Variables	• Area (A) of the cross-section • Choice of the material

DATA
F =1000 N
Dimensions:
Length: 300 mm
Thickness = 1 mm
Width = 25 mm



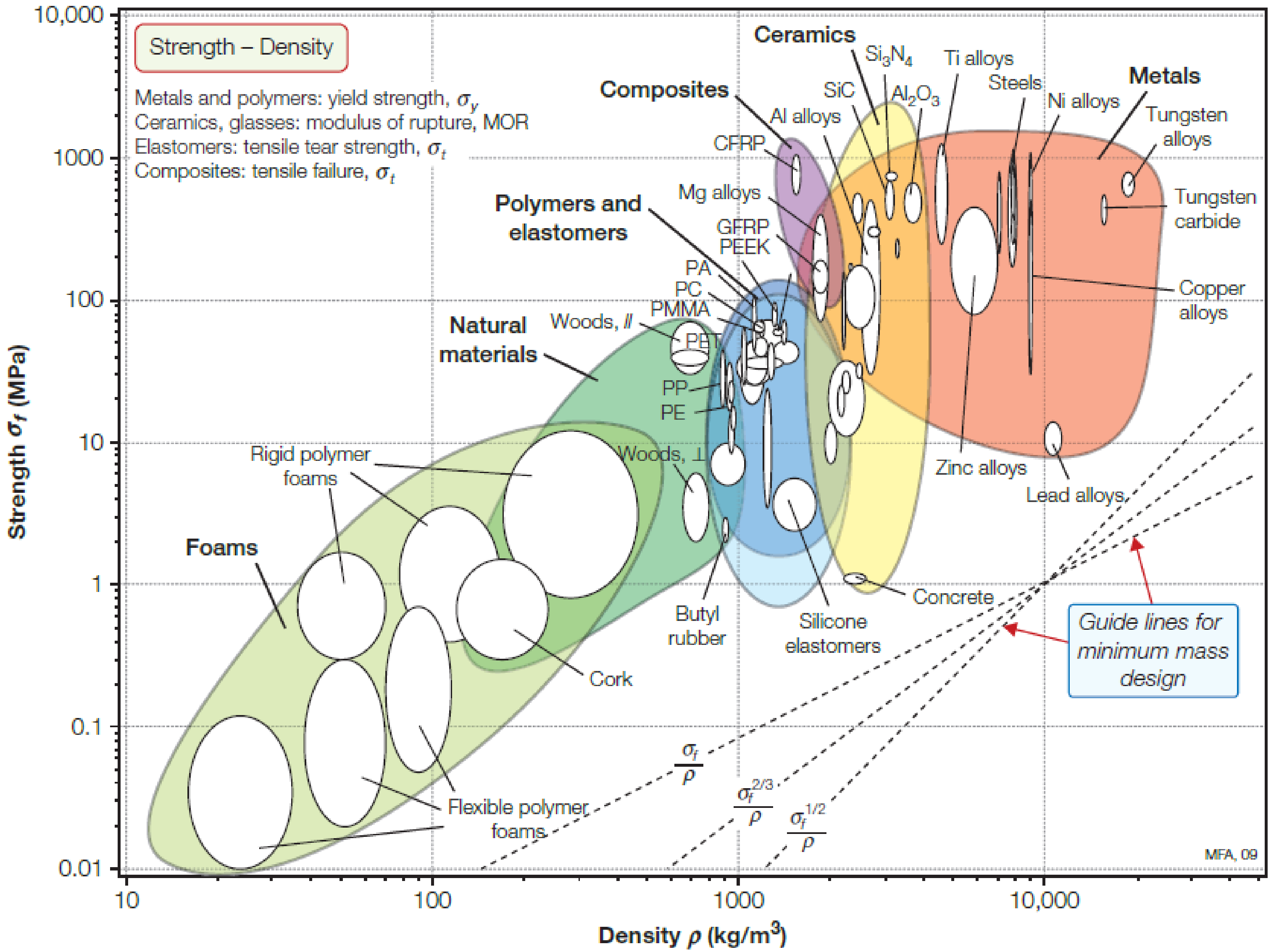
In Traction,
the shape of the cross-section is not important

$$m = A \cdot L \cdot \rho \longrightarrow A = \frac{m}{L \cdot \rho}$$

$$From\ material: \frac{F}{A} \leq \sigma_y$$

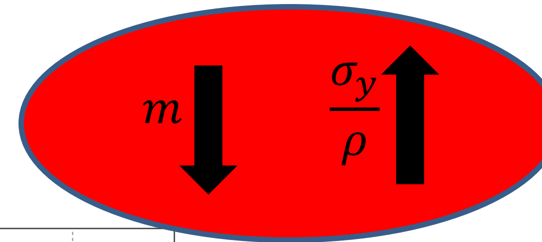
$$\Rightarrow m \geq F \cdot L \cdot \frac{\rho}{\sigma_y}$$

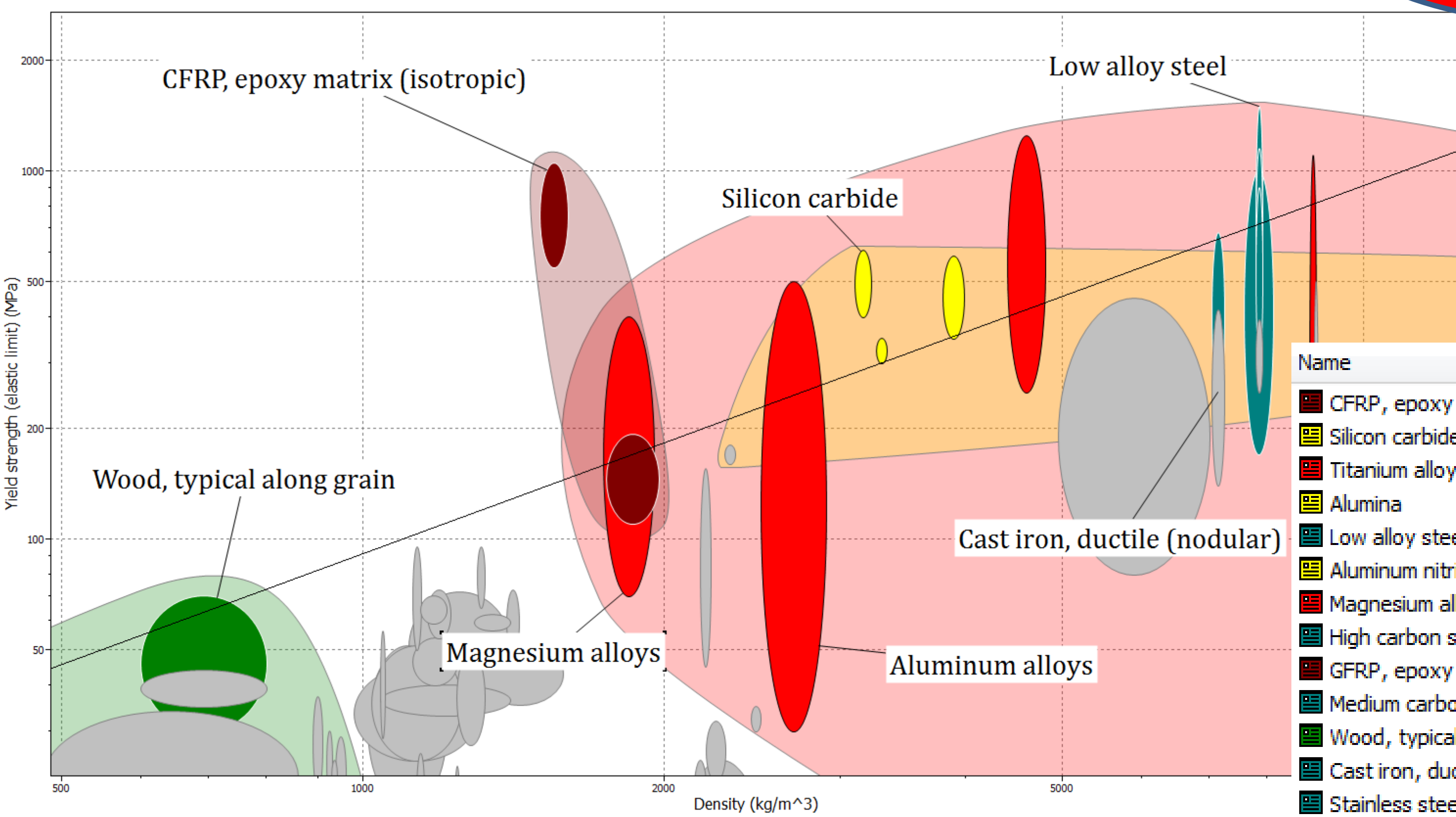
Ashby Diagrams



CES

Case Study 6:
Find the Lightest STRONG <u>Tie-Rod</u>

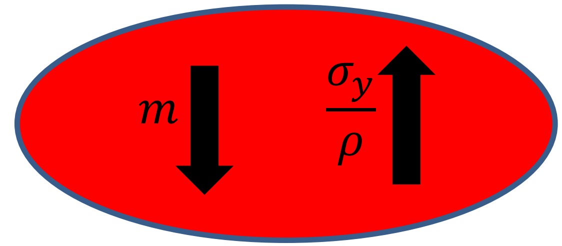




Name	Stage 1: Index
CFRP, epoxy matrix (isotropic)	0.491
Silicon carbide	0.157
Titanium alloys	0.121
Alumina	0.117
Low alloy steel	0.0987
Aluminum nitride	0.0983
Magnesium alloys	0.0908
High carbon steel	0.0866
GFRP, epoxy matrix (isotropic)	0.0783
Medium carbon steel	0.0667
Wood, typical along grain	0.0661
Cast iron, ductile (nodular)	0.0577
Stainless steel	0.0526
Aluminum alloys	0.0455
Nickel alloys	0.0312

Lightest Tie-Rod (Traction conditions)

Case Study 6:
Find the Lightest STRONG Tie-Rod



$$m \geq F \cdot L \cdot \frac{\rho}{\sigma_y}$$

It is possible to do as before, but let's calculate the maximum F on the precedent Tie-Rod

Material	Weight (kg)	Width and Thickness (mm)
Al Alloys	1,25	63

Stainless Steel (σ_y = 600 MPa; ρ = 7800 kg/m^3)
Wood (σ_y = 50 MPa; ρ = 700 kg/m^3)
Al Alloys (σ_y = 270 Mpa; ρ = 75 kg/m^3)

$$F \leq \frac{m}{L} \cdot \frac{\sigma_y}{\rho} = 416\ kN$$

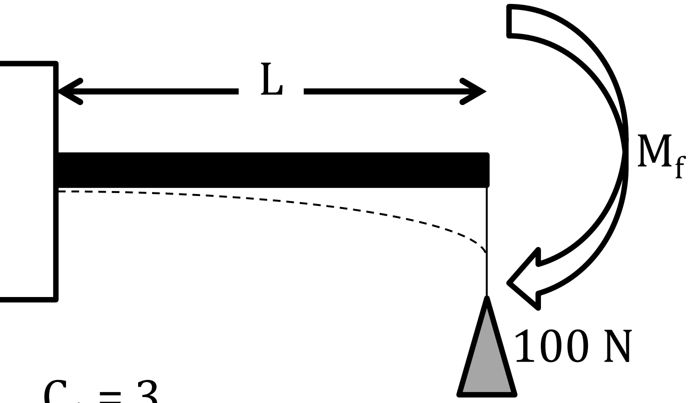
0 kN → **X kN**

Elastic Throughout | **Plastic deformation/ Collapse**

Lightest Beam (Bending conditions)

Case Study 7:
Find the Lightest STRONG Beam

Objective	• Minimize the mass
Constraints	• Stiffness specified • Length L • Square shape
Free Variables	• Area (A) of the cross-section • Choice of the material



$C_1 = 3$

Length: 300 mm

Hypothesis:

- $y_{max} = h/2$
- $\sigma_{max} \geq \sigma$

M = Moment
σ = Stress
y_{max} = max distance from the neutral axis → σ_{max}

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

$$m = A \cdot L \cdot \rho \longrightarrow A = \frac{m}{L \cdot \rho}$$

<u>Beam: Square Section</u>

b=h

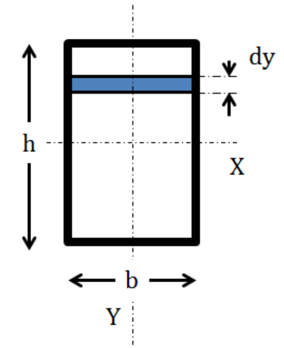
Since $A = b^2$

$$I = \frac{bh^3}{12} \twoheadrightarrow \frac{A^{3/2}}{6}$$

Lightest Beam (Bending conditions)

Case Study 7:
Find the Lightest STRONG Beam

$$I' = \frac{bh^2}{6} \, -\!\gg \, \frac{A^{3/2}}{6}$$

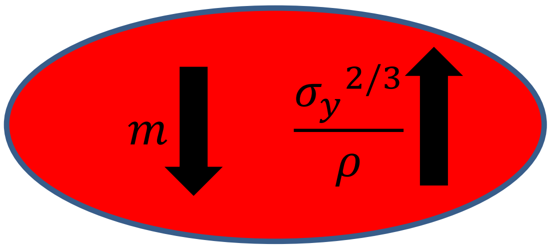


$$\begin{cases} \sigma_{max} = \dfrac{M_f \cdot y_{max}}{I} = \dfrac{M_f \cdot \frac{h}{2}}{\frac{bh^3}{12}} = \dfrac{M_f}{I'} \leq \sigma_f \\ m = A \cdot L \cdot \rho \longrightarrow A = \dfrac{m}{L \cdot \rho} \end{cases}$$

$$\sigma_f \geq \frac{M_f \cdot 6}{A^{3/2}} = \frac{M_f \cdot 6 \cdot L^{3/2} \cdot \rho^{3/2}}{m^{3/2}}$$

$$\downarrow$$

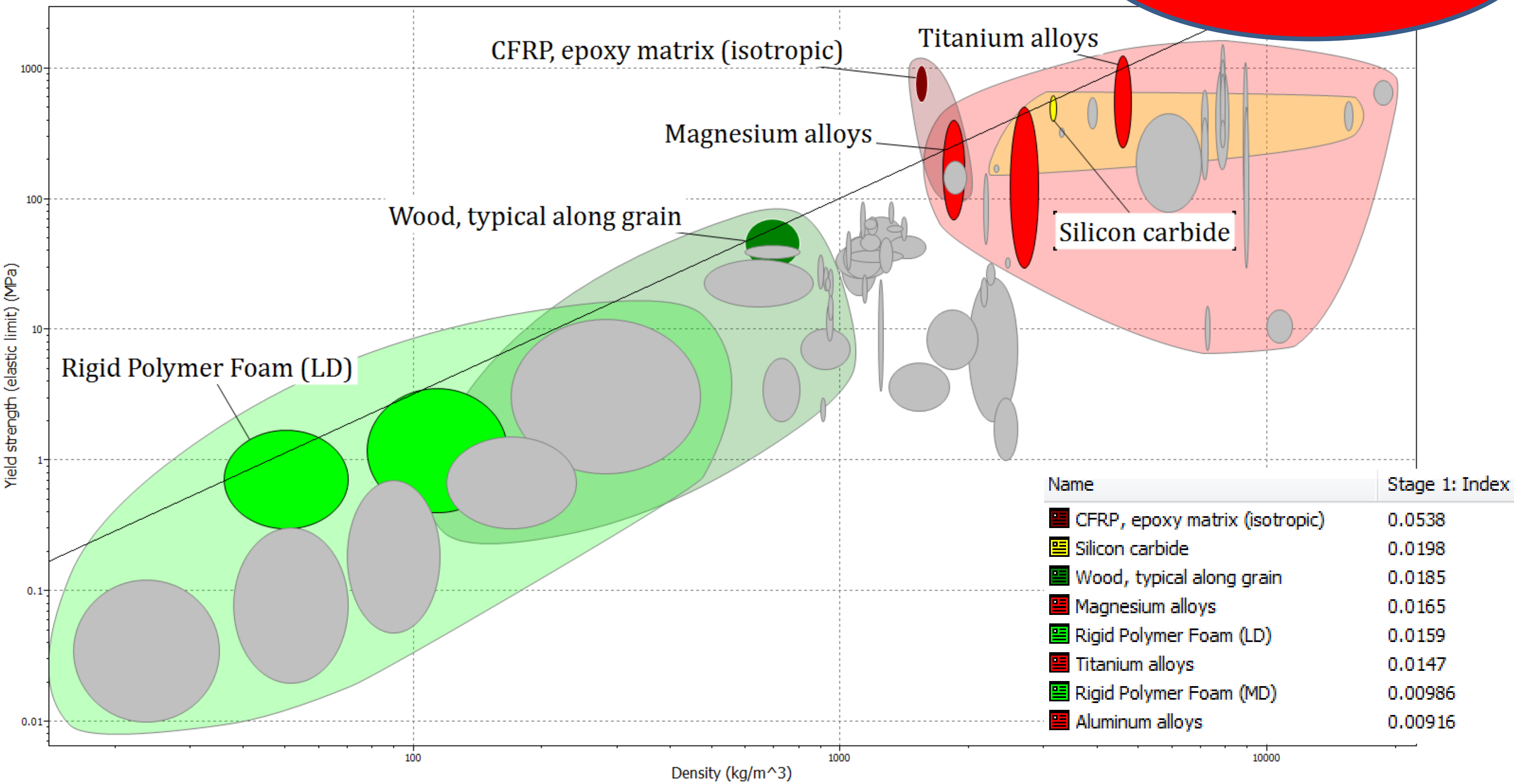
$$m \geq (M_f \cdot 6)^{2/3} \cdot \mathrm{L} \cdot \frac{\rho}{{\sigma_f}^{2/3}}$$



