INSA INSTITUT NATIONAL DES SCIENCES APPLIQUÉES LYON

GM 5

Conception Non Conventionnelle : Art, Vivant, Design, Environnement

Unconventional conception: Art, living, Design, environment

GM 5 – CE

Cellular (solids) materials

Renaud	**Rinaldi**	Mateis

Contributors:

Jérôme	***Adrien***	*Mateis*
Florian	***Martoïa***	*LaMCoS*

I. Introduction

I.1. Context & objective

Arts, Vivant, Design, Environnement

Matière & perception

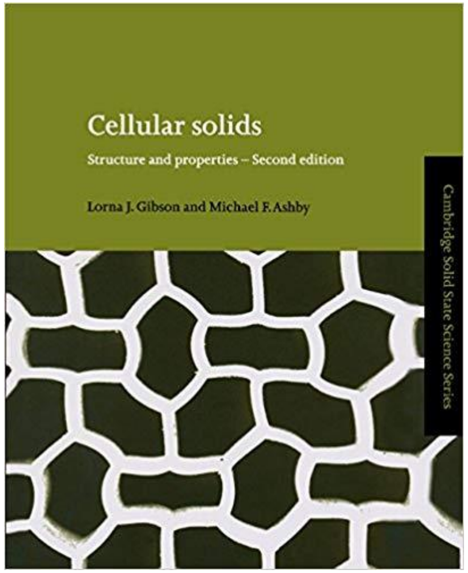
Perception sensorielle

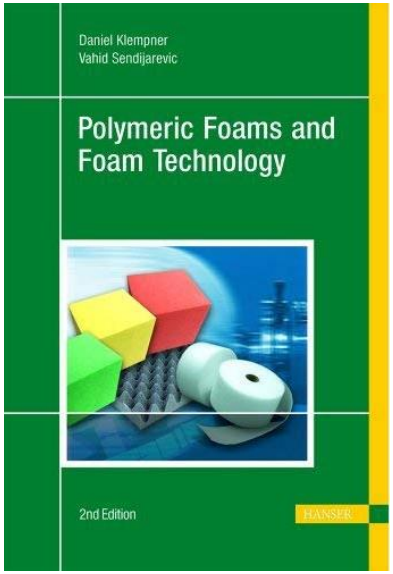
Matériaux non conventionnels :

Bois, Verres, Tissus humains, **Matériaux Cellulaires**, Céramiques …

I. Introduction

I.2. References





[1] Gibson, L., Ashby, M. F. (1988).
Cellular Solids, Structure and Properties.
Cambridge Solid State Science Series

[2] Klempner, D., & Sendijarevic, V. (2000).
Handbook Of Polymeric Foams
And Foam Technology.
Hanser Publishers.

[…] *Specialized literature and internet sources that will be listed throughout the document.*

These two books can be found at the INSA Marie Curie Library

I.3. Outline

Introduction

Context & objectives

Generalities — Overall understanding

- Definitions, & descriptions of the different families
- Key metrics and properties
- Charaterization tools

Foams

Honeycombs

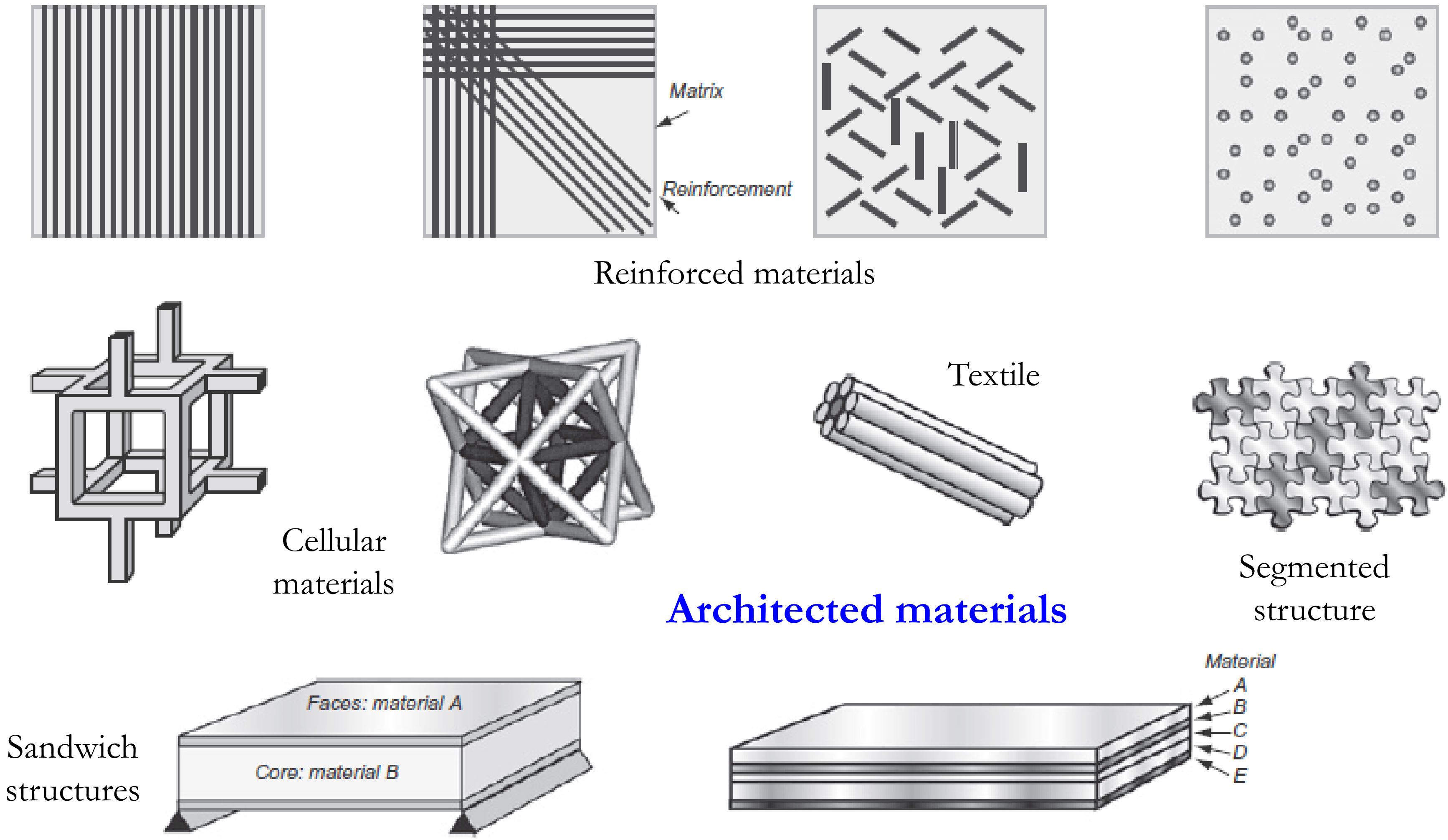
(Rapid overview)

- Processing
- Microstructures
- Properties

Lattices — An example

II. Generalities

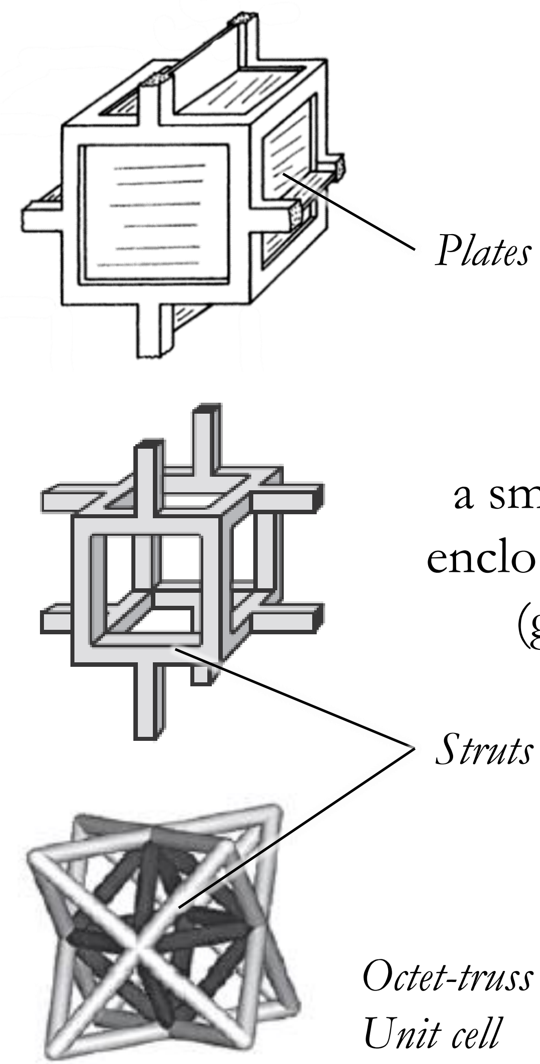
II.1. Architected materials: family picture



II. Generalities

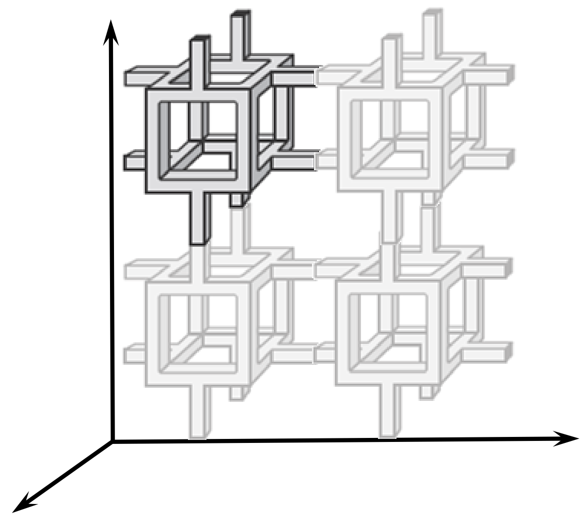
II.2. Cellular (solids) materials

II.2.1. Definition



Cella **(Latin):**
a small compartment,
enclosed **space = voids**
(gaseous phase)

Cellular solids:
an assembly of packed cells
within 3D space.



Interconnected network of solid struts or plates composing the edges and/or faces of the numerous cells.

II. Generalities

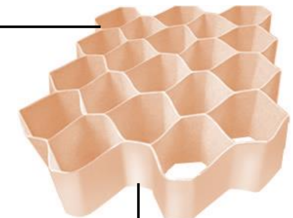
II.2. Cellular (solids) materials

II.2.2. Classification

Stochastic

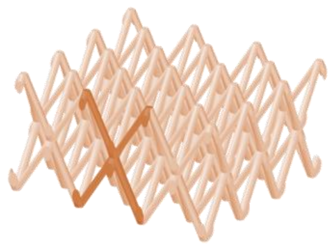
- Foams (Mousses)

- Honeycomb structures (Structures en nid d'abeilles)

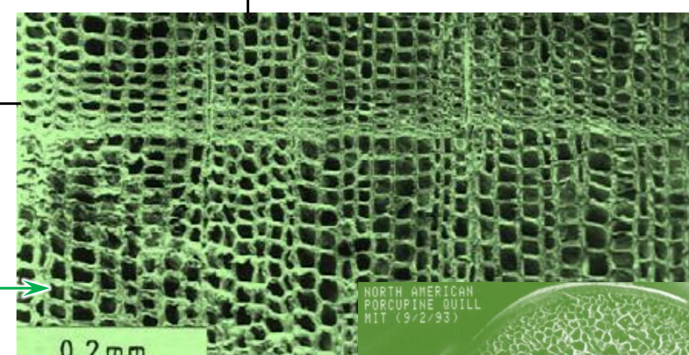


Periodic

- Lattices (Treillis)

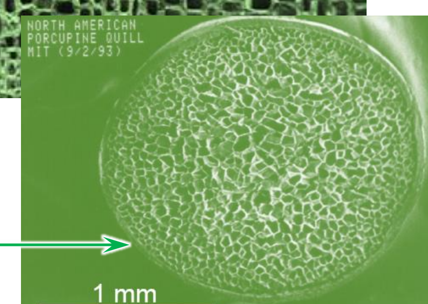


- Wood, leaves, fruits (bois, feuilles, fruits…)