CES

Case Study 7:
Find the Lightest STRONG Beam

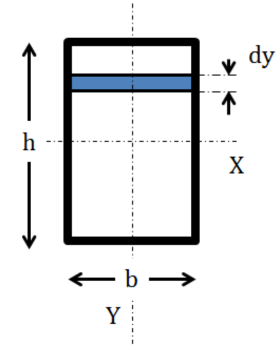
$m \downarrow \qquad \frac{\sigma_y^{2/3}}{\rho} \uparrow$



Lightest Beam (Bending conditions)

Case Study 7:
Find the Lightest STRONG Beam

$$I' = \frac{bh^2}{6} \gg \frac{A^{3/2}}{6}$$



$$\sigma_{max} = \frac{M_f \cdot y_{max}}{I} = \frac{M_f \cdot \frac{h}{2}}{\frac{bh^3}{12}} = \frac{M_f}{I'} \leq \sigma_f$$

$$m = A \cdot L \cdot \rho \longrightarrow A = \frac{m}{L \cdot \rho}$$

$$\sigma_f \geq \frac{M_f \cdot 6}{A^{3/2}} = \frac{M_f \cdot 6 \cdot L^{3/2} \cdot \rho^{3/2}}{m^{3/2}}$$

$$\downarrow$$

$$m \geq (M_f \cdot 6)^{2/3} \cdot \mathrm{L} \cdot \frac{\rho}{{\sigma_f}^{2/3}}$$

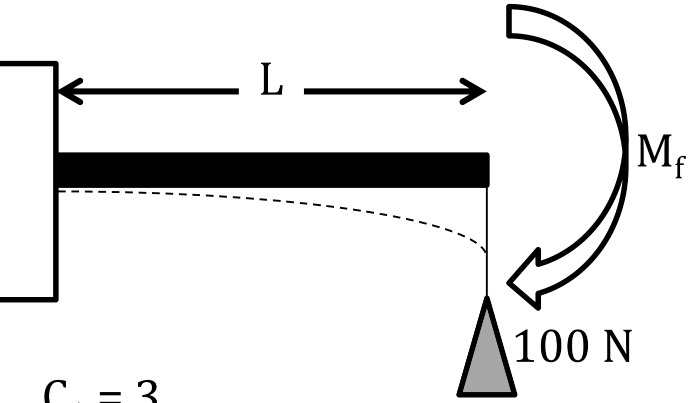
- **It is always better to choose a shape that uses less material to provide the same strength TO SUPPORT BENDING**

$m \downarrow \quad \frac{{\sigma_y}^{2/3}}{\rho} \uparrow$

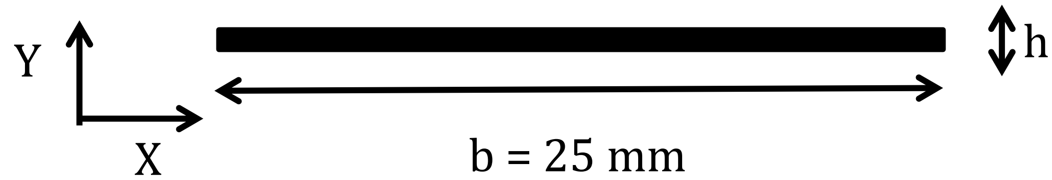
Lightest Panel (Bending conditions)

Case Study 8:
Find the Lightest STRONG Panel

Objective	• Minimize the mass
Constraints	• Stiffness specified • Length L and b specified
Free Variables	• h (thickness) of the cross-section • Choice of the material



$C_1 = 3$



Length: 300 mm

Hypothesis:
- $y_{max} = h/2$
- $\sigma_{max} \geq \sigma$

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

$$m = A \cdot L \cdot \rho \longrightarrow A = \frac{m}{L \cdot \rho}$$

$$I' = \frac{bh^2}{6} \gg \frac{A^2}{b \cdot 6}$$

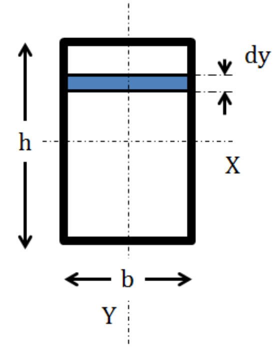
Since A = bh

$$h = \frac{A}{b}$$

Lightest Panel (Bending conditions)

Case Study 8:
Find the Lightest STRONG Panel

$$I' = \frac{bh^2}{6} \gg \frac{A^2}{b \cdot 6}$$

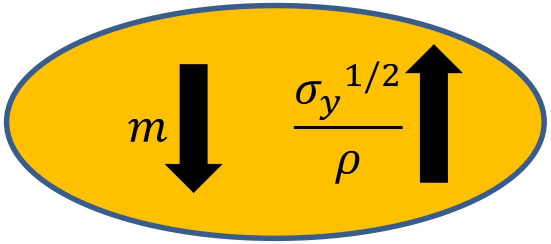


$$\begin{cases} \sigma_{max} = \dfrac{M_f \cdot y_{max}}{I} = \dfrac{M_f \cdot b \cdot 6}{A^2} = \dfrac{M_f}{I'} \leq \sigma_f \\ \boxed{m = A \cdot L \cdot \rho} \longrightarrow A = \dfrac{m}{L \cdot \rho} \end{cases}$$

$$\sigma_f \geq \frac{M_f \cdot b \cdot 6}{A^2} = \frac{M_f \cdot 6 \cdot b \cdot L^2 \cdot \rho^2}{m^2}$$

$$\downarrow$$

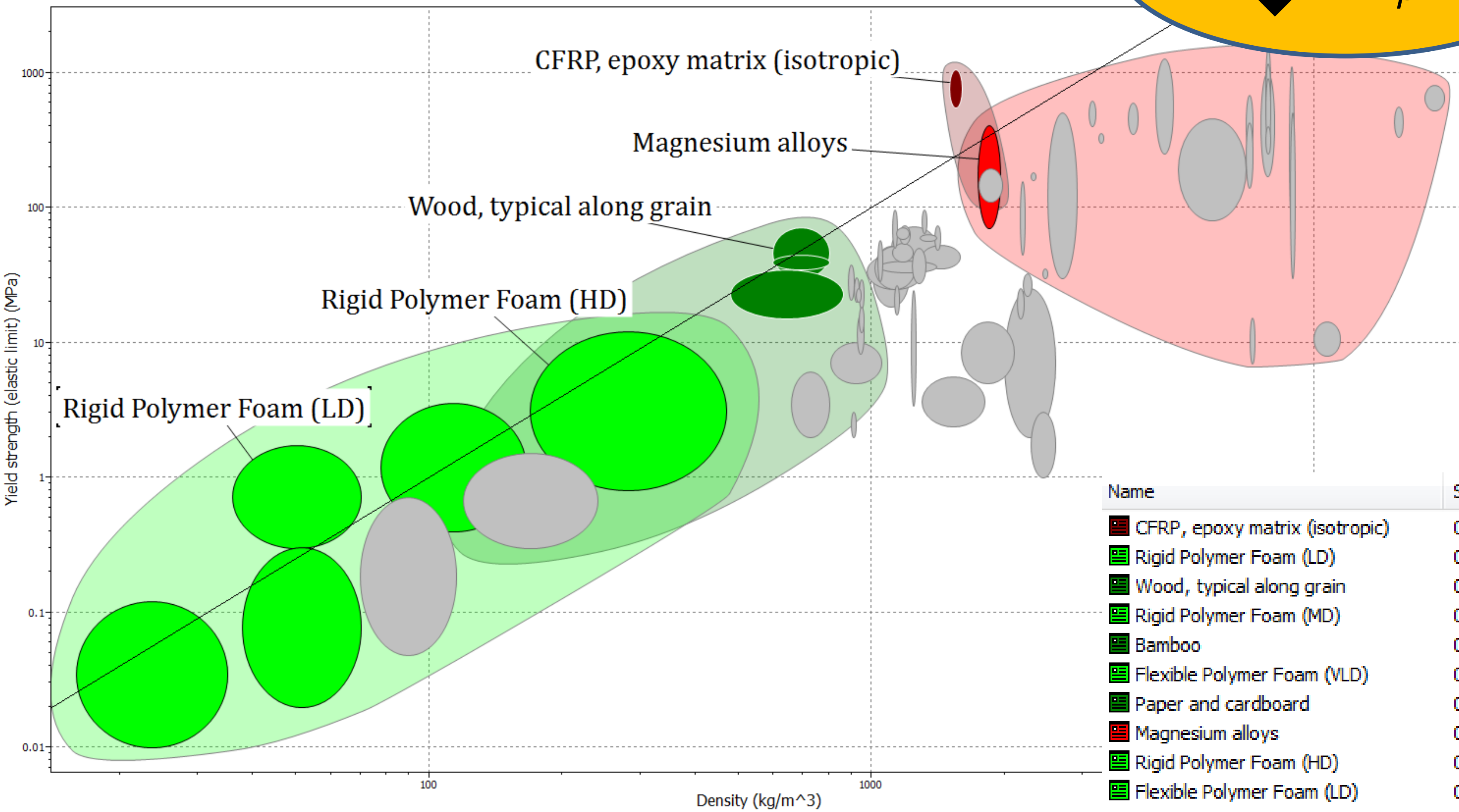
$$m \geq (M_f \cdot 6 \cdot b)^{1/2} \cdot \mathrm{L} \cdot \frac{\rho}{\sigma_f^{1/2}}$$



CES

Case Study 8:
Find the Lightest STRONG Panel

$m \downarrow \qquad \frac{\sigma_y^{1/2}}{\rho} \uparrow$

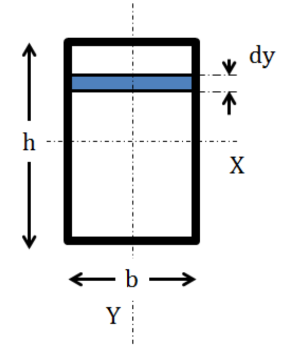


Name	Stage 1: Index
CFRP, epoxy matrix (isotropic)	0.0178
Rigid Polymer Foam (LD)	0.0168
Wood, typical along grain	0.00977
Rigid Polymer Foam (MD)	0.00959
Bamboo	0.00904
Flexible Polymer Foam (VLD)	0.00787
Paper and cardboard	0.0074
Magnesium alloys	0.00702
Rigid Polymer Foam (HD)	0.00623
Flexible Polymer Foam (LD)	0.0054

Lightest Panel (Bending conditions)

Case Study 8:
Find the Lightest STRONG Panel

$$I' = \frac{bh^2}{6} \gg \frac{A^{3/2}}{6}$$



$$\sigma_{max} = \frac{M_f \cdot y_{max}}{I} = \frac{M_f \cdot \frac{h}{2}}{\frac{bh^3}{12}} = \frac{M_f}{I'} \leq \sigma_f$$

$$m = A \cdot L \cdot \rho \longrightarrow A = \frac{m}{L \cdot \rho}$$

$$\sigma_f \geq \frac{M_f \cdot 6}{A^{3/2}} = \frac{M_f \cdot 6 \cdot L^{3/2} \cdot \rho^{3/2}}{m^{3/2}}$$

$$\downarrow$$

$$m \geq (M_f \cdot 6 \cdot b)^{1/2} \cdot \mathrm{L} \cdot \frac{\rho}{\sigma_f^{1/2}}$$

- **It is always better to choose a shape that uses less material to provide the same strength TO SUPPORT BENDING**

$$m \downarrow \quad \frac{\sigma_y^{1/2}}{\rho} \uparrow$$

Summary (to minimize the mass)

Stiffness – Traction :

Name	Stage 1: Index
Silicon carbide	0.136
Aluminum nitride	0.0984
Alumina	0.094
CFRP, epoxy matrix (isotropic)	0.0657
Silicon	0.0634
Tungsten carbides	0.0425
Silica glass	0.0323
Soda-lime glass	0.0284
Borosilicate glass	0.0278
Aluminum alloys	0.0277
Bamboo	0.025
Wood, typical along grain	0.0158

Stiffness – Bending (Beam):

Name	Stage 1: Index
Silicon carbide	0.00657
CFRP, epoxy matrix (isotropic)	0.00651
Bamboo	0.00601
Aluminum nitride	0.00546
Silicon	0.00522
Alumina	0.00492
Wood, typical along grain	0.00478
Rigid Polymer Foam (LD)	0.00413
Silica glass	0.00384
Magnesium alloys	0.00362
Paper and cardboard	0.00354
Rigid Polymer Foam (MD)	0.00314

Stiffness – Bending (Panel):

Name	Stage 1: Index
Rigid Polymer Foam (LD)	0.00697
Rigid Polymer Foam (MD)	0.00442
Bamboo	0.00373
Flexible Polymer Foam (VLD)	0.00335
Wood, typical along grain	0.00321
CFRP, epoxy matrix (isotropic)	0.00301
Paper and cardboard	0.00269
Rigid Polymer Foam (HD)	0.00239
Flexible Polymer Foam (LD)	0.00233
Flexible Polymer Foam (MD)	0.00212
Cork	0.00173

$\frac{E}{\rho}$	$\frac{E^{1/2}}{\rho}$	$\frac{E^{1/3}}{\rho}$
$\frac{\sigma_y}{\rho}$	$\frac{\sigma_y^{2/3}}{\rho}$	$\frac{\sigma_y^{1/2}}{\rho}$

Strength – Traction :

Name	Stage 1: Index
CFRP, epoxy matrix (isotropic)	0.491
Silicon carbide	0.157
Titanium alloys	0.121
Alumina	0.117
Low alloy steel	0.0987
Aluminum nitride	0.0983
Magnesium alloys	0.0908
High carbon steel	0.0866
GFRP, epoxy matrix (isotropic)	0.0783
Medium carbon steel	0.0667
Wood, typical along grain	0.0661
Cast iron, ductile (nodular)	0.0577
Stainless steel	0.0526
Aluminum alloys	0.0455
Nickel alloys	0.0312

Strength – Bending :

Name	Stage 1: Index
CFRP, epoxy matrix (isotropic)	0.0538
Silicon carbide	0.0198
Wood, typical along grain	0.0185
Magnesium alloys	0.0165
Rigid Polymer Foam (LD)	0.0159
Titanium alloys	0.0147
Rigid Polymer Foam (MD)	0.00986
Aluminum alloys	0.00916

Strength – Bending (Panel):

Name	Stage 1: Index
CFRP, epoxy matrix (isotropic)	0.0178
Rigid Polymer Foam (LD)	0.0168
Wood, typical along grain	0.00977
Rigid Polymer Foam (MD)	0.00959
Bamboo	0.00904
Flexible Polymer Foam (VLD)	0.00787
Paper and cardboard	0.0074
Magnesium alloys	0.00702
Rigid Polymer Foam (HD)	0.00623
Flexible Polymer Foam (LD)	0.0054

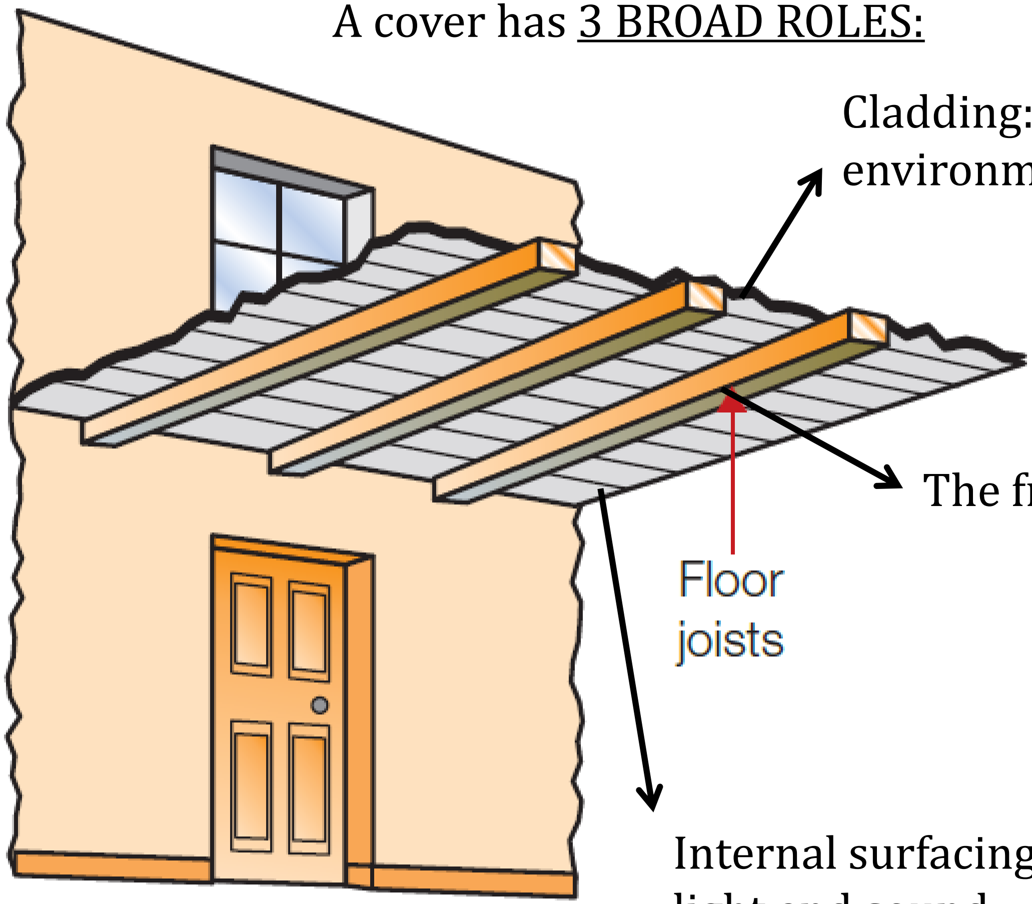
Case Study 9:
Materials for Constructions

Some data : Nowadays, half the expense of building a house is the cost of the materials
Family house : 200 tons
Large apartment block : 20,000 tons

Case Study 9:
Materials for Constructions

Mr. Pincopallo asks a new cover → Understand the problem and translate it in selection criteria, thus properties,

A cover has <u>3 BROAD ROLES:</u>



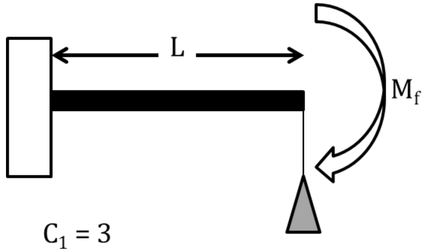
Cladding: Protection from the environment

The frames: Mechanical support

Internal surfacing: Control heat, light and sound

Case Study 9:
Materials for Constructions (Structural Frame)

Objective	• Minimize the cost
Constraints	• Length L specified • Stiffness: must not deflect too much under loads • Strength: must not fall under design loads
Free Variables	• Area (A) of the cross-section • Choice of the material



Hypothesis:

- $\frac{F}{\delta} \geq S_{min} = S$

Floor joints are beams, loaded in bending.

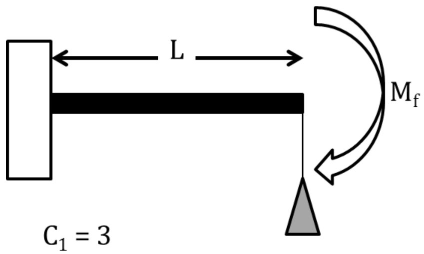
$$\frac{F}{\delta} \geq S_{min} = \frac{C_1 E I}{L^3} \longrightarrow C \geq \left(\frac{4 \cdot \pi \cdot S \cdot L^5}{3}\right)^{1/2} \cdot \frac{\rho \cdot C_m}{E^{1/2}}$$

$$m = A \cdot L \cdot \rho \longrightarrow A = \frac{m}{L \cdot \rho}$$

$$C = m \cdot C_m \longrightarrow m = \frac{C}{C_m}$$

$C \downarrow \quad \frac{E^{1/2}}{\rho \cdot C_m} \uparrow$

Case Study 9:
Materials for Constructions
(Structural Frame)



Objective	• Minimize the cost
Constraints	• Length L specified • Stiffness: must not deflect too much under loads • Strength: must not fall under design loads
Free Variables	• Area (A) of the cross-section • Choice of the material

$$I = \frac{bh^3}{12} \gg \frac{A^{3/2}}{6}$$

Floor joints are beams, loaded in bending.

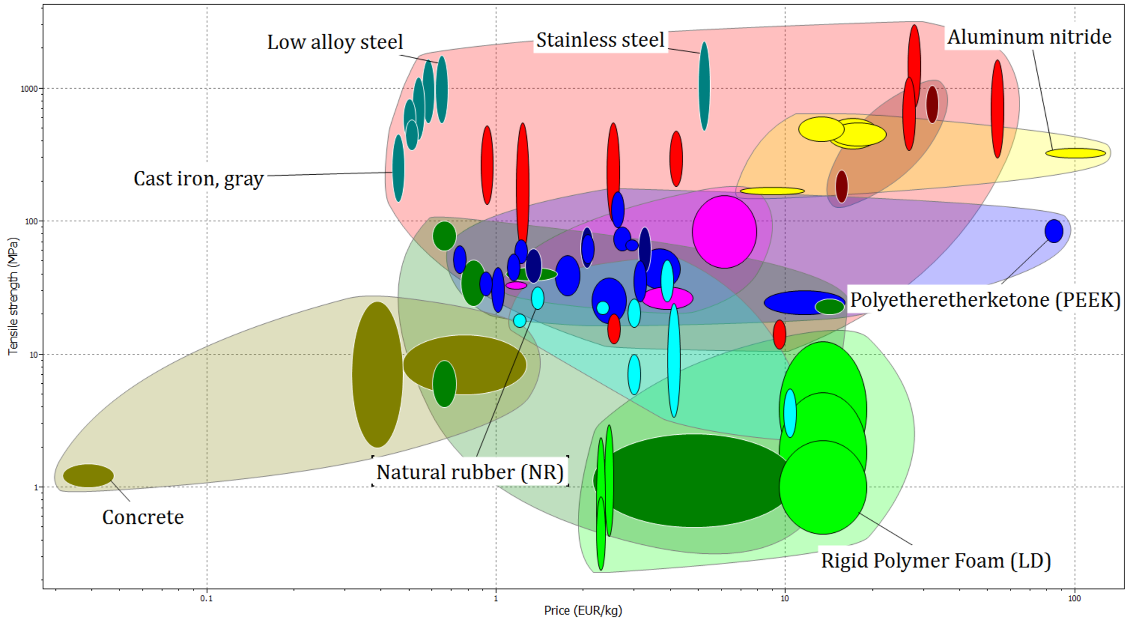
$$\sigma_{max} = \frac{M_f \cdot y_{max}}{I} \leq \sigma_f \longrightarrow C \geq (M_f \cdot 6)^{2/3} \cdot \mathrm{L} \cdot \frac{\rho \cdot C_m}{{\sigma_f}^{2/3}}$$

$$m = A \cdot L \cdot \rho \longrightarrow A = \frac{m}{L \cdot \rho}$$

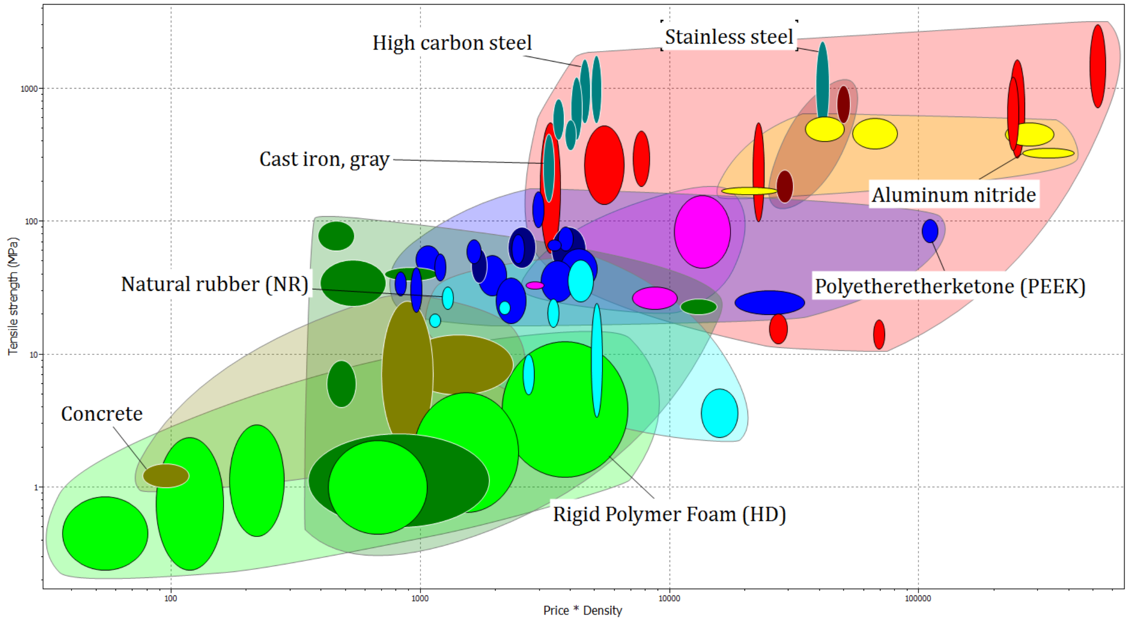
$$C = m \cdot C_m \longrightarrow m = \frac{C}{C_m}$$

$$C \downarrow \quad \frac{{\sigma_f}^{2/3}}{\rho \cdot C_m} \uparrow$$

Case Study 9: Materials for Constructions

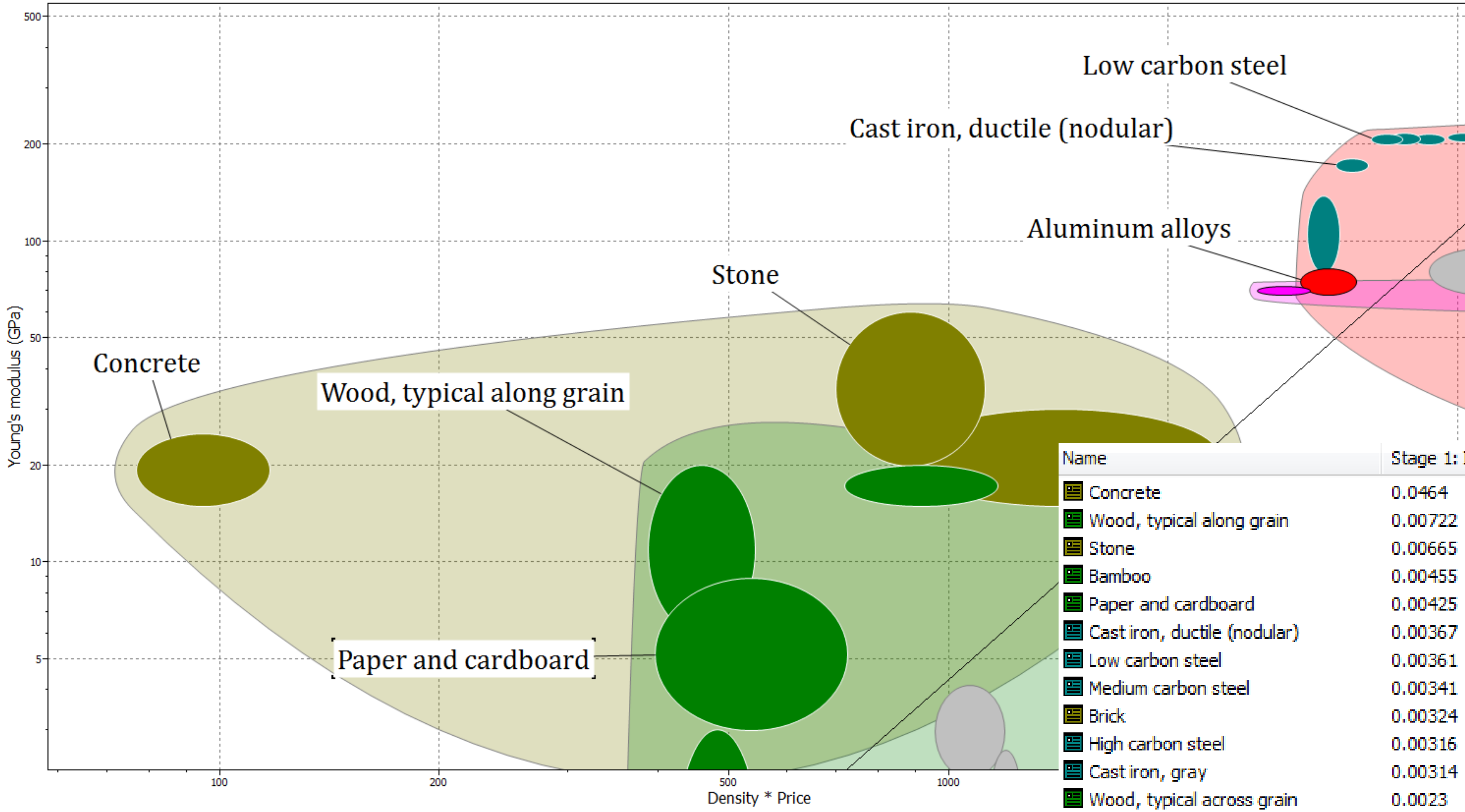


ATTENTION!!!
Selection with the cost/kg and with the cost/m^3 is DIFFERENT



Case Study 9: Materials for Constructions

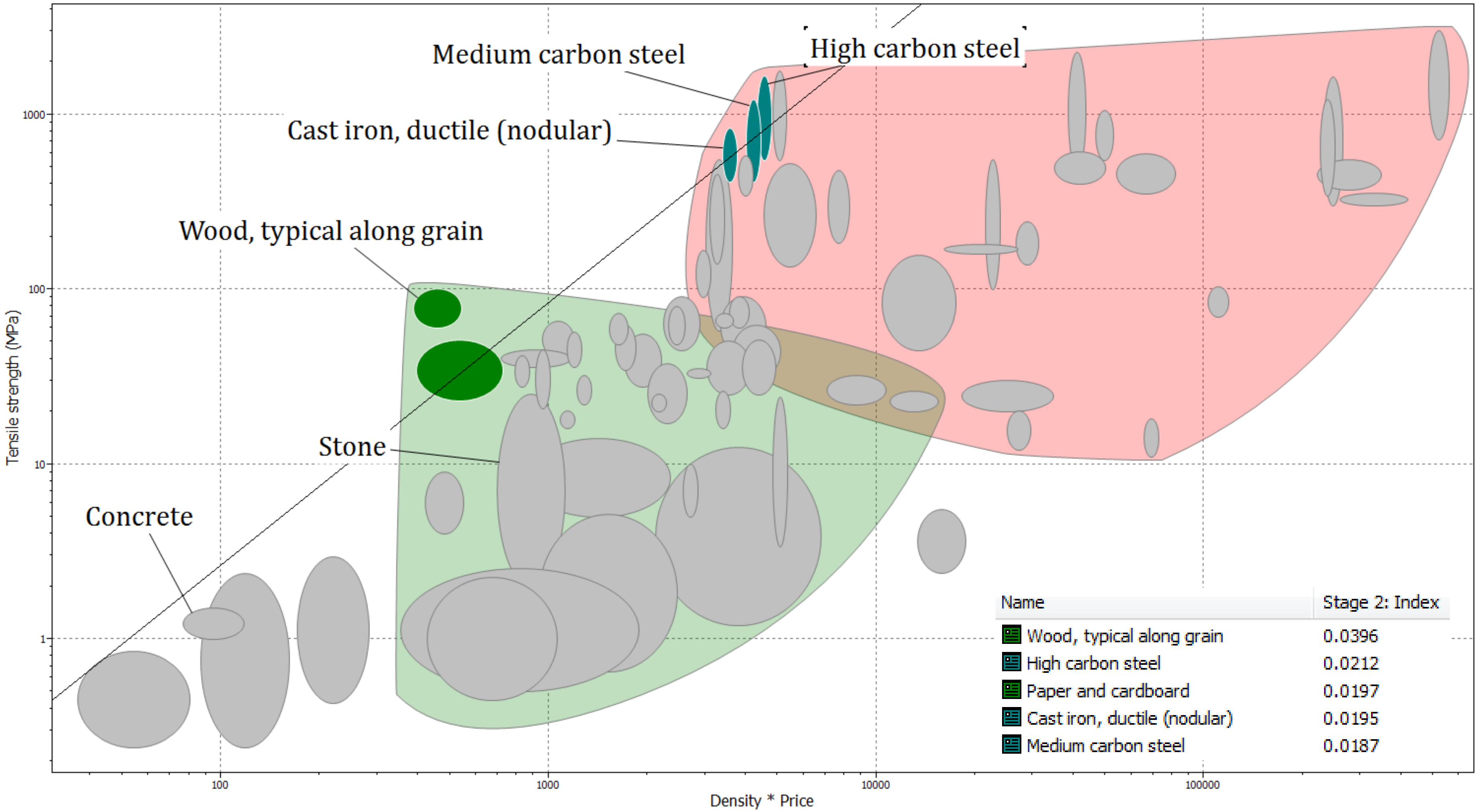
$$C \downarrow \qquad \frac{E^{1/2}}{\rho \cdot C_m} \uparrow$$