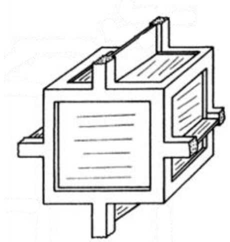


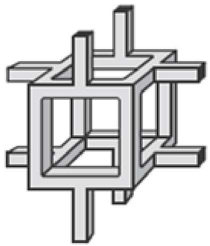
- Cellulose, bone, hair, feathers (cellules, os, poils, plumes,…)

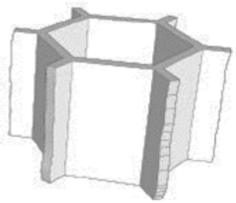
Porcupine

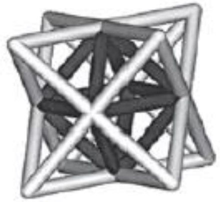


II.3. Cellular material properties







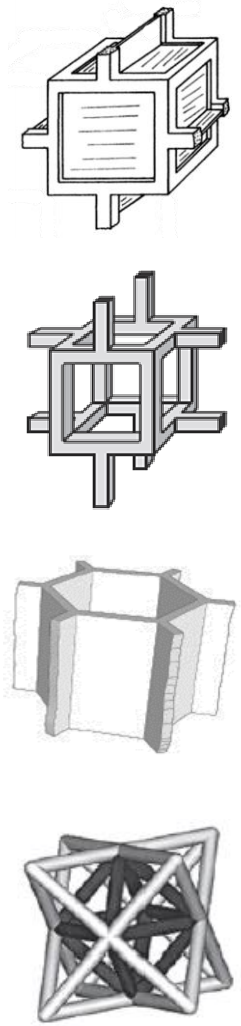


The Cellular solids can be seen as an assembly of **materials** and **voids** in 3D space.

⇒ Peculiar **properties** that first come to mind:

And the less obvious:

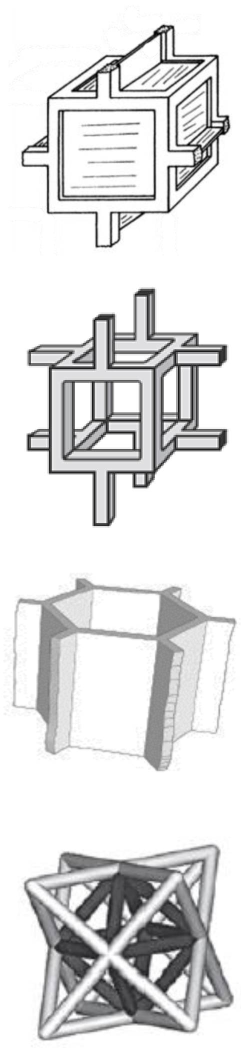
* *total surface area of a material per unit of mass (with units of m^2/kg or m^2/g) or solid or bulk volume (units of m^2/m^3 or m^{-1})*



The Cellular solids can be seen as an assembly of **materials** and **voids** in 3D space.

⇒ Its **properties** mainly depend on:

-
-
-



The **volume fraction** or **relative density** characterizes the ratio between matter and “void”:

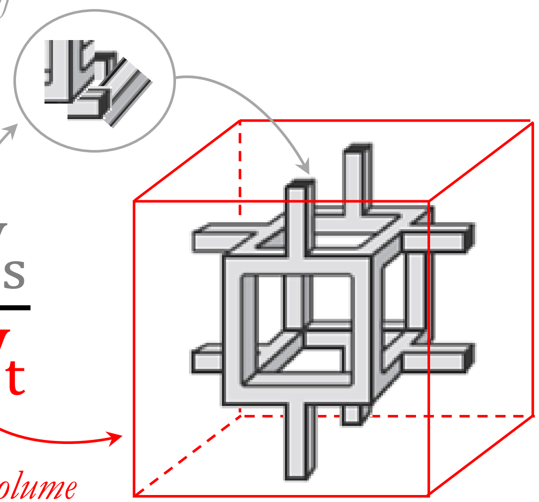
Density of the cellular solid (kg/m^3)

Volume of the solid matter

$$\bar{\rho} = \frac{\rho}{\rho_s} = \frac{V_s}{V_t}$$

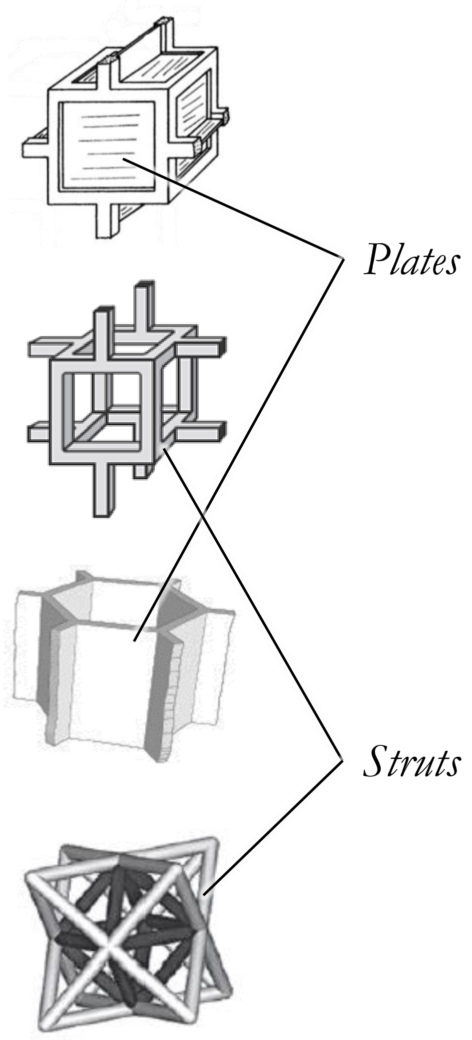
Density of the parent material (kg/m^3)

Total volume (occupation)

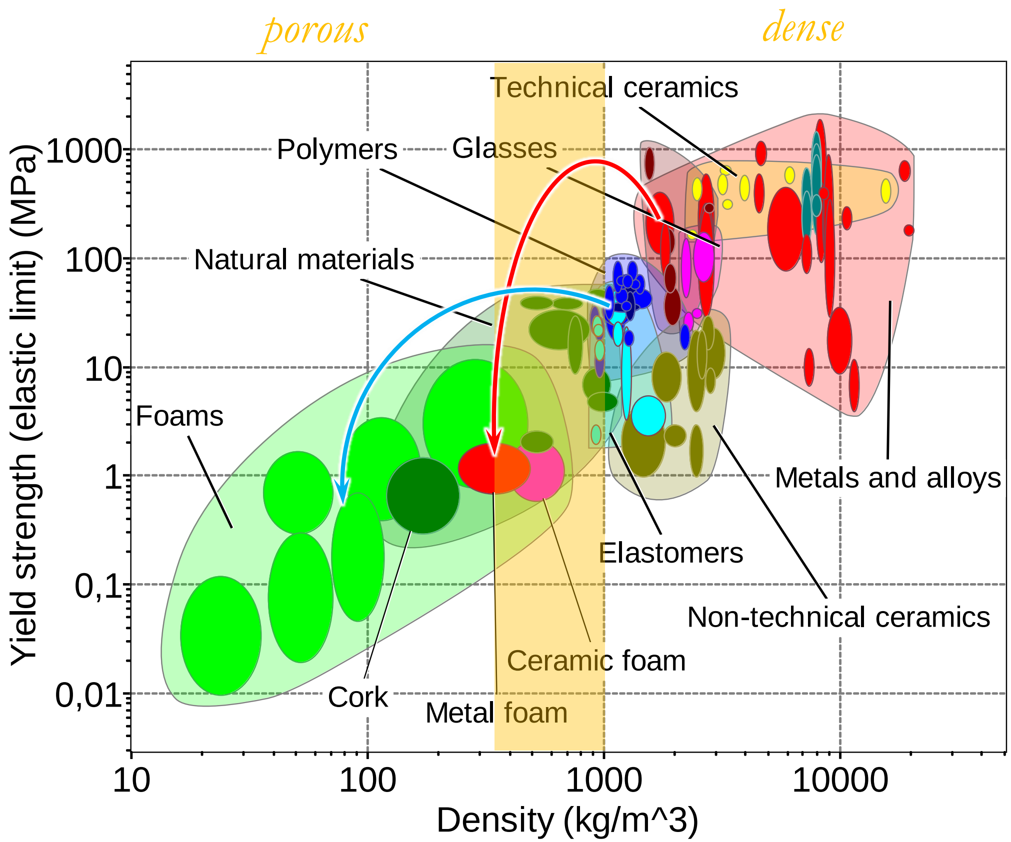


$$\bar{\rho} = 1 - p$$

Porosity: volume fraction of pores



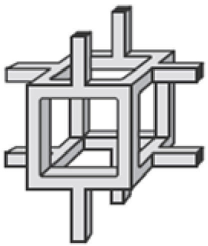
The constitutive material(s) has(ve) its own intrinsic properties:



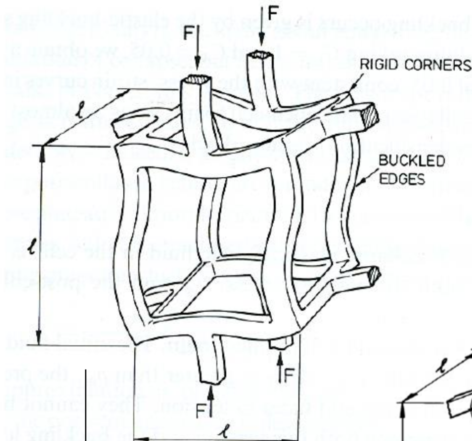
Ashby map from CES Edupack © with Level 2 database

II.3. Cellular material properties

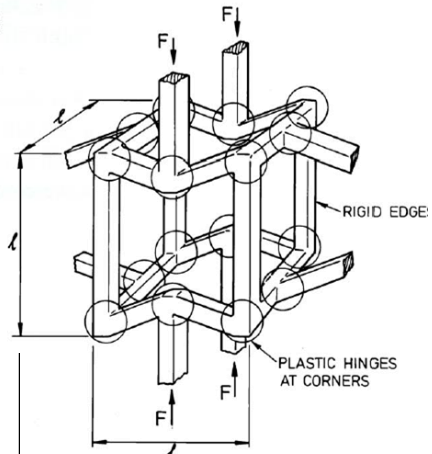
II.3.2b. Parent material properties



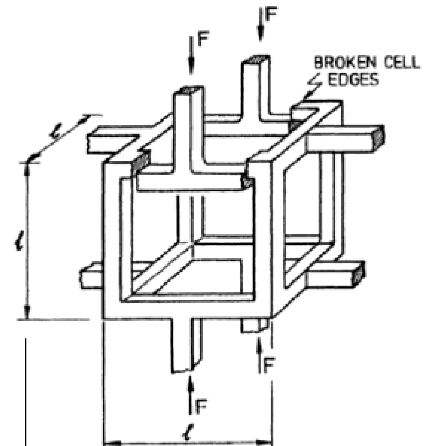
The yielding (onset of non-linear behaviour) of the cellular material does not necessarily depend on the yield strength of the parent material.