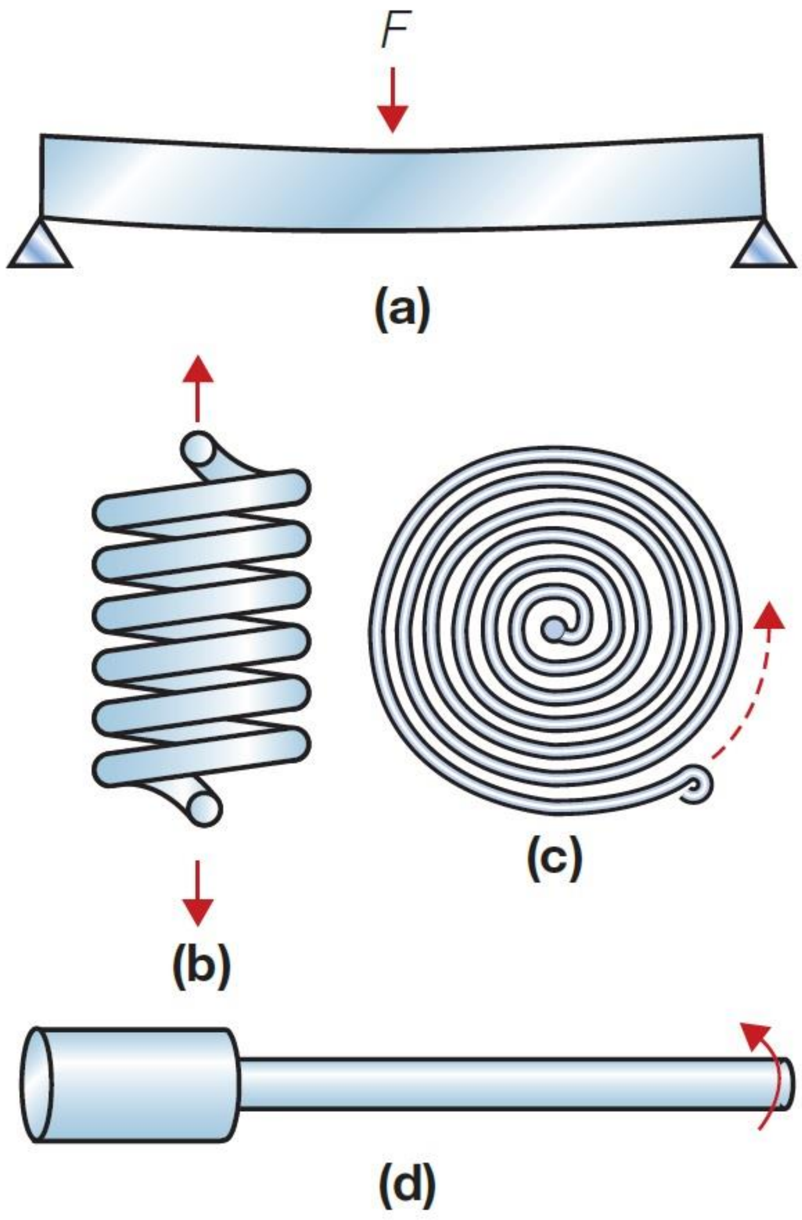
Name	Stage 1: Index
Concrete	0.0464
Wood, typical along grain	0.00722
Stone	0.00665
Bamboo	0.00455
Paper and cardboard	0.00425
Cast iron, ductile (nodular)	0.00367
Low carbon steel	0.00361
Medium carbon steel	0.00341
Brick	0.00324
High carbon steel	0.00316
Cast iron, gray	0.00314
Wood, typical across grain	0.0023

Case Study 9: Materials for Constructions

$$C \downarrow \quad \frac{\sigma_f^{2/3}}{\rho \cdot C_m} \uparrow$$

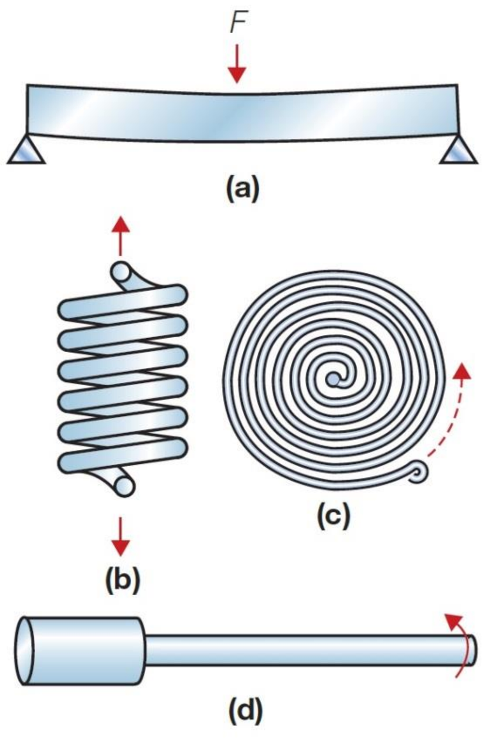


Case Study :
Materials for Springs



Case Study 10: Materials for Small Springs

Objective	• Maximize stored elastic energy
Constraints	• No failure → $\sigma < \sigma_f$ throughout the spring
Free Variables	• Choice of the material

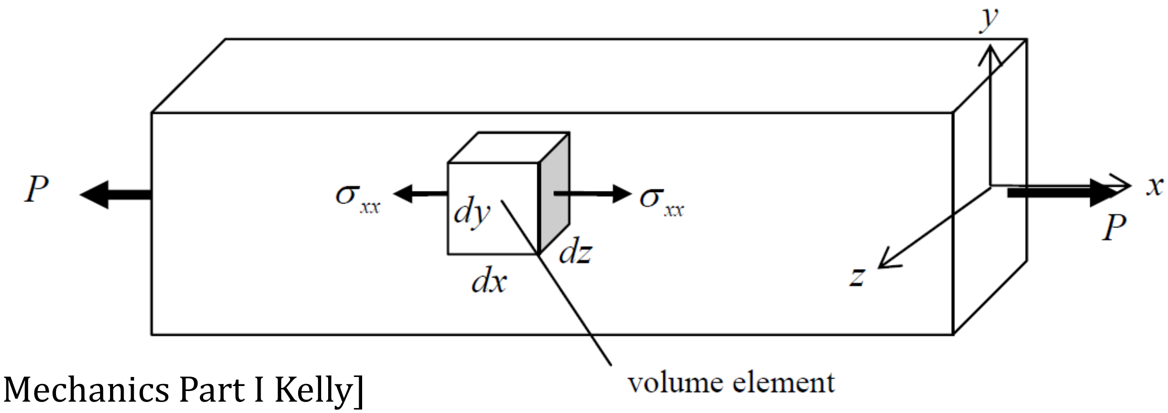


Condition of elasticity

$$\begin{cases} \sigma_y \geq \sigma \\ \sigma = E \cdot \varepsilon \longrightarrow \varepsilon = \frac{\sigma}{E} \end{cases}$$

$SMALL?? \rightarrow \boldsymbol{V}$ FREE VARIABLE!!

$dV = dxdydz$

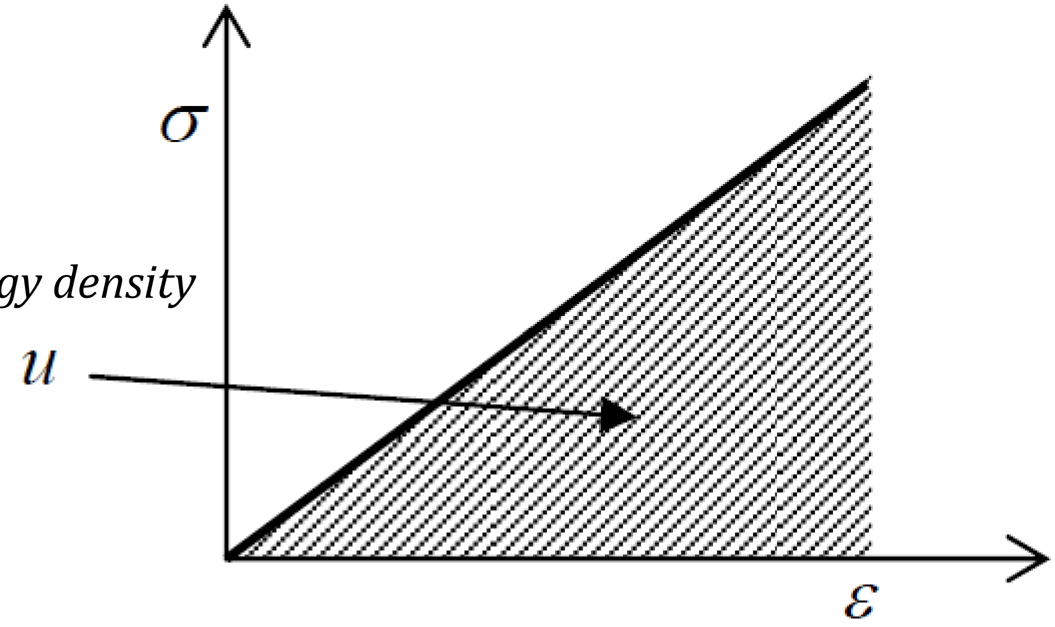


[Solid Mechanics Part I Kelly]

Case Study 10:
Materials for Small Springs

$$\begin{cases} \sigma_y \geq \sigma \\ \varepsilon = \frac{\sigma}{E} \end{cases}$$

Strain energy density



$dV = dxdydz$

$$\begin{cases} m = V \cdot \rho \\ W_{el} = \frac{1}{2}\int \sigma \cdot \varepsilon \, dV = \frac{1}{2}\, \sigma \cdot \varepsilon \cdot V \end{cases}$$

Total strain energy in the piece considered

$$W_{el} = \frac{{\sigma_y}^2}{2E} = M_1$$

Total strain energy
PER UNIT OF VOLUME

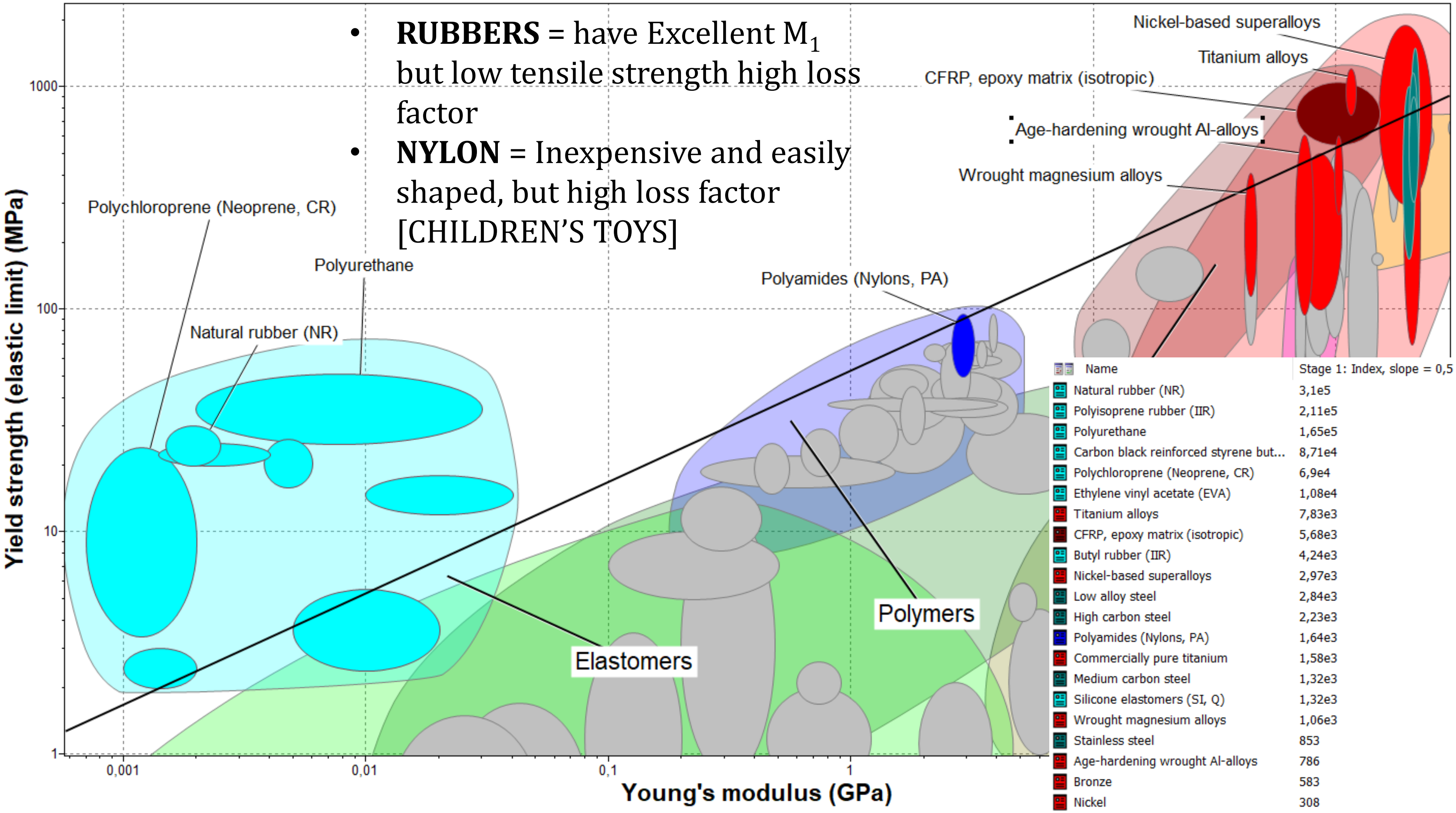
$$U = \frac{\left(\sigma_{xx} dydz\right)^2 dx}{2Edydz}$$

[Solid Mechanics Part I Kelly]

Case Study 10: Materials for Small Springs

- **CFRP** = Comparable in performance with steel; expensive [TRUCK SPRINGS]
- **STEEL** = The traditional choice: easily formed and heat treated
- **TITANIUM** = Expensive, corrosion resistant

- **RUBBERS** = have Excellent M_1 but low tensile strength high loss factor
- **NYLON** = Inexpensive and easily shaped, but high loss factor [CHILDREN'S TOYS]



Name	Stage 1: Index, slope = 0,5
Natural rubber (NR)	3,1e5
Polyisoprene rubber (IIR)	2,11e5
Polyurethane	1,65e5
Carbon black reinforced styrene but...	8,71e4
Polychloroprene (Neoprene, CR)	6,9e4
Ethylene vinyl acetate (EVA)	1,08e4
Titanium alloys	7,83e3
CFRP, epoxy matrix (isotropic)	5,68e3
Butyl rubber (IIR)	4,24e3
Nickel-based superalloys	2,97e3
Low alloy steel	2,84e3
High carbon steel	2,23e3
Polyamides (Nylons, PA)	1,64e3
Commercially pure titanium	1,58e3
Medium carbon steel	1,32e3
Silicone elastomers (SI, Q)	1,32e3
Wrought magnesium alloys	1,06e3
Stainless steel	853
Age-hardening wrought Al-alloys	786
Bronze	583
Nickel	308

Case Study
Materials for Springs

$$W_{el} = \frac{{\sigma_y}^2}{2E}$$

Valid for axial springs
Because much of the material is not fully loaded

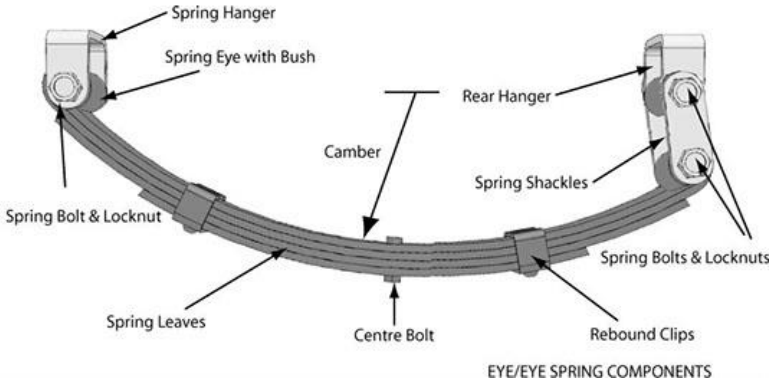
PAY ATTENTION

$$W_{el} = \frac{{\sigma_y}^2}{3E}$$

For torsion springs (less efficient)

Case Study Materials for Springs

$$W_{el} = \frac{{\sigma_y}^2}{4E}$$

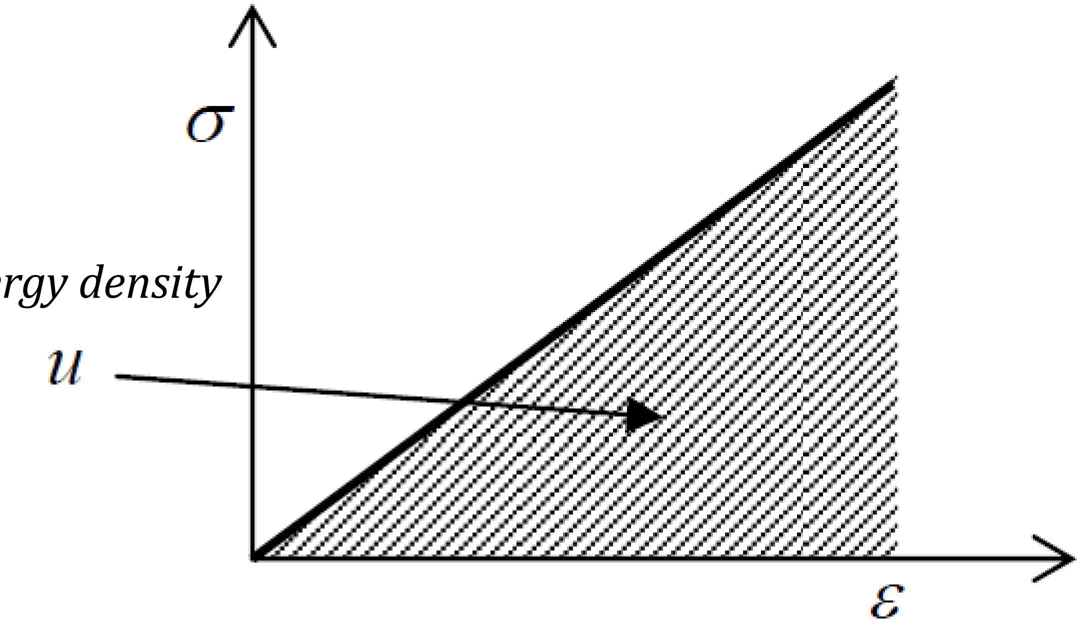


For leaf springs (less efficient)

Case Study 9: Materials for Light Springs

$$\begin{cases} \sigma_y \geq \sigma \\ \varepsilon = \frac{\sigma}{E} \end{cases}$$

Strain energy density



$dV = dxdydz$

$$\begin{cases} m = V \cdot \rho \\ W_{el} = \frac{1}{2} \int \sigma \cdot \varepsilon \, dV = \frac{1}{2} \sigma \cdot \varepsilon \cdot V \end{cases}$$

Total strain energy in the piece considered

$LIGHT?? \rightarrow \frac{V}{\rho}$ FREE VARIABLE!!

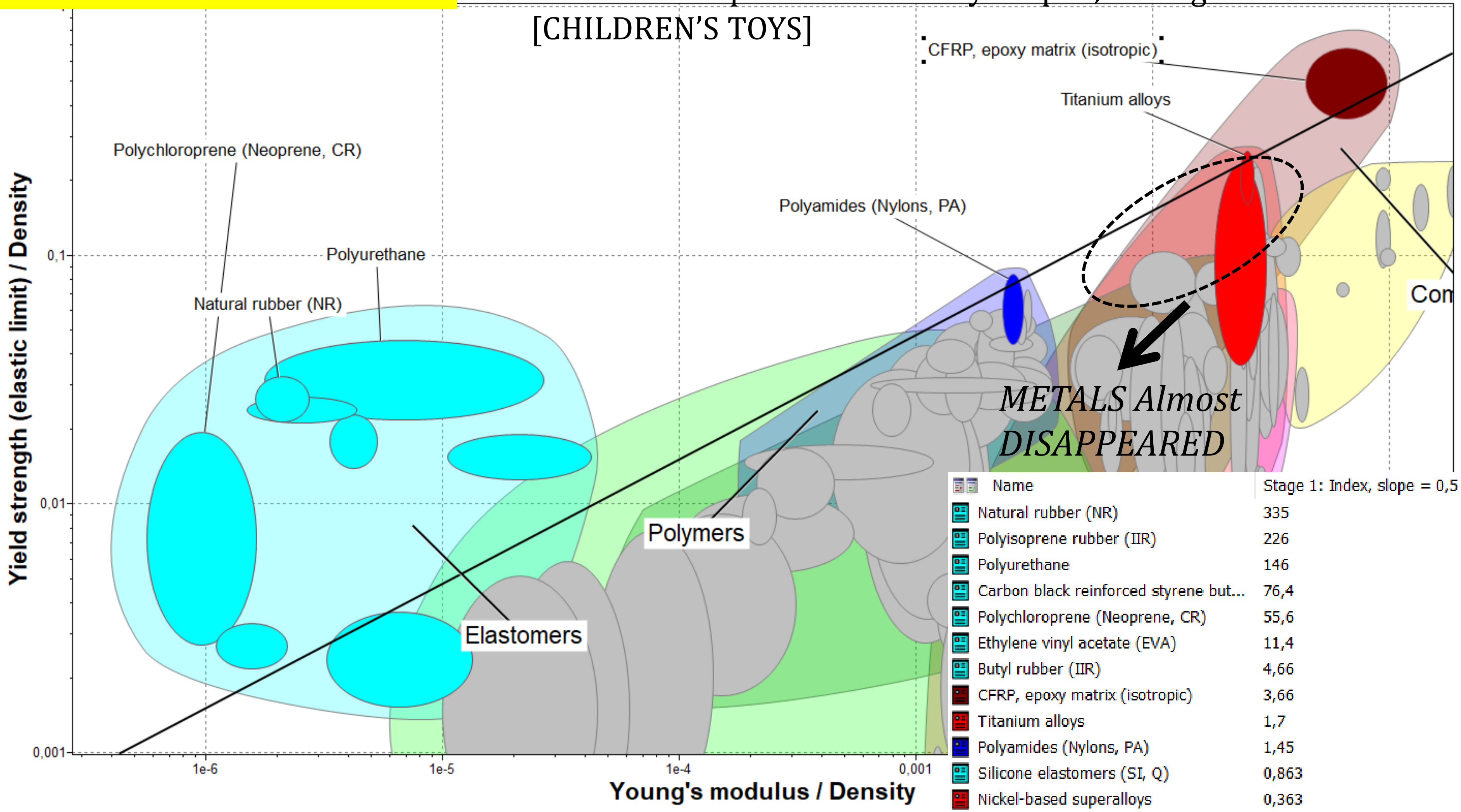
$$\frac{W_{el}}{\rho} = \frac{{\sigma_f}^2}{2 \cdot E \cdot \rho} = M_2$$

Total strain energy PER UNIT OF MASS

[Solid Mechanics Part I Kelly]

Case Study 11: Materials for Light Springs

- **CFRP** = Comparable in performance with steel; expensive [TRUCK SPRINGS]
- **RUBBERS** = 20 times better than Steel; but low tensile strength high loss factor
- **NYLON** = Inexpensive and easily shaped, but high loss factor [CHILDREN'S TOYS]



Name	Stage 1: Index, slope = 0,5
Natural rubber (NR)	335
Polyisoprene rubber (IIR)	226
Polyurethane	146
Carbon black reinforced styrene but...	76,4
Polychloroprene (Neoprene, CR)	55,6
Ethylene vinyl acetate (EVA)	11,4
Butyl rubber (IIR)	4,66
CFRP, epoxy matrix (isotropic)	3,66
Titanium alloys	1,7
Polyamides (Nylons, PA)	1,45
Silicone elastomers (SI, Q)	0,863
Nickel-based superalloys	0,363

Case Study 12:
Materials for Car Body

Some context → Car Evolution

1932 Ford Model B

1934 Bonnie and Clyde car

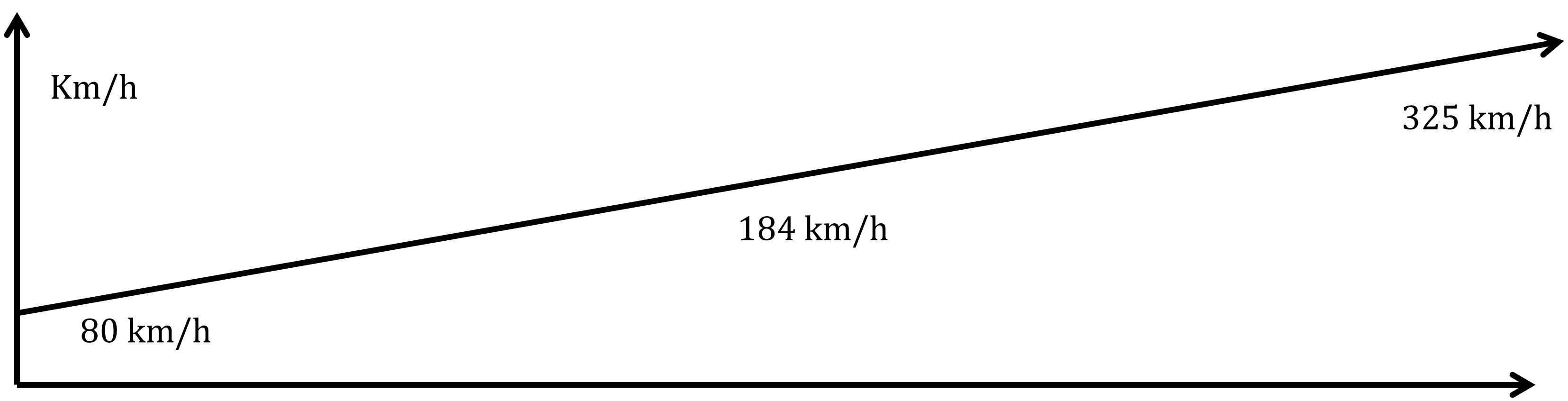
Case Study 12:
Materials for Car Body

Some context → Car Evolution

1932 Ford Model B

1970 Buick GSX

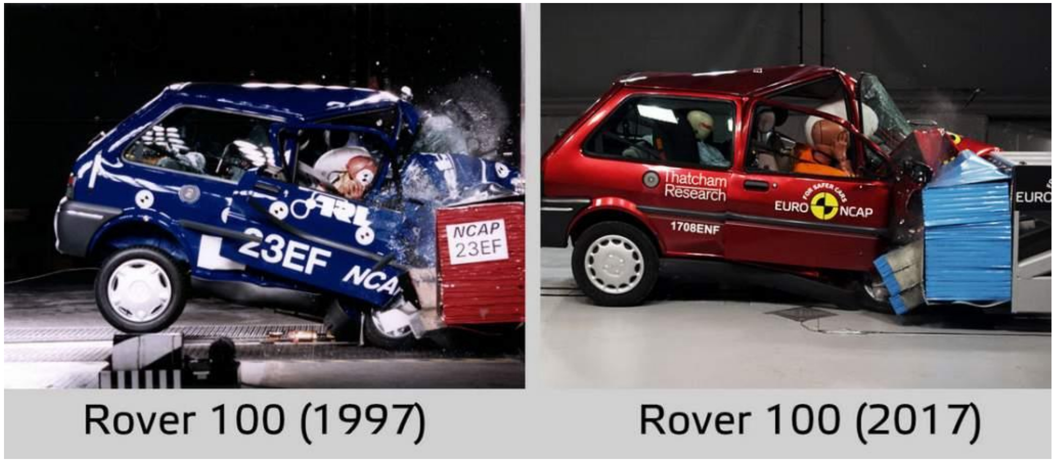
2010 Ferrari 458 Italia



Case Study 12: Materials for Car Body

$$Deformation?? \rightarrow ENERGY\ CONSUMPTION$$

At first, automotive industry move to too deformable cars and then move to have a mix FOR PEOPLE SAFETY



Sometimes exaggerate

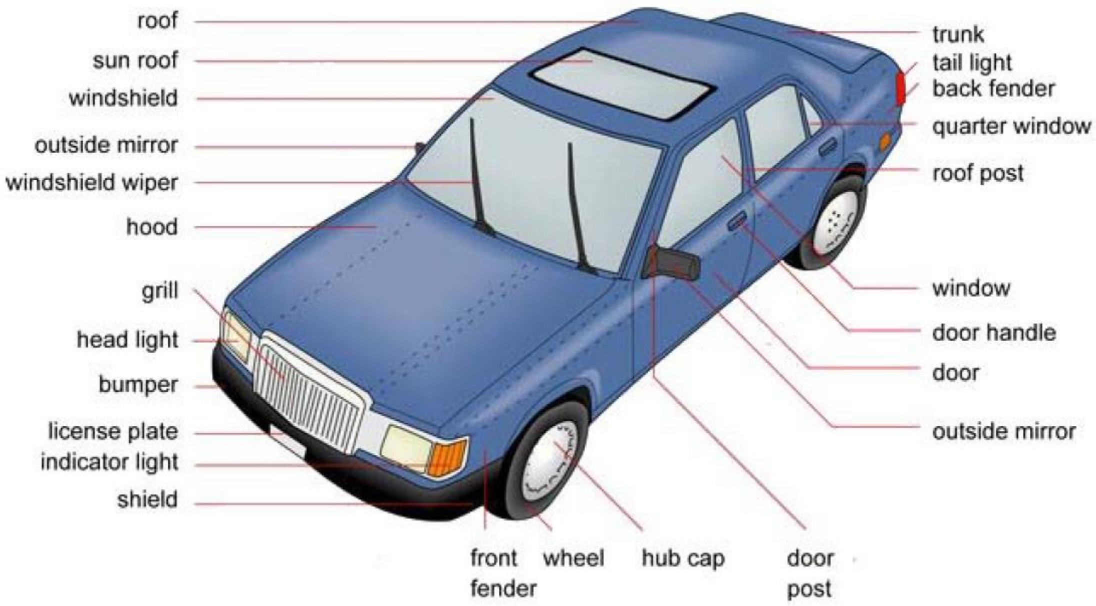
Case Study 12: Materials for Car Body (Car Hood or Car Door)

Objective	• Maximize plastic deformation at high load
Constraints	• *Geometry* • *High* σ_y • Division for price • Consider manufacture
Free Variables	• Choice of the material

$$LIGHT?? \rightarrow m$$

$$\frac{W_{el}}{\rho} = \frac{{\sigma_f}^2}{2 \cdot E \cdot \rho} = M_2$$

Total strain energy PER UNIT OF MASS



Case Study 12: Materials for Car Body (Car Hood or Car Door)

Objective	• Maximize plastic deformation at high load
Constraints	• *Geometry* • $High\ \sigma_y$ • Division for price • Consider manufacture
Free Variables	• Choice of the material

$$LIGHT??\rightarrow m$$

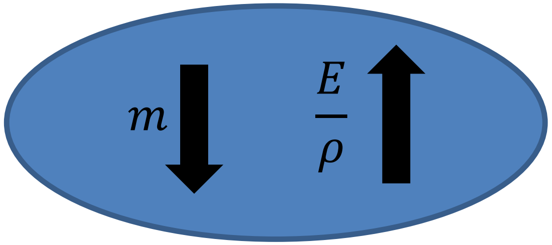
$$\frac{W_{el}}{\rho}=\frac{{\sigma_f}^2}{2\cdot E\cdot\rho}=M_2$$