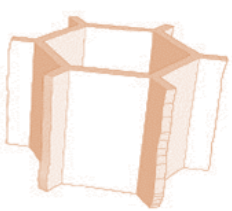
"soft"

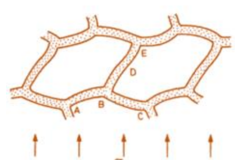


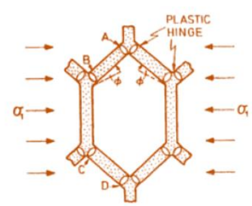
"ductile"

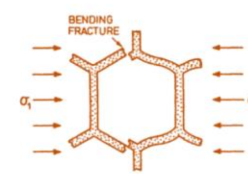


"brittle"



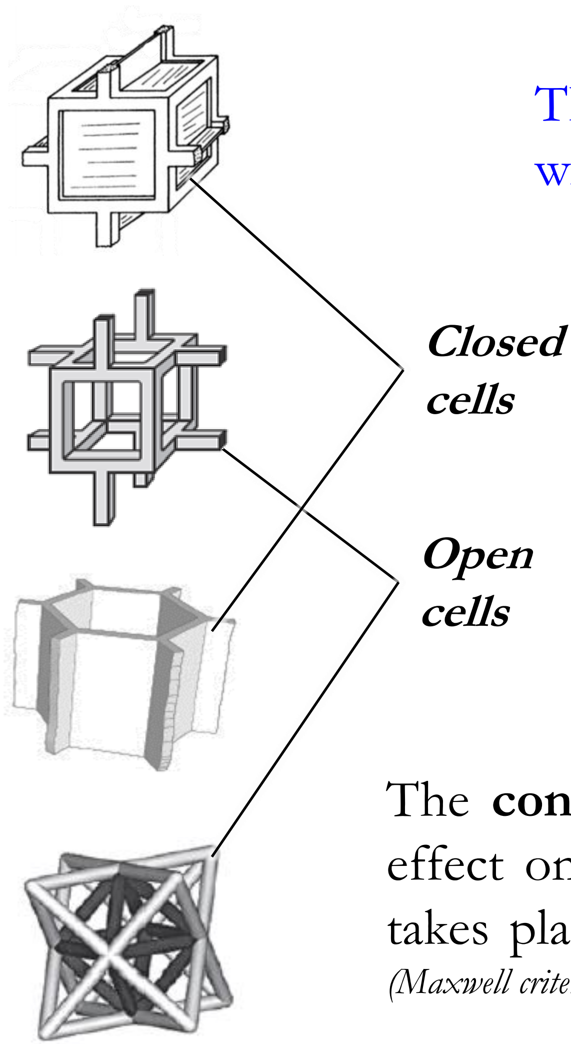


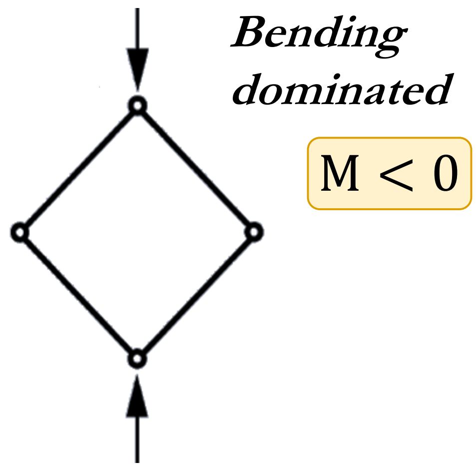


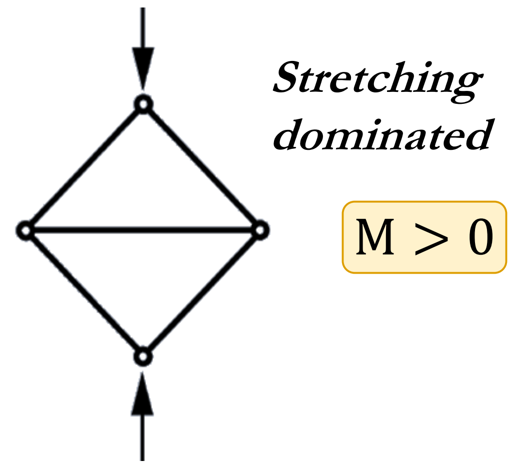


L. Gibson and M. Ashby, Cellular Solids, 1988

The **architecture**, *i.e.* the way the matter is distributed within space:







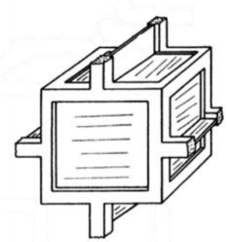
The **connectivity** has a crucial effect on how the deformation takes place within the structure *(Maxwell criteria)*

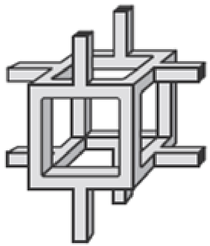
$$M = b - 3j + 6$$

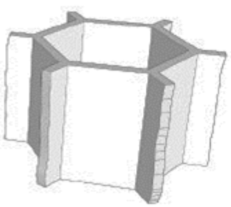
b: nb of struts
j: nb of frictionless joints

II.4. Cellular material characterization

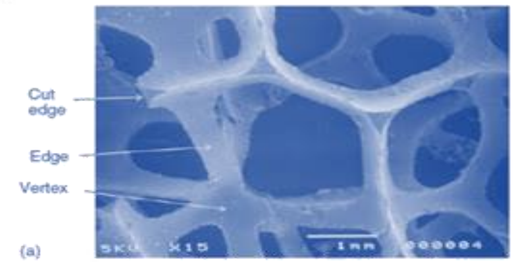
II.4.1. Geometry (architectures)

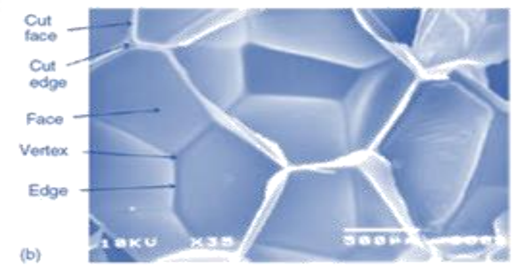






Material	Rigid polyurethane (Fig. 2.19)
Density, ρ^* (kg/m^3)	32
Open or closed cells	Closed
Edge connectivity, Z_e	4
Face connectivity, Z_f	3
Mean edges/face, $\bar{n}^*$	—
Mean faces/cell, $\bar{f}^*$	—
Cell shape*	—
Symmetry of structure	Axisymmetric
Cell edge thickness, t_e (μm)	30
Cell face thickness, t_f (μm)	3
Fraction of material in cell edges, ϕ	0.70
Largest principal cell dimension, $\bar{L}_1$ (mm)	0.53
Smallest principal cell dimension, $\bar{L}_3$ (mm)	0.44
Intermediate principal cell dimension, $\bar{L}_2$ (mm)	0.53
Shape anisotropy ratios, $R_{12} = \bar{L}_1/\bar{L}_2$ and $R_{13} = \bar{L}_1/\bar{L}_3$	$R_{12} = 1.0$; $R_{13} = 1.2$
Standard deviation of cell size (mm)	0.075
Other specific features (periodic variations in density, cell size, etc.)	None





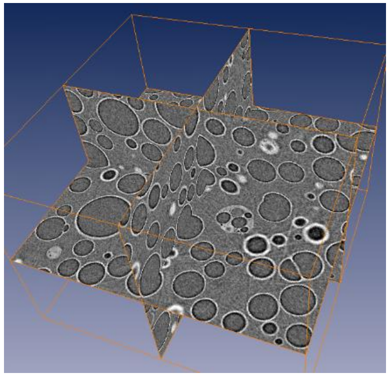
Tricky to characterize such microstructures based on 2D imaging techniques *(SEM, Optical microscope …)*

L. Gibson and M. Ashby, Cellular Solids, 1988

SEM photograph of (a) PU open-cell foam of density 28 kg m^{-3}; low density polyethylene (LDPE) foam of density 24 kg m^{-3}.

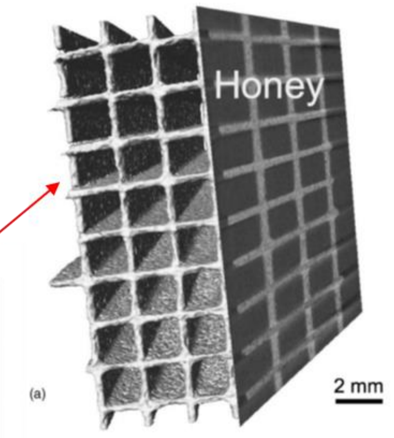
II.4. Cellular material characterization

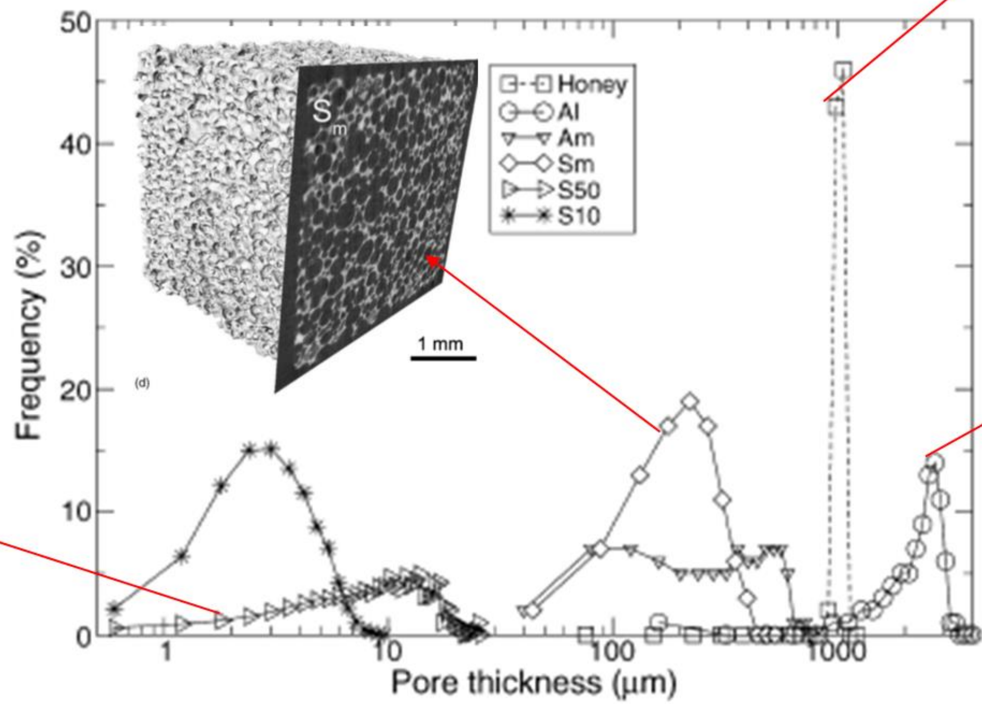
II.4.1. Geometry (architectures)



3D imaging techniques
& associated image processing

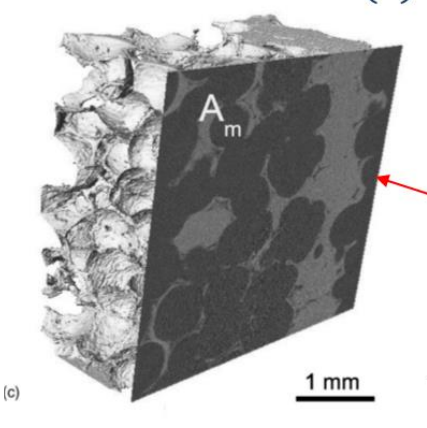
(X-ray computed tomography)

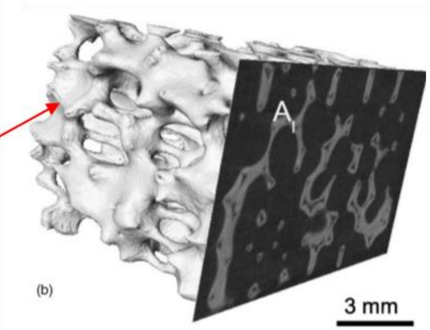




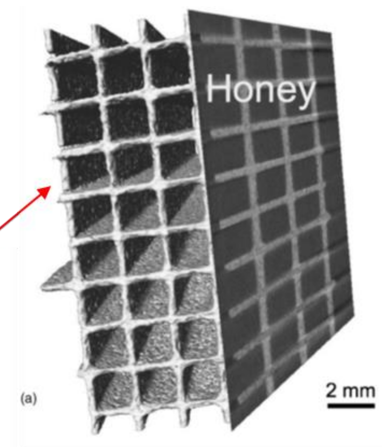
G(λ)

(λ)

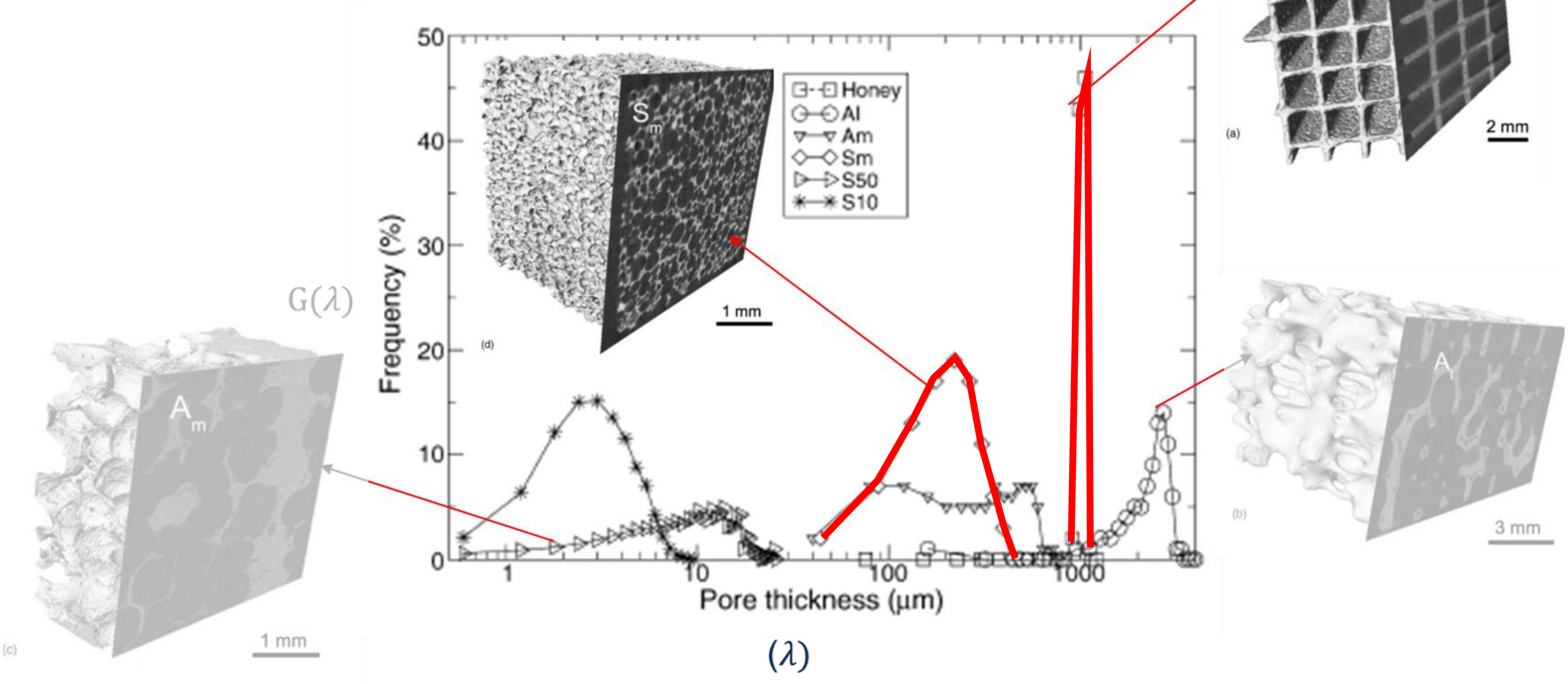




Specifically for stochastic materials, the number of cells along the main dimensions of the tested sample need to be sufficiently large so that the measured properties can be considered representative of the material.

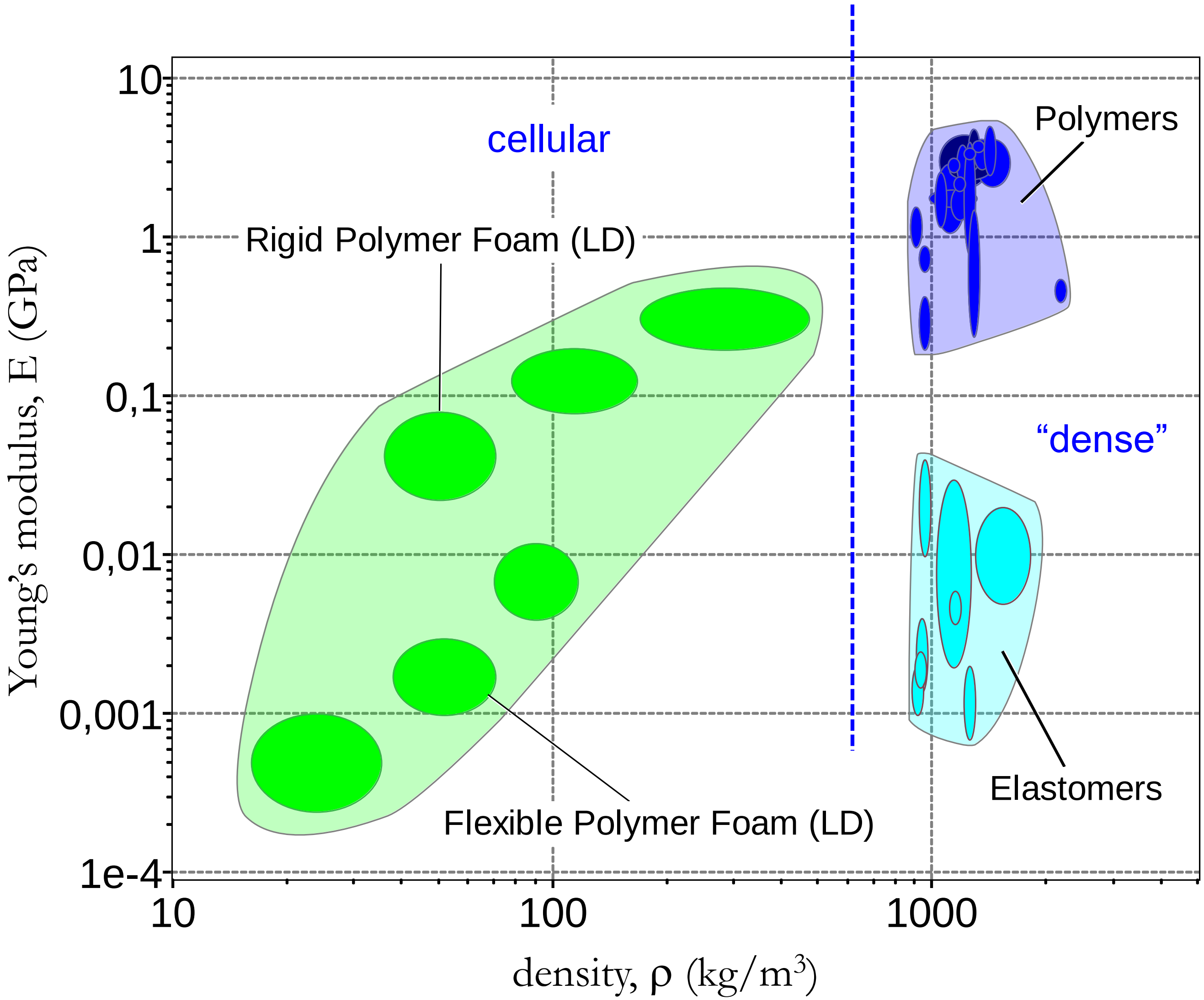


Statistically Representative Volume Element (SRVE)



II.5. Material & geometrical contributions

II.5.1. Open question



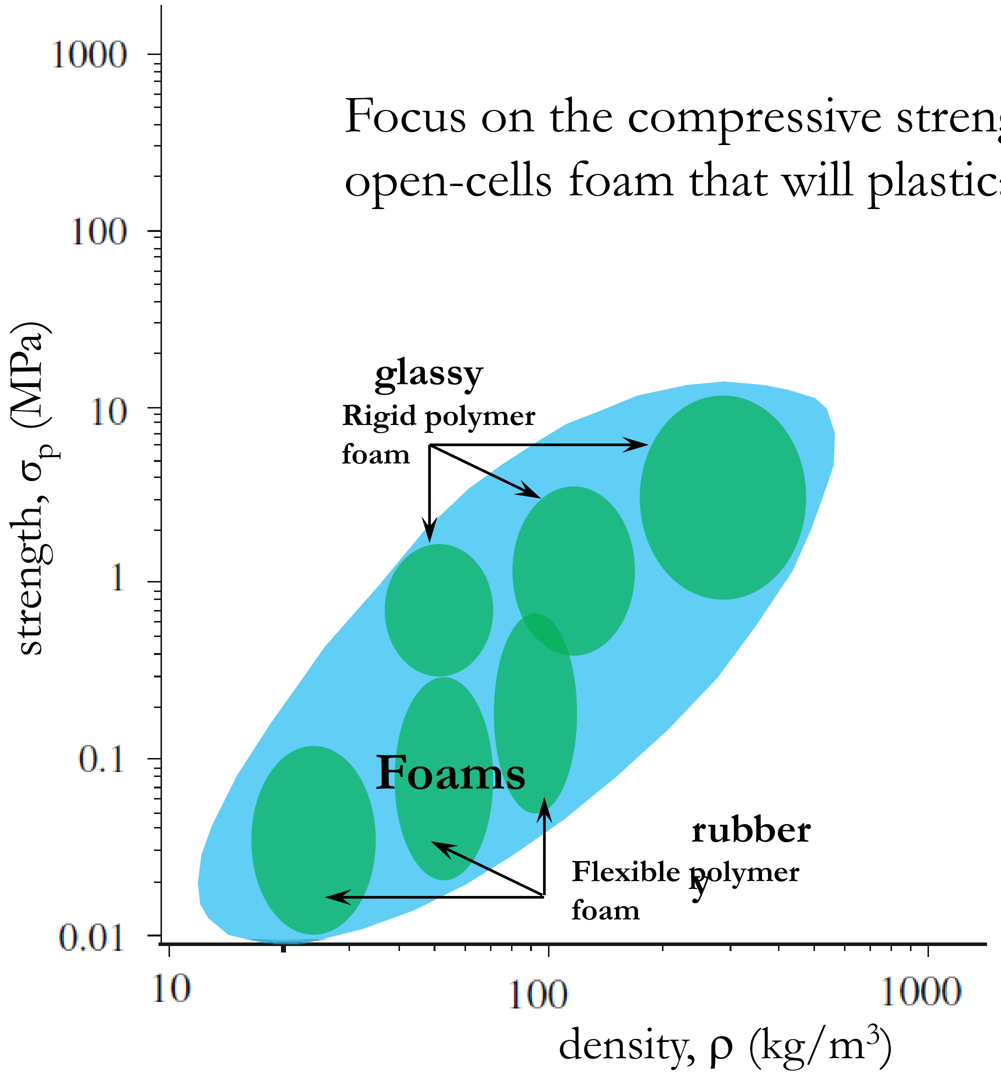
- Same architecture
- Different parent material

- Different architecture
- Same parent material

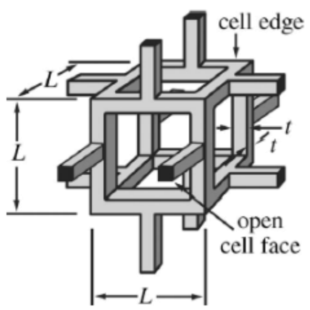
- Different architecture
- Different parent material

Dissociate the 2 contributions in order to "rank" the architectures

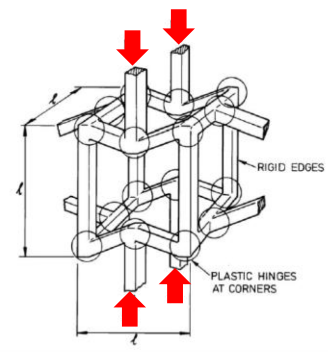
Focus on the compressive strength of an open-cells foam that will plastically "yield":