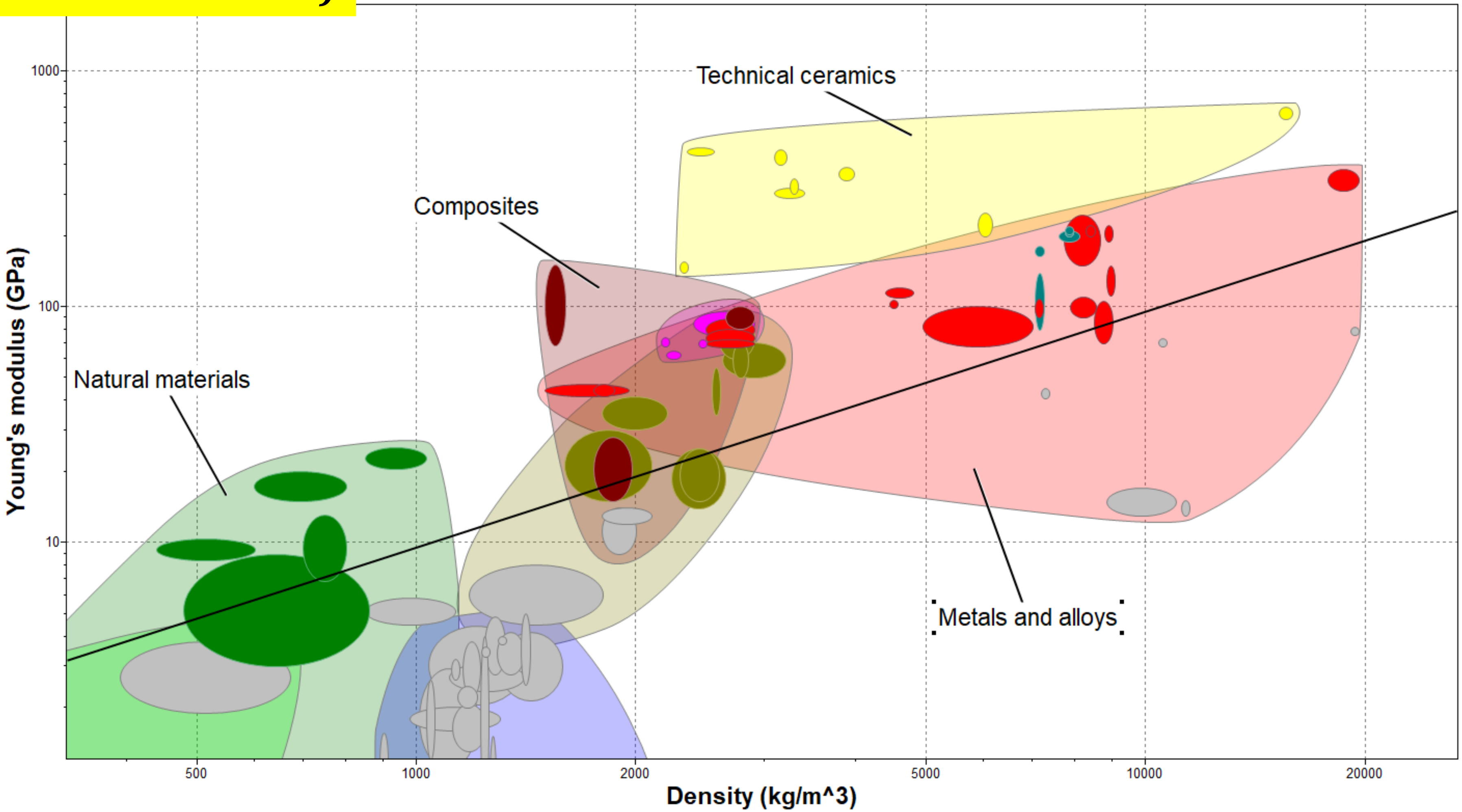
Total strain energy PER UNIT OF MASS

Steps:

- *Stiffness selection (Take off flexible materials)*
- *Yield strength selection to minimize the costs (Automotive)*
- *Minimum Yield Strength*
- *Maximization of stored energy*

Case Study 12:
Materials for Car Body (Car Hood or Car Door)





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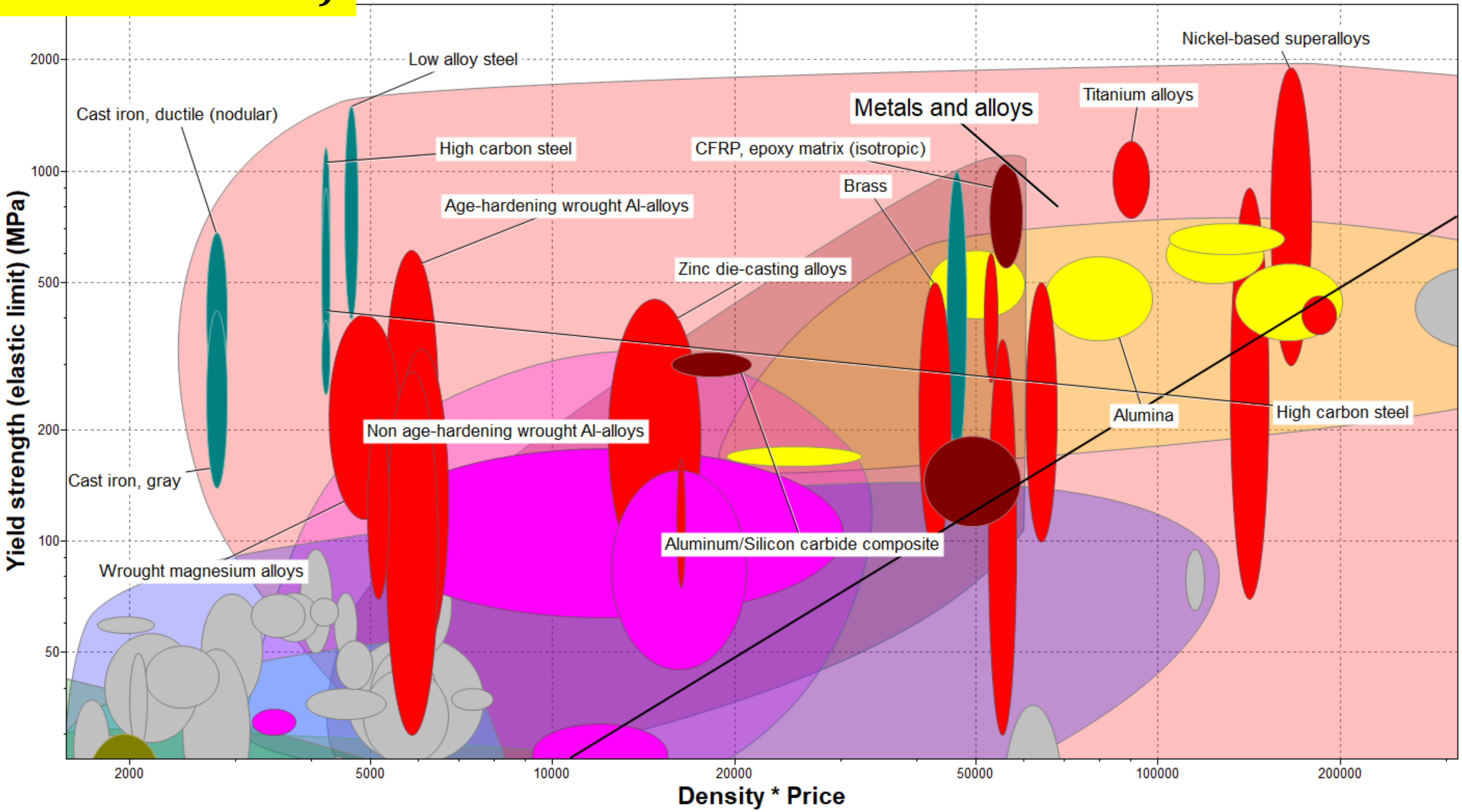
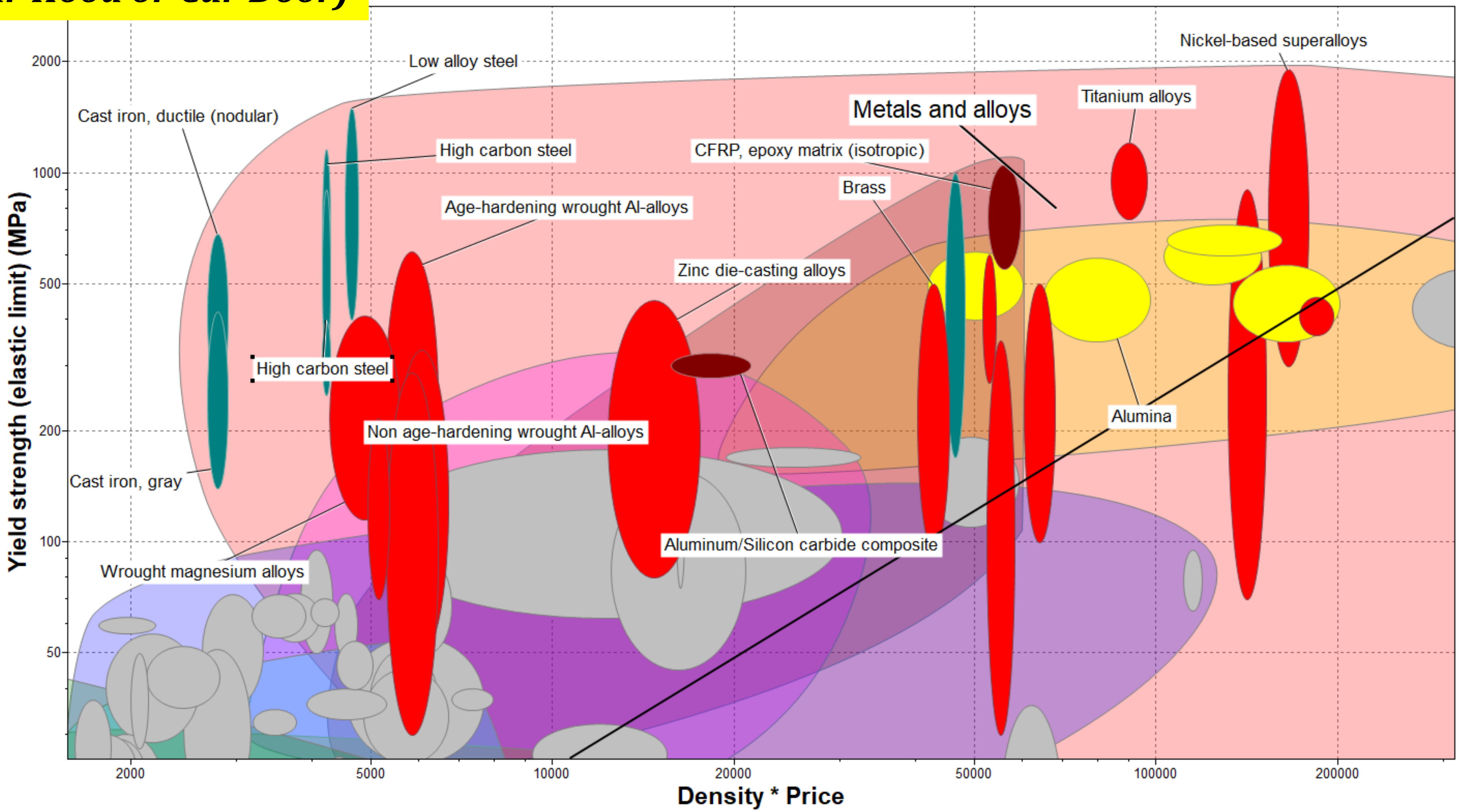


Case Study 12: Materials for Car Body (Car Hood or Car Door)

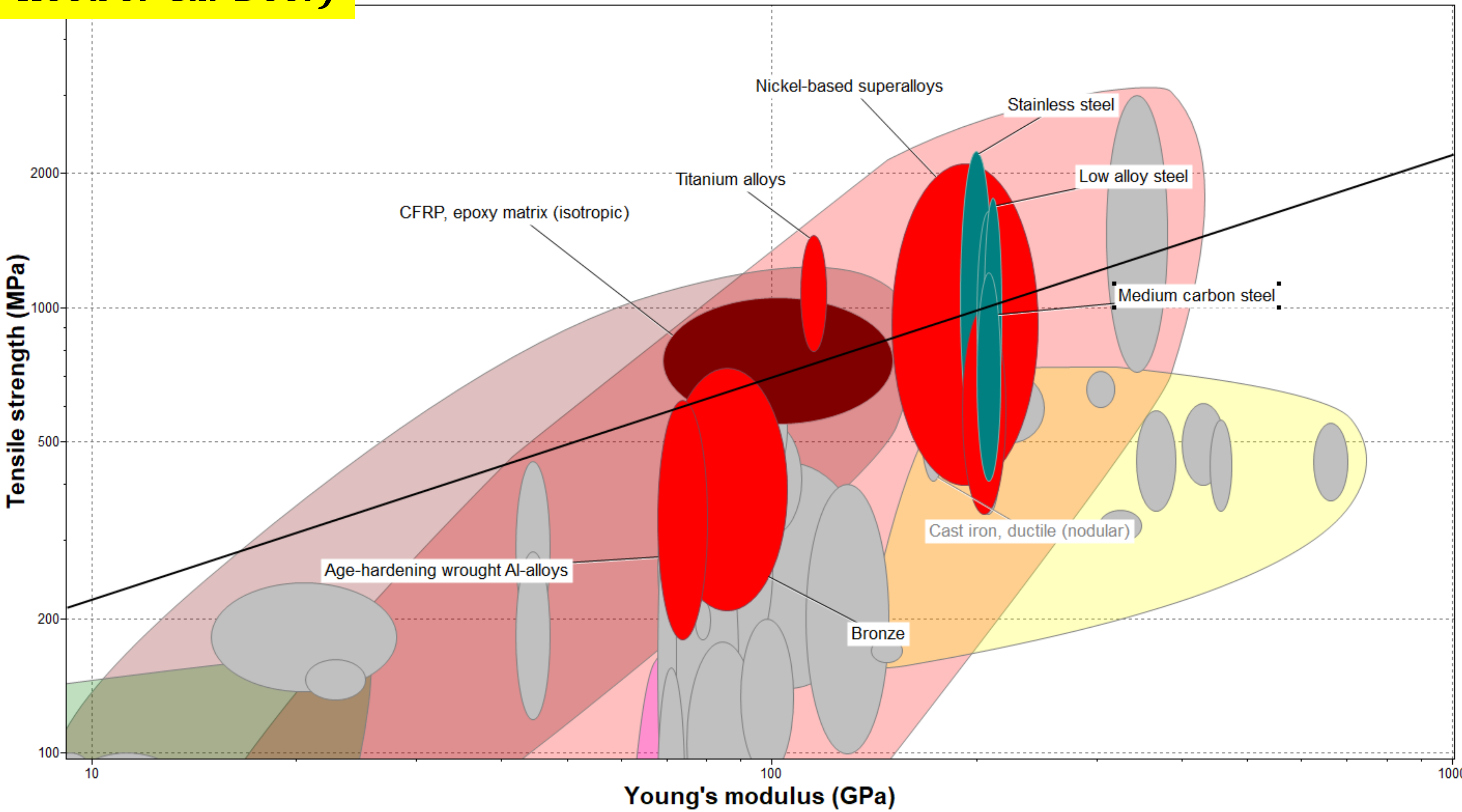
$+ \; minimum \; \sigma_y$ (200 MPa)