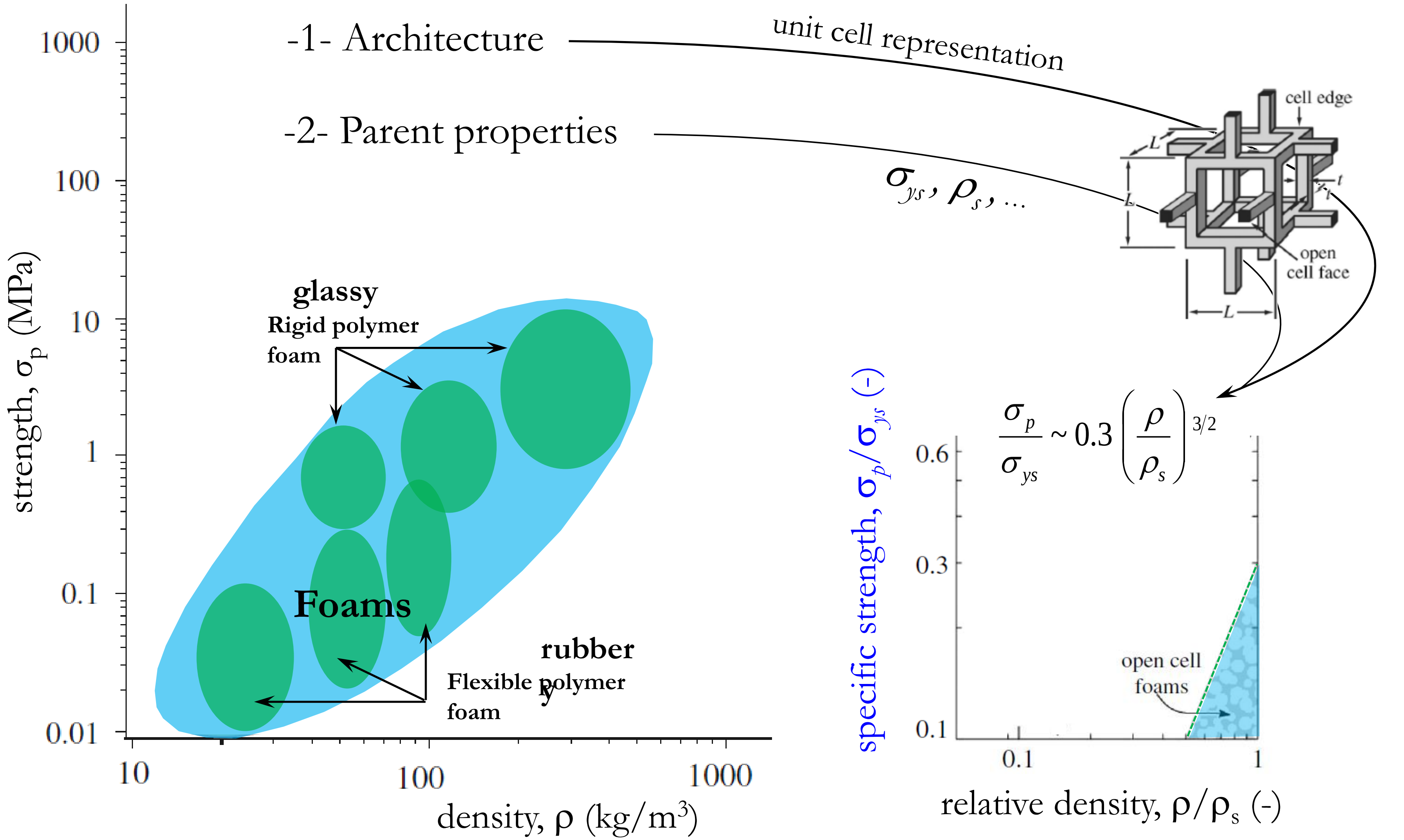
Ideal RVE



(at rest)



(yielded)

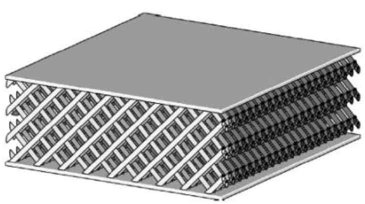


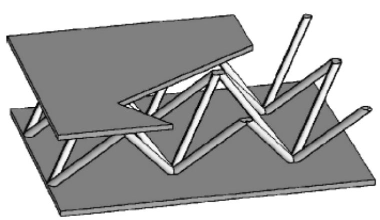
-1- Architecture
unit cell representation
-2- Parent properties
$\sigma_{ys}, \rho_s, \dots$
cell edge
open cell face
L
t
glassy
Rigid polymer foam
Foams
rubber
Flexible polymer foam
strength, σ_p (MPa)
1000
100
10
1
0.1
0.01
10
100
1000
density, ρ (kg/m^3)
$\frac{\sigma_p}{\sigma_{ys}} \sim 0.3 \left(\frac{\rho}{\rho_s}\right)^{3/2}$
specific strength, σ_p/σ_{ys} (-)
0.6
0.3
0.1
open cell foams
relative density, ρ/ρ_s (-)

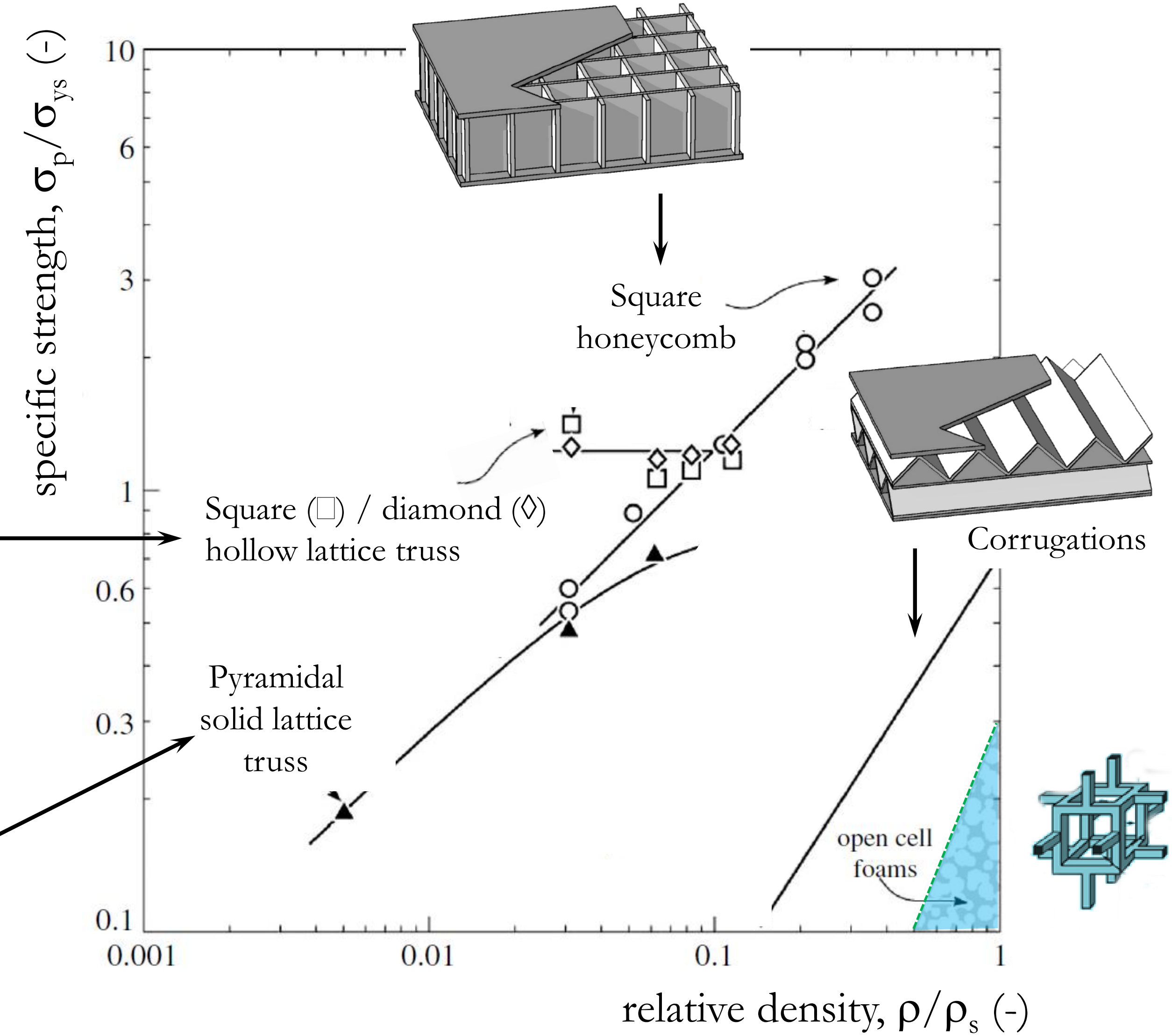
II.5. Material & geometrical contributions