Case Study 12:
Materials for Car Body
(Car Hood or Car Door)

$$W_{el} = \frac{{\sigma_f}^2}{2E} = M_1$$

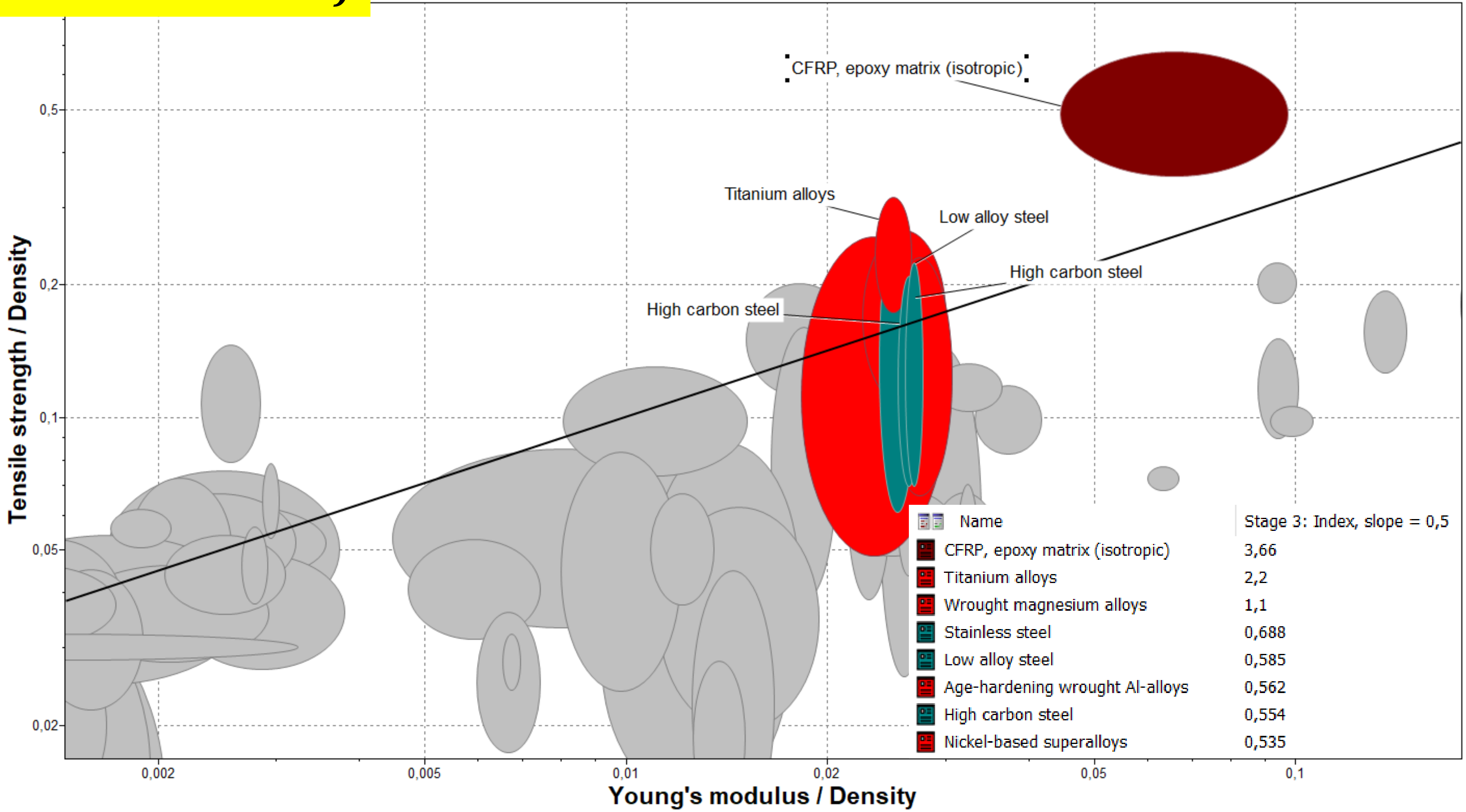
Total strain energy
PER UNIT OF VOLUME



Case Study 12: Materials for Car Body (Car Hood or Car Door)

$$\frac{W_{el}}{\rho} = \frac{{\sigma_f}^2}{2 \cdot E \cdot \rho} = M_2$$

Total strain energy PER UNIT OF MASS



Name	Stage 3: Index, slope = 0,5
CFRP, epoxy matrix (isotropic)	3,66
Titanium alloys	2,2
Wrought magnesium alloys	1,1
Stainless steel	0,688
Low alloy steel	0,585
Age-hardening wrought Al-alloys	0,562
High carbon steel	0,554
Nickel-based superalloys	0,535

$$\frac{W_{el}}{\rho} = \frac{{\sigma_f}^2}{2 \cdot E \cdot \rho} = M_2$$

Total strain energy PER UNIT OF MASS

Case Study 12: Materials for Car Body (Car Hood or Car Door)

Lamborghini Huracan 2015

Name	Stage 3: Index, slope = 0,5
CFRP, epoxy matrix (isotropic)	3,66
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Case Study 12: Materials for Car Body (Car Hood or Car Door)

Manufacturing Consideration

Changing the carbon fiber manufacturing process

Lamborghini's innovation is a product and a process called Forged Composite. This material starts off as a sheet of uncured plastic that is mixed with short lengths of randomly placed carbon fiber strands. Unlike traditional pre-preg carbon fiber cloth, you don't have to carefully cut this material and lay it out precisely in a mold. You just have to cut off the right mass and put the chunk into a hot press mold. You squeeze it, heat it and you're done. The part that comes out of the mold is as light (or lighter) and as stiff (or stiffer) than a conventionally laid-up carbon fiber part, and you can produce it in minutes rather than hours.

> You can now treat carbon fiber the way the automobile industry has treated steel, aluminum, and unreinforced plastic for decades.

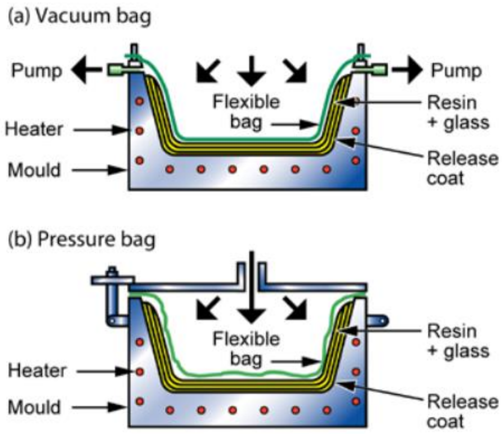
This changes the rules of manufacturing because you can now treat carbon fiber the way the automobile industry (and every other manufacturing industry) has treated steel, aluminum, and unreinforced plastic for decades: You just stamp out the parts you need. As automakers look to the future of increased CAFE standards and lighter-weight vehicles, making parts out of carbon fiber without the extra labor expense is a killer app.

"By continuing to develop our patented forged composite materials, we are able to create a product that can enhance Lamborghini super sports cars in both their performance and their appearance," said Maurizio Reggiani, Director of R&D for Lamborghini. "The ability to leverage this kind of lightweight material gives Lamborghini an advantage that will benefit our cars – as well as production process – in the future."

[www.digitaltrends.com/cars/lamborghini-forged-carbon-fiber-manufacturing-process]

Vacuum and pressure bag molding

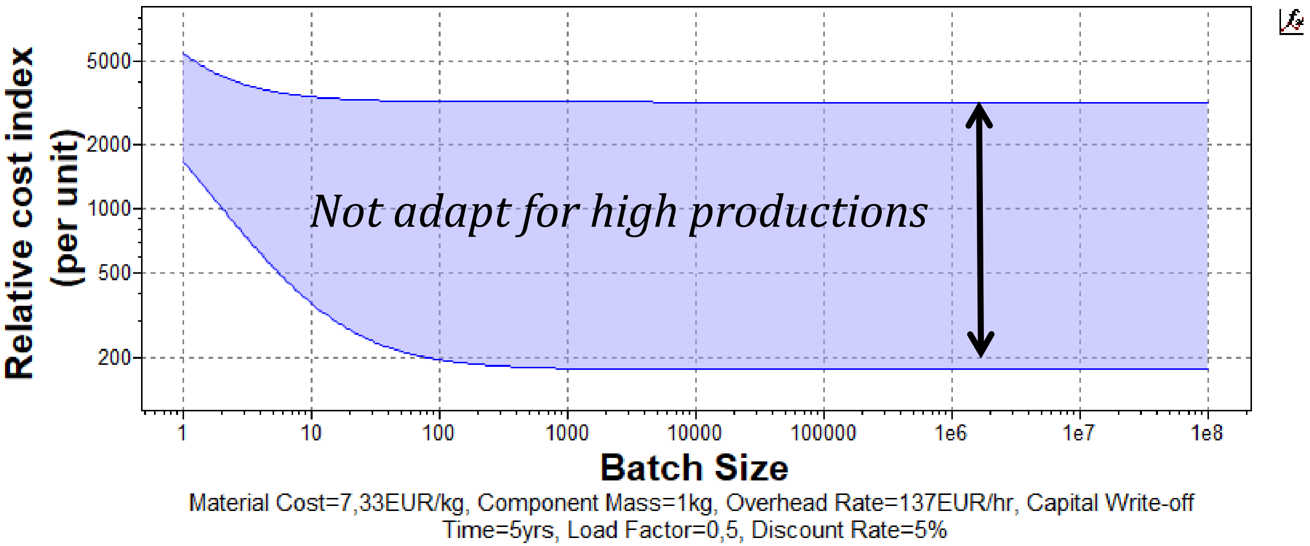
Case Study 12: Materials for Car Body (Car Hood or Car Door)



Cost model and defaults

Relative cost index (per unit)	ⓘ	178	-	3,2e3	

Parameters: Material Cost = 7,33EUR/kg, Component Mass = 1kg, Batch Size = 1e3, Overhead Rate = 137EUR/hr, Discount Rate = 5%, Capital Write-off Time = 5yrs, Load Factor = 0,5



Capital cost	ⓘ	3,01e4	-	7,52e5	EUR
Material utilization fraction	ⓘ	0,85	-	0,95	
Production rate (units)	ⓘ	0,05	-	1	/hr
Tooling cost	ⓘ	752	-	3,01e3	EUR
Tool life (units)	ⓘ	100	-	1e3	

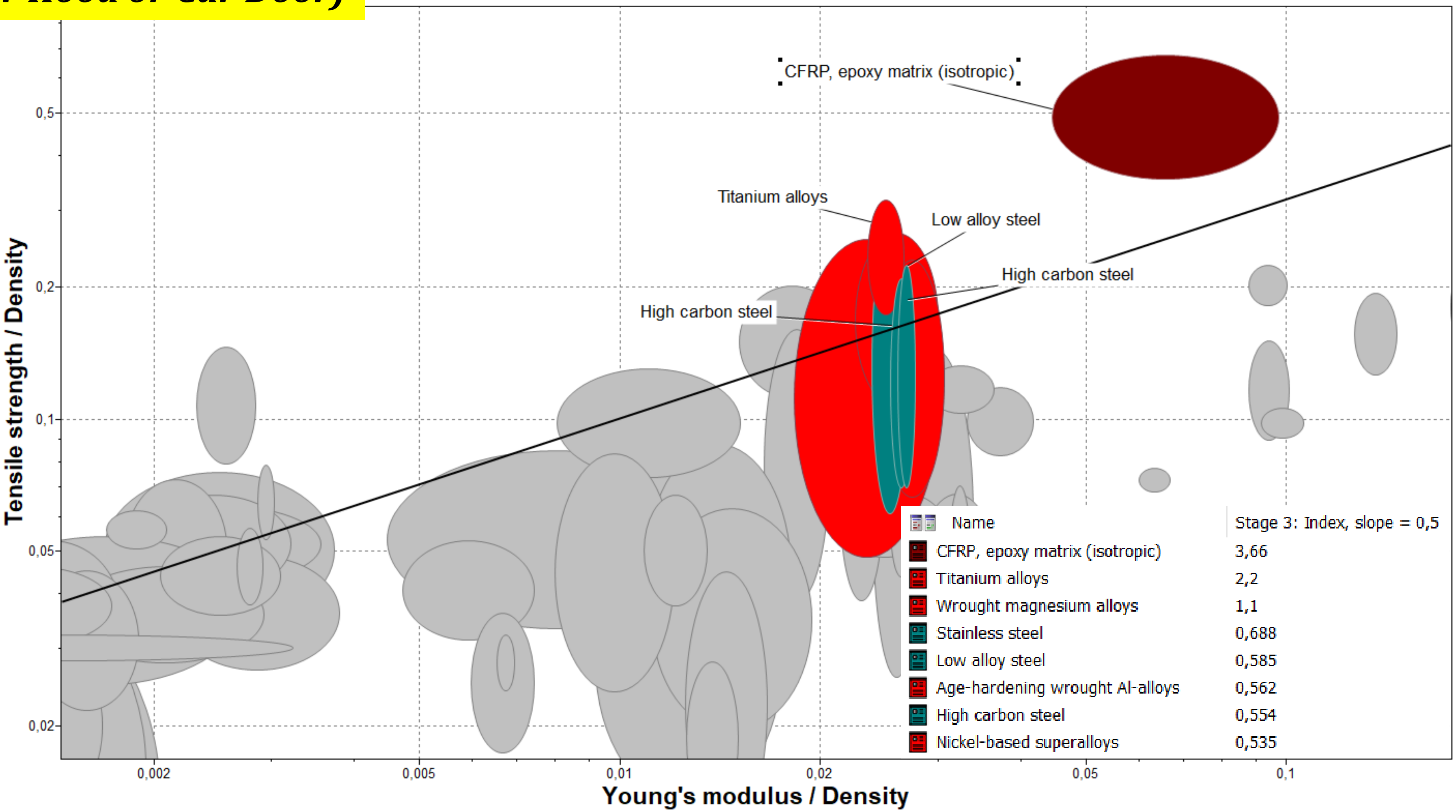
No way for a commercial car

Case Study 12: Materials for Car Body (Car Hood or Car Door)

And which Metal?

$$\frac{W_{el}}{\rho} = \frac{{\sigma_f}^2}{2 \cdot E \cdot \rho} = M_2$$

Total strain energy PER UNIT OF MASS



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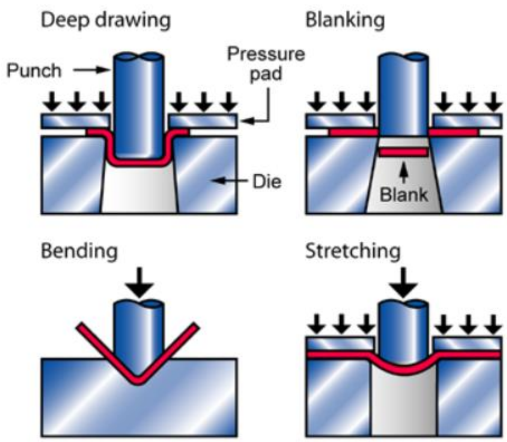
Stamping

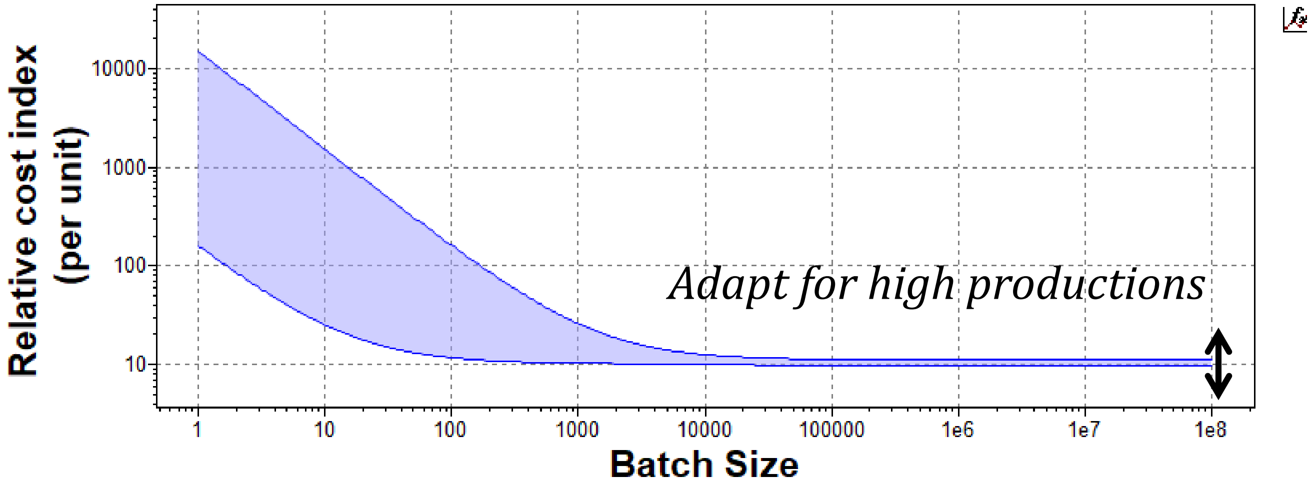
Case Study 12: Materials for Car Body (Car Hood or Car Door)



Cost model and defaults

Relative cost index (per unit)	10,3	-	26	

Parameters: Material Cost = 7,33EUR/kg, Component Mass = 1kg, Batch Size = 1e3, Overhead Rate = 137EUR/hr, Discount Rate = 5%, Capital Write-off Time = 5yrs, Load Factor = 0,5