II.5.2. Specific properties

Foams seem useless …



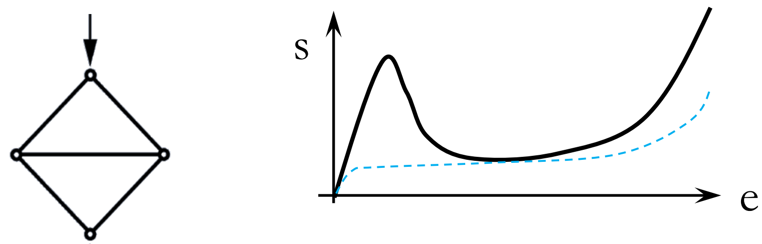




II. Generalities

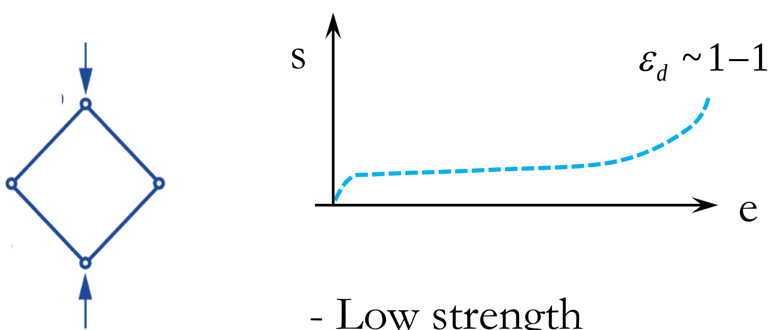
II.6. Crushing response

stretching dominated



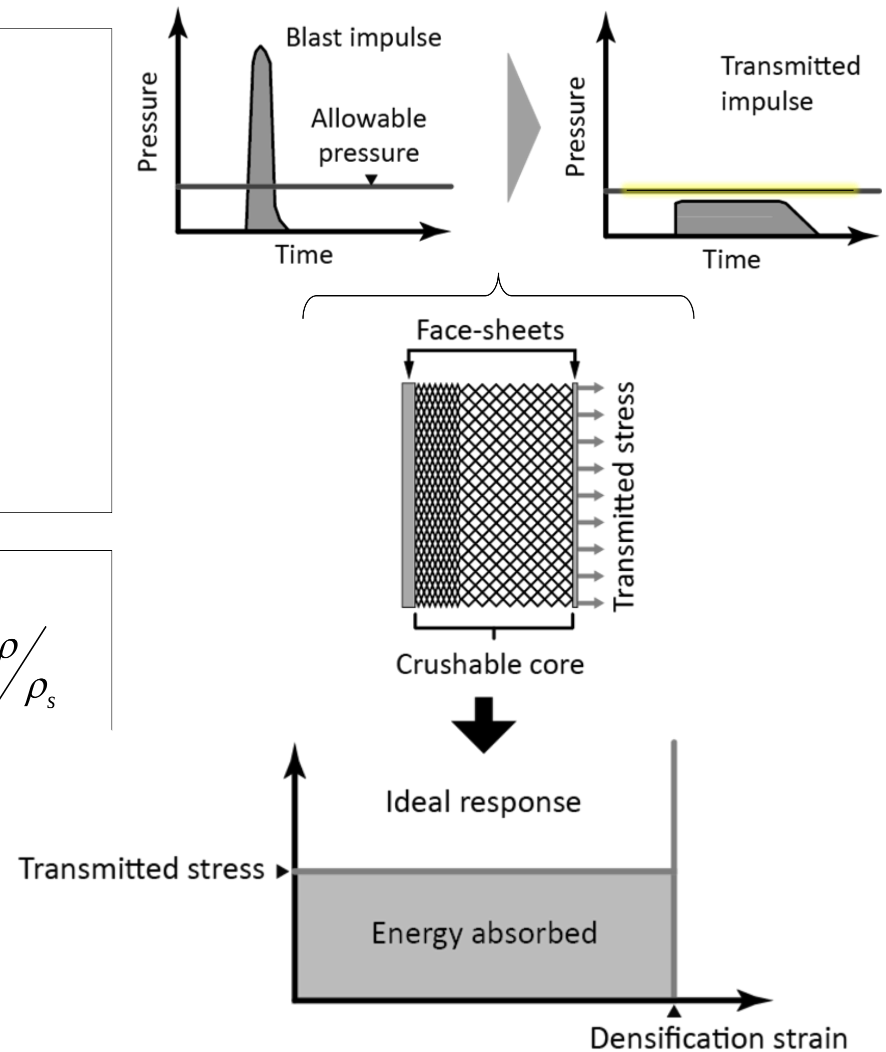
- High strength

bending dominated

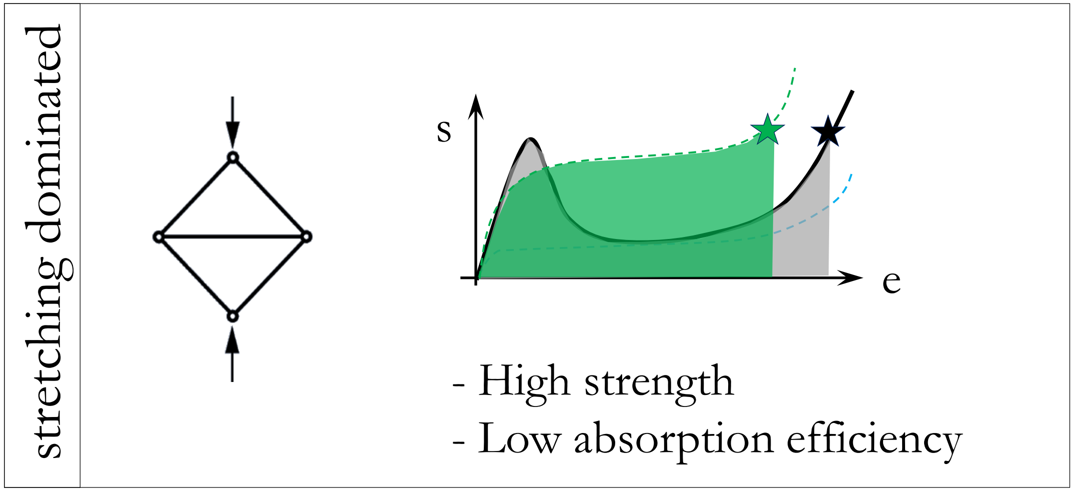


$\varepsilon_d \sim 1 - 1.4 \, \rho / \rho_s$

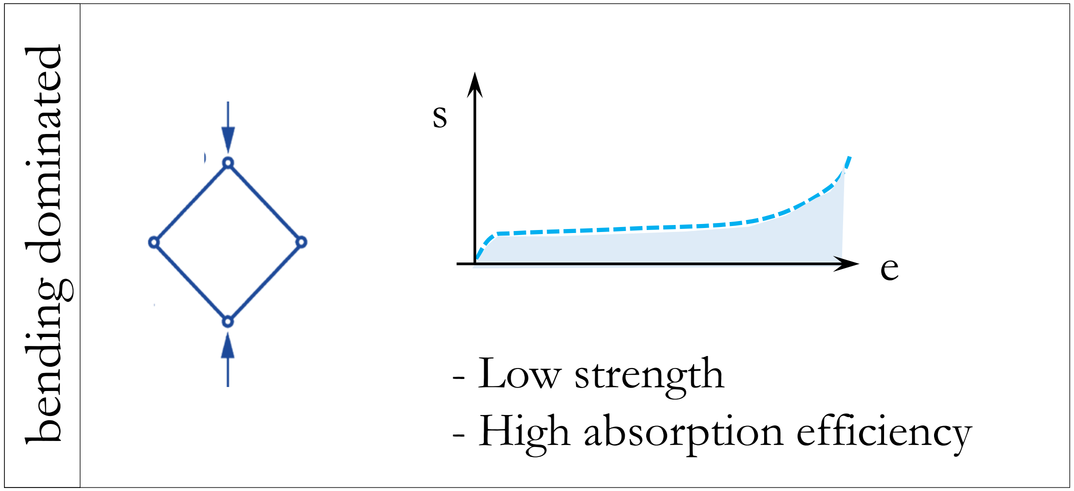
- Low strength



II.6. Crushing response

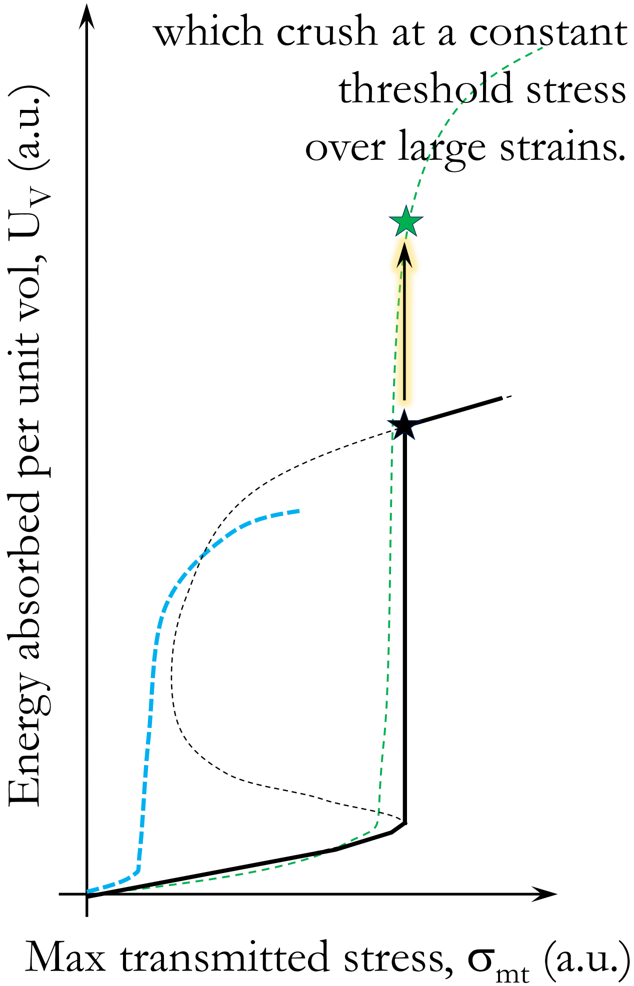


- High strength
- Low absorption efficiency

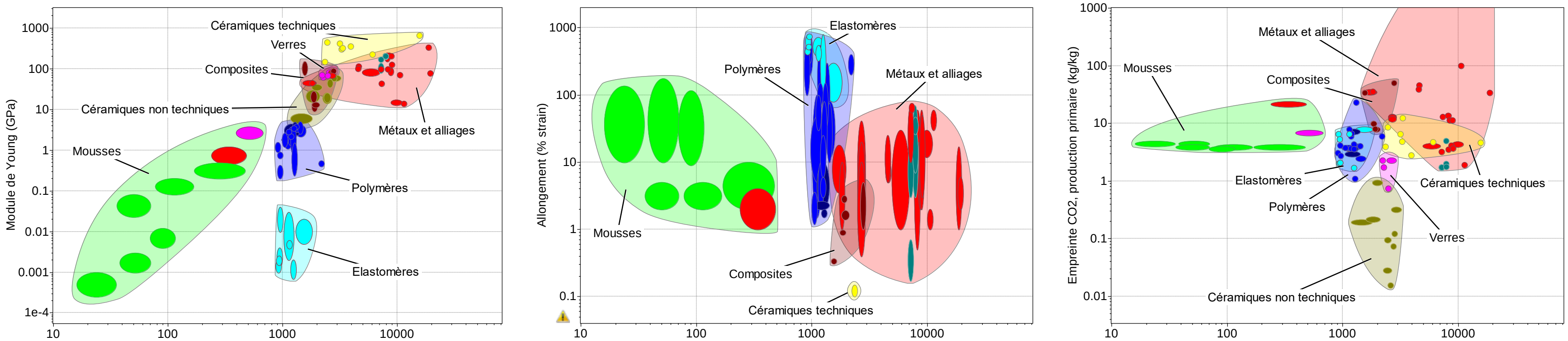


- Low strength
- High absorption efficiency

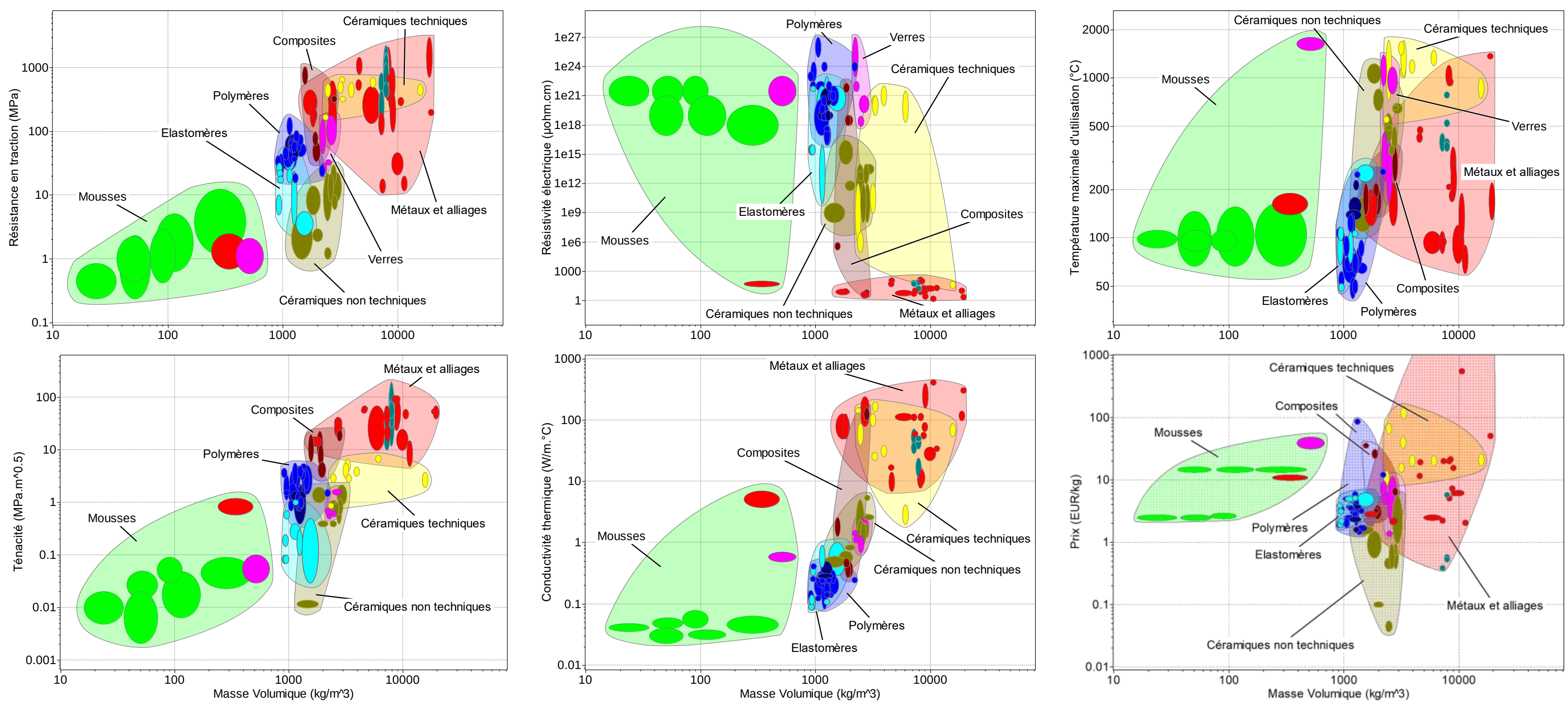
Energy absorption applications demand (lightweight) materials which crush at a constant threshold stress over large strains.