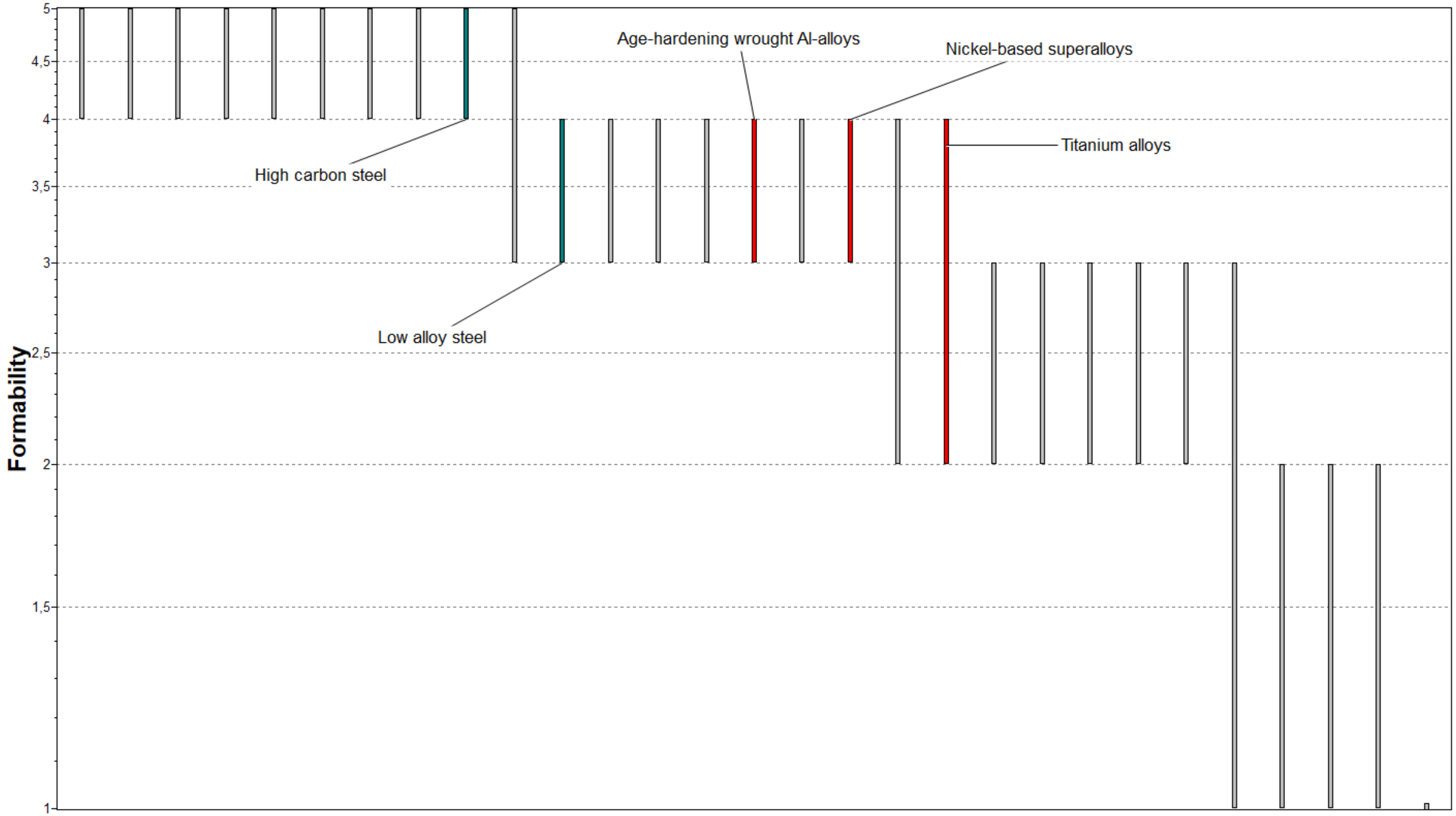
Material Cost=7,33EUR/kg, Component Mass=1kg, Overhead Rate=137EUR/hr, Capital Write-off Time=5yrs, Load Factor=0,5, Discount Rate=5%

Capital cost	7,52e3	-	7,52e4	EUR
Material utilization fraction	0,7	-	0,8	
Production rate (units)	200	-	5e3	/hr
Tooling cost	150	-	1,5e4	EUR
Tool life (units)	1e4	-	1e6	

PROCESSABILITY

Case Study 12: Materials for Car Body (Car Hood or Car Door)

Metals easy to stamp

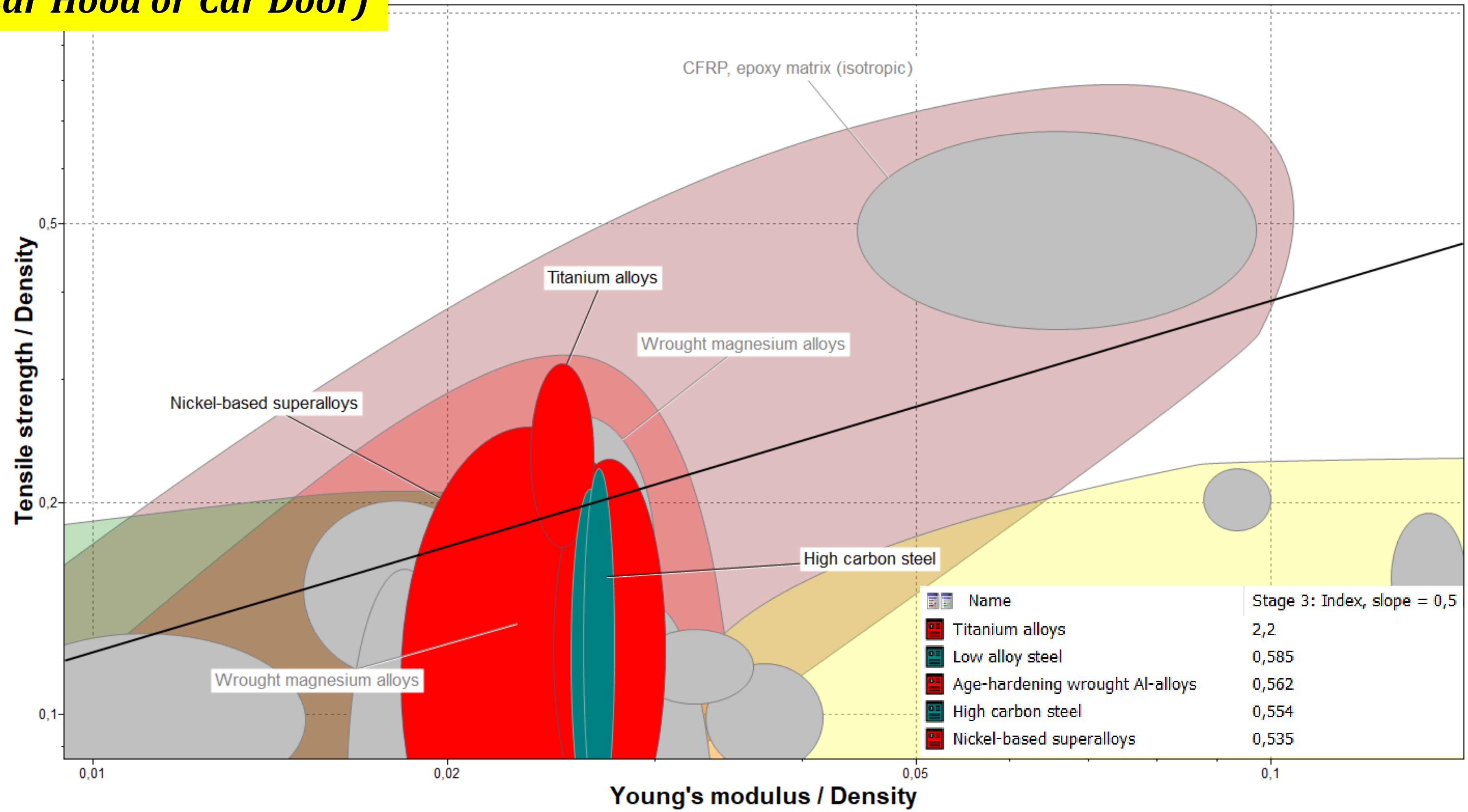


$$\frac{W_{el}}{\rho} = \frac{\sigma_f{}^2}{2 \cdot E \cdot \rho} = M_2$$

Total strain energy PER UNIT OF MASS

+ Minimum Formability (4)

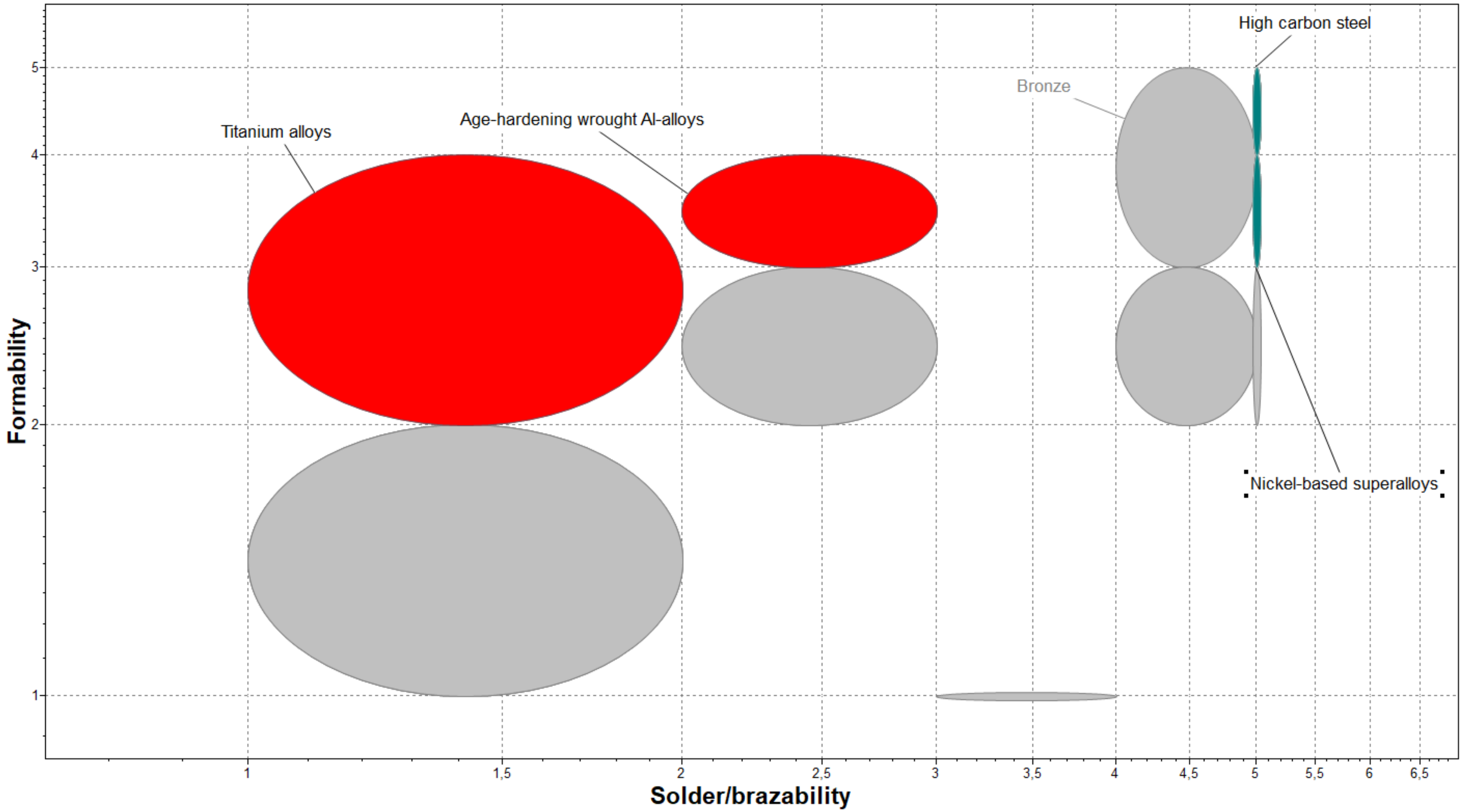
Case Study 12: Materials for Car Body (Car Hood or Car Door)



PROCESSABILITY

Case Study 12: Materials for Car Body (Car Hood or Car Door)

Metals easy to stamp

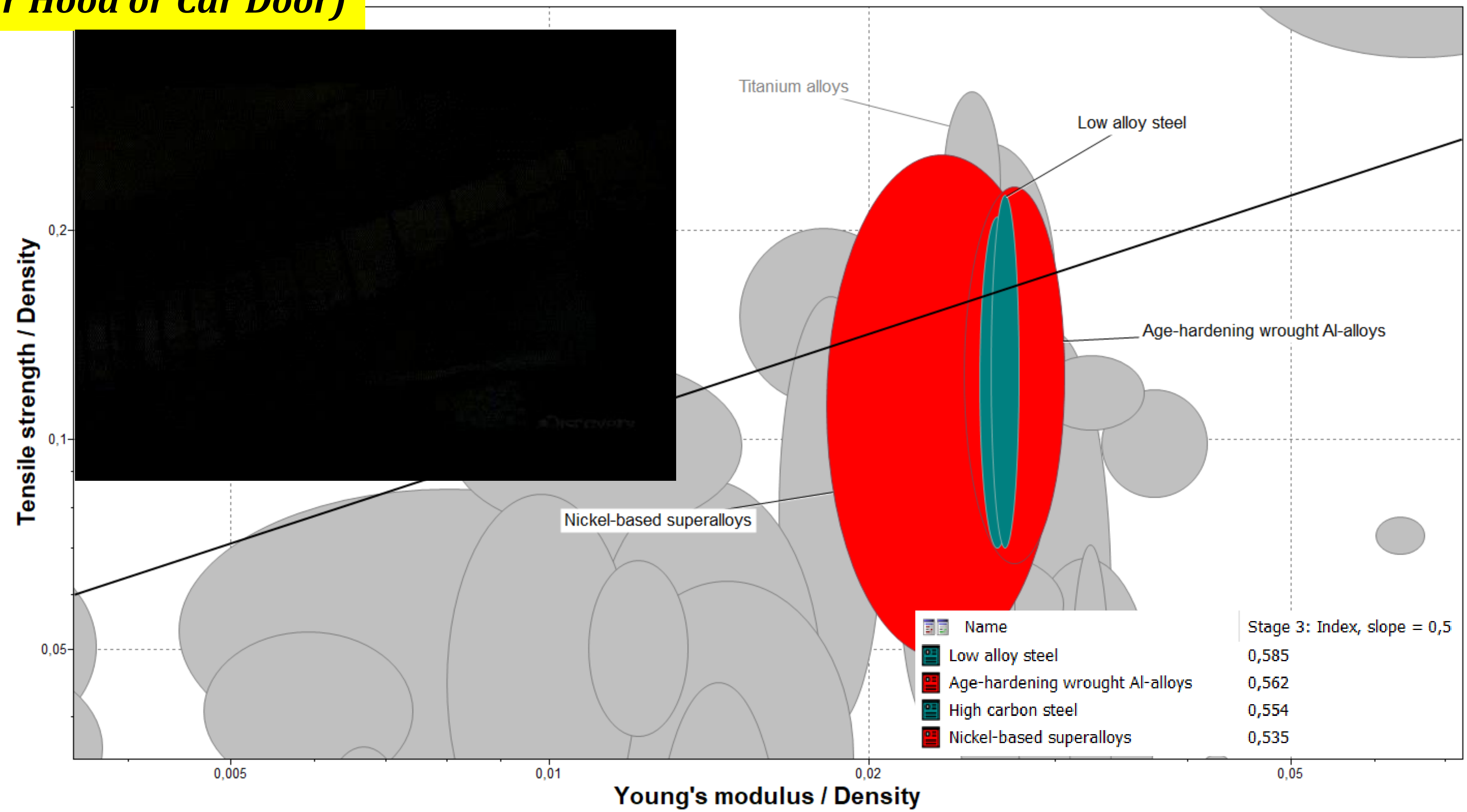


Case Study 12: Materials for Car Body (Car Hood or Car Door)

$$\frac{W_{el}}{\rho} = \frac{{\sigma_f}^2}{2 \cdot E \cdot \rho} = M_2$$

Total strain energy PER UNIT OF MASS

+ Minimum Formability (4)
+ Minimum Brazability (3)



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Materials for Car Body
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Name	Stage 3: Index, slope = 0,5
Low alloy steel	0,585
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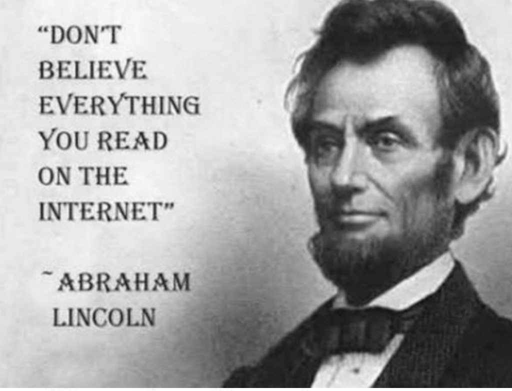
Nickel-based superalloys	0,535

Deeper selection?

LEVEL 3

[https://www.cartalk.com/blogs/jim-motavalli/steel-vs-aluminum-lightweight-wars-heat]

Materials Selection Steps



Decide Design Requirements

Get rid of Candidates that don't fit constraints e.g. max service temperature isn't high enough

Optimize on Objectives e.g. low mass, low cost, high strength

Scrutinize candidate shortlist – do I have valid properties

- Materials Selection is about trade-offs, not one right answer
- Environmental legislation, processability and the security of the supply chain are important factors, along side mechanical and thermal performance

Optional:

Decide on strategy to fill knowledge gaps