II. Generalities: Summary



Parent material properties & **geometry** trigger the cellular materials properties



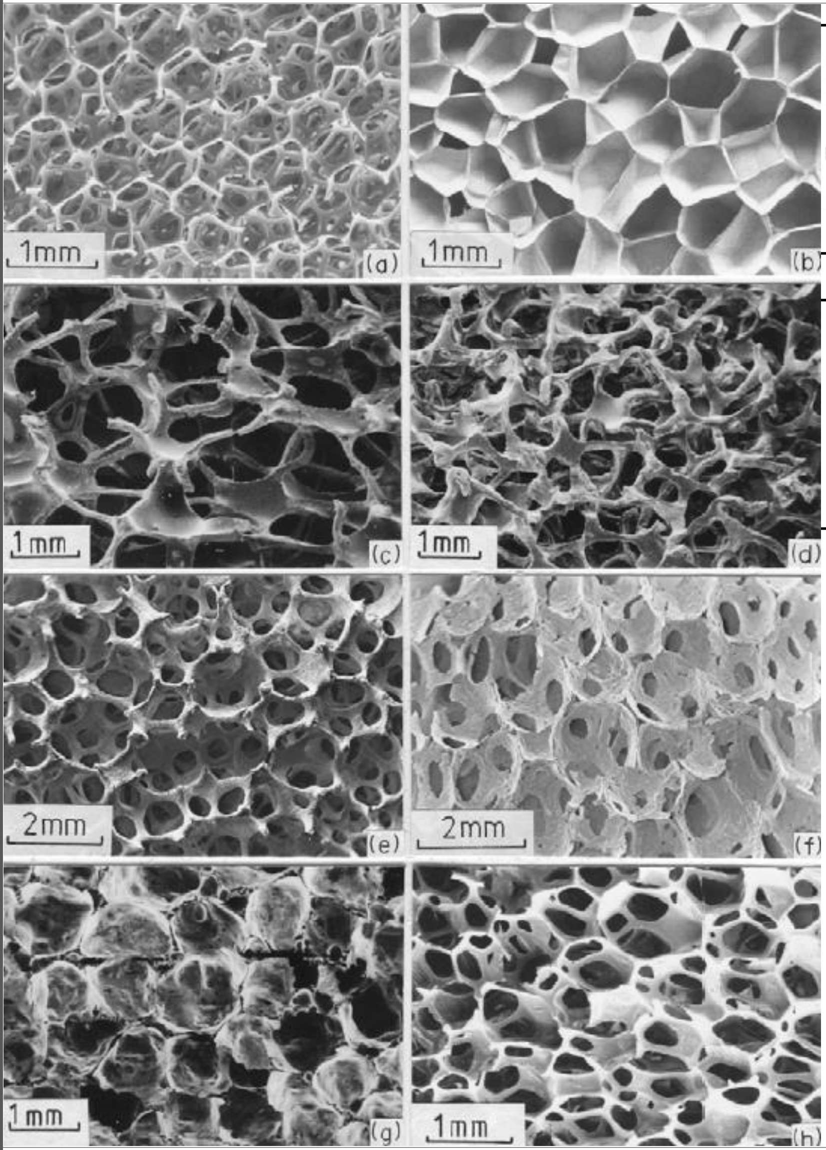
Cellular (solids) materials

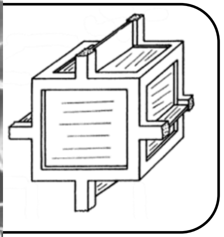
GM5 – CE

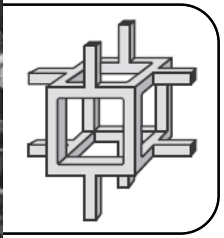
III - FOAMS

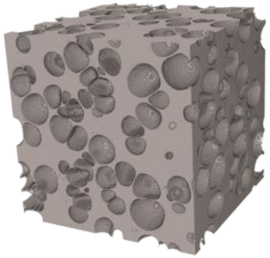
III. Foams

III.1. Examples





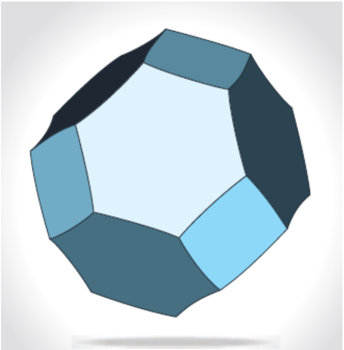




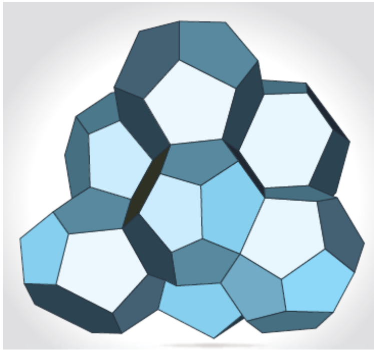
← *Elastomeric foam of a table tennis racket pad*

Various microstructures justifying the use/definition of different ideal unit cells (RVE)

Kelvin cell
Tetrakaidecahedron
(14 faces)

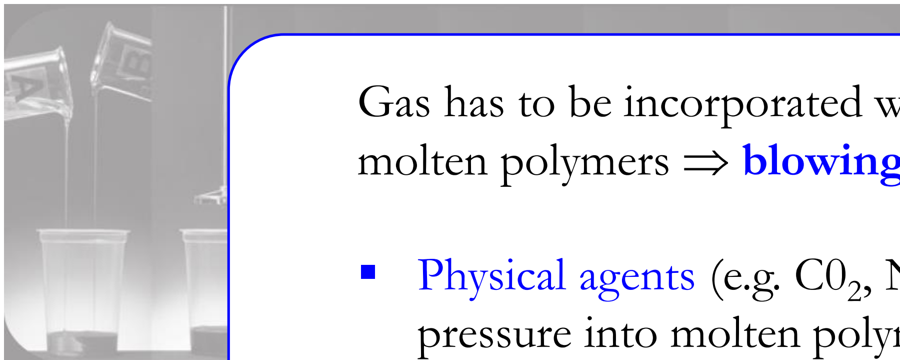


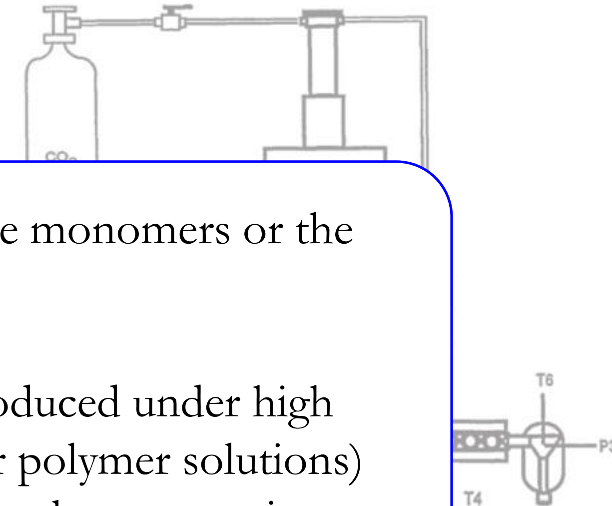
Weaire & Phelan cells
(isovolume and maximized specific surface area)



↑ *L. Gibson and M. Ashby, Cellular Solids, 1988*

III.2. Processing



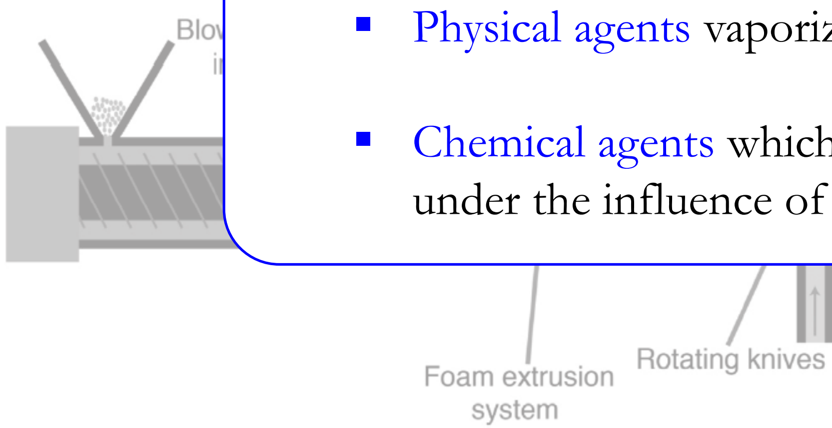


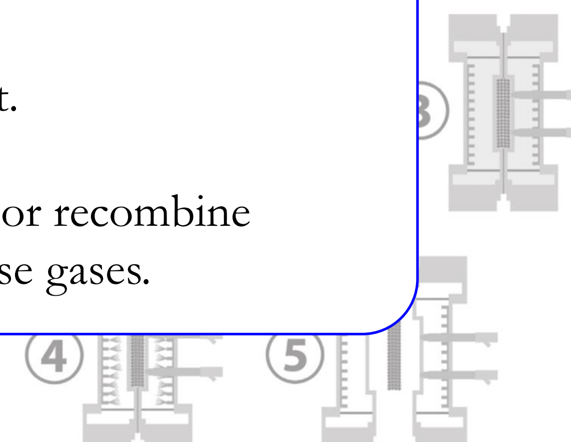
Gas has to be incorporated within the monomers or the molten polymers ⇒ **blowing agent**

- Physical agents (e.g. $C0_2$, N_2) introduced under high pressure into molten polymers (or polymer solutions) which then expand to form bubbles by progressive pressure reduction.

- Physical agents vaporizing with heat.

- Chemical agents which decompose or recombine under the influence of heat to release gases.



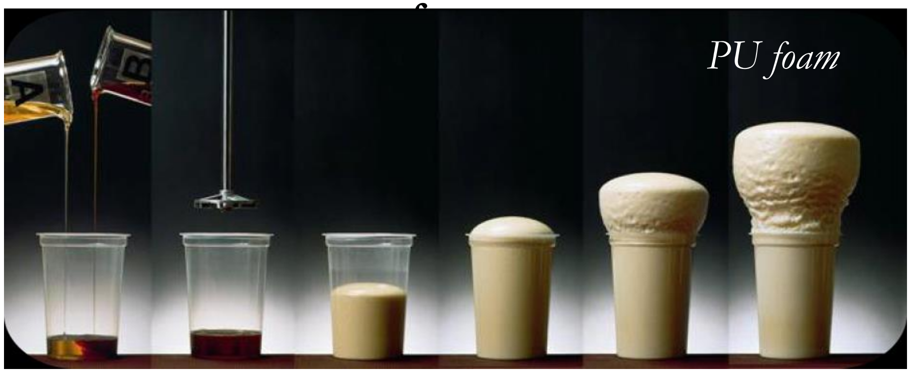


Raps et. al., Polymer, 2015

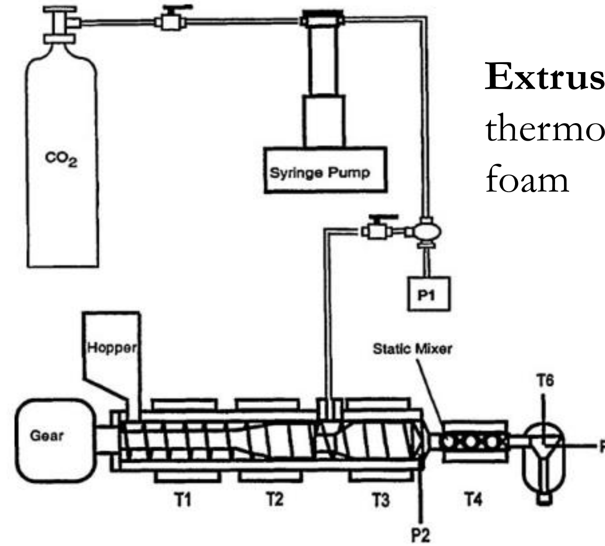
III. Foams

III.2. Processing

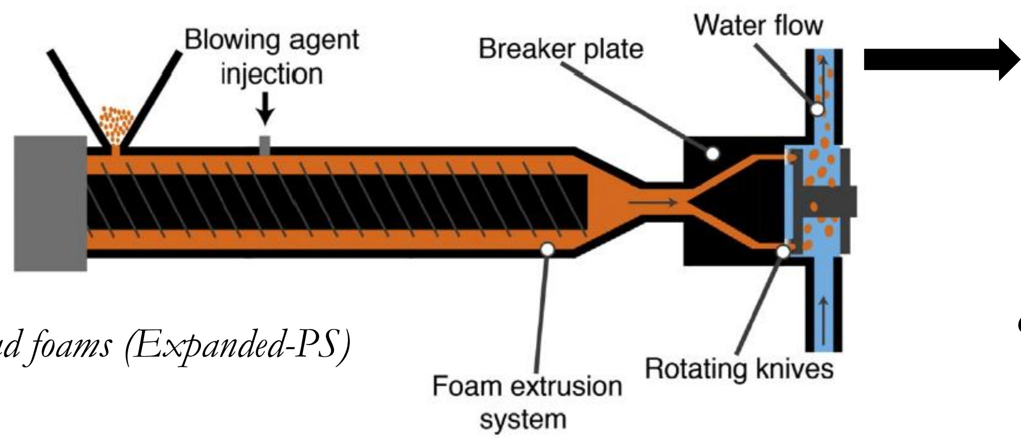
Part A & B are **mixed** + **blowing agent** +



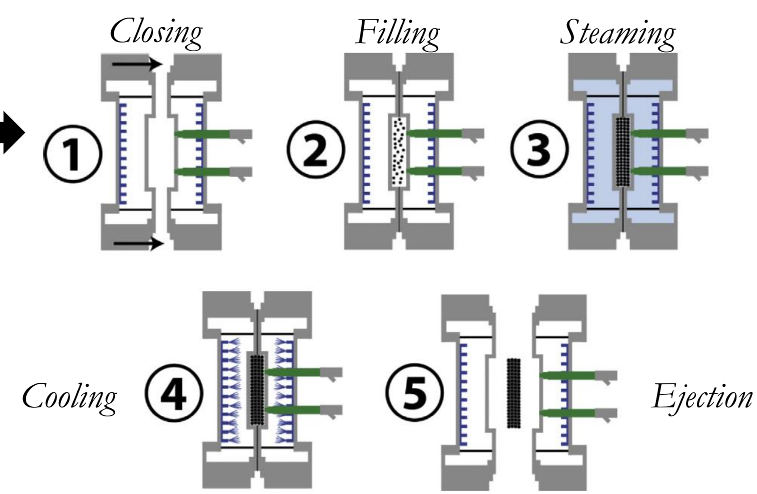
Extrusion of thermoplastic foam



Steam chest molding



Bead foams (Expanded-PS)

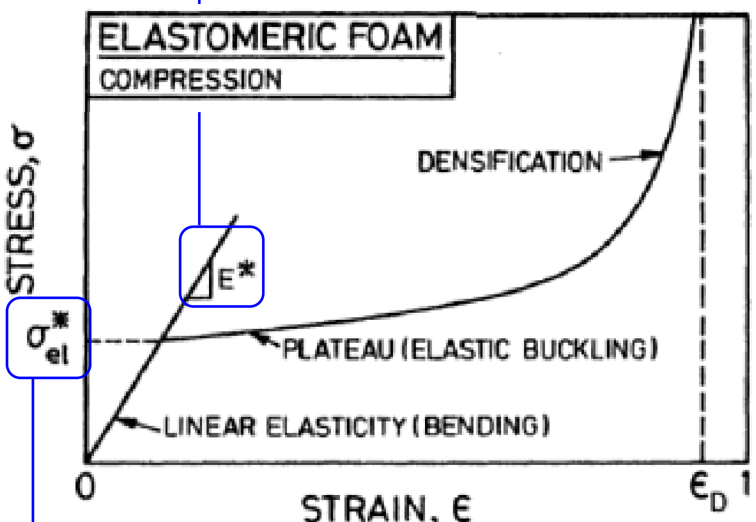


III. Foams

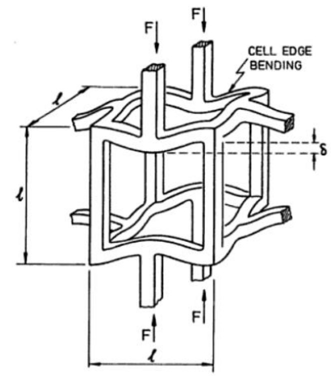
III.3. Mechanical properties: compression

Macroscopic behavior

3 regimes are evidenced:
Linear, Plateau, densification



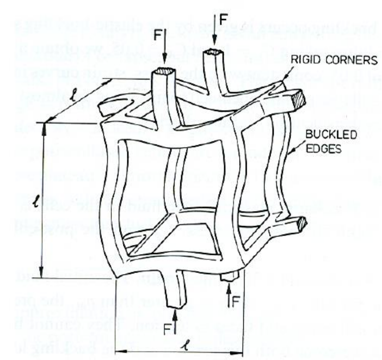
Micromechanical predictions



Bending of the edges

$$\frac{E}{E_s} = C_1 \left[\frac{\rho}{\rho_s}\right]^2$$

$C_1 \approx 1$ (exp. data)



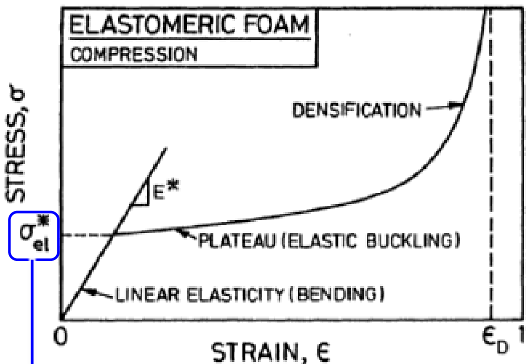
Elastic buckling of the edges

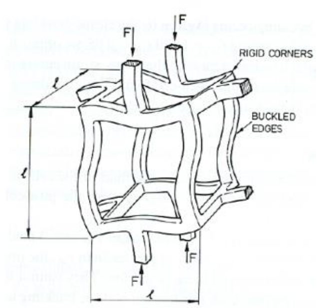
$$\frac{\sigma_y}{E_s} = C_4 \left[\frac{\rho}{\rho_s}\right]^2$$

$C_4 \approx 0.05$ (exp. data)

L. Gibson and M. Ashby, Cellular Solids, 1988

III.3. Mechanical properties: compression

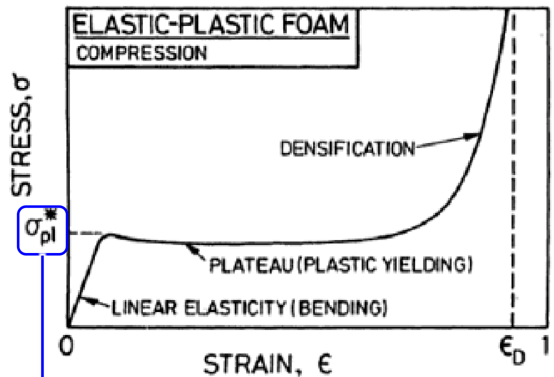


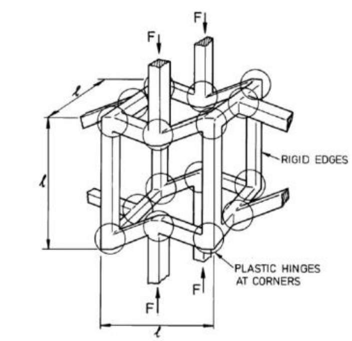


Elastic buckling *of the edges*

$$\sigma_y = C_4 \left[\frac{\rho}{\rho_s}\right]^2 E_s$$

$C_4 \approx 0.05$ (exp. data)

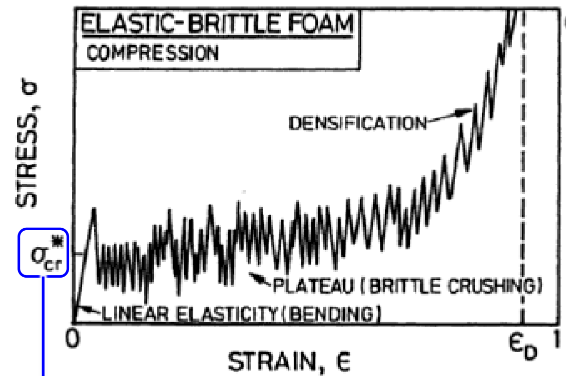


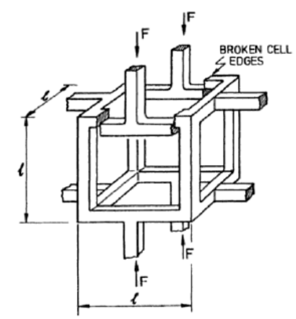


Plastic hinging *of the edges*

$$\sigma_y = C_5 \left[\frac{\rho}{\rho_s}\right]^{3/2} \sigma_{ys}$$

$C_5 \approx 0.3$ (exp. data)





Brittle failure *of the edges*

$$\sigma_y = C_6 \left[\frac{\rho}{\rho_s}\right]^{3/2} \sigma_{rs}$$

$C_6 \approx 0.2$ (exp. data)

L. Gibson and M. Ashby, Cellular Solids, 1988

INSA INSTITUT NATIONAL DES SCIENCES APPLIQUÉES LYON

GM5

Cellular (solids) materials

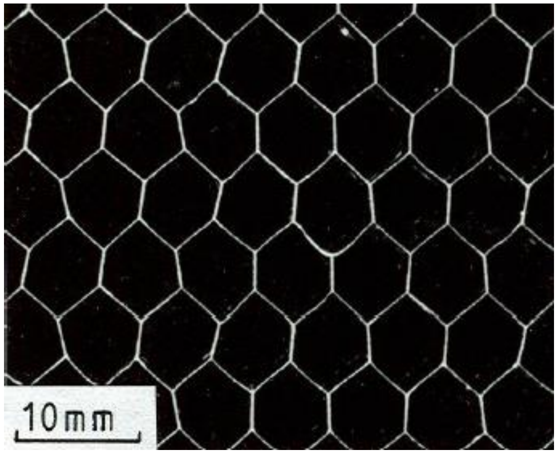
GM5 – CE

IV - HONEYCOMBS

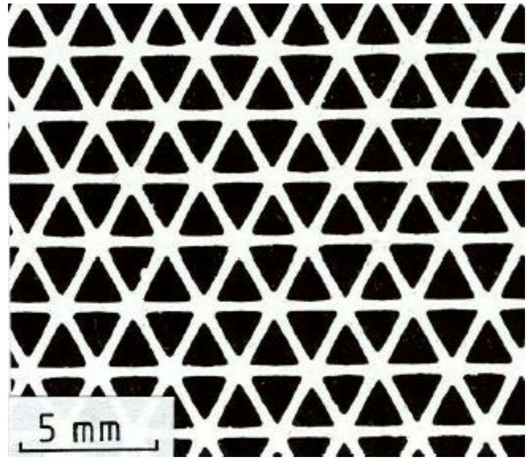
IV. Honeycombs

IV.1. Examples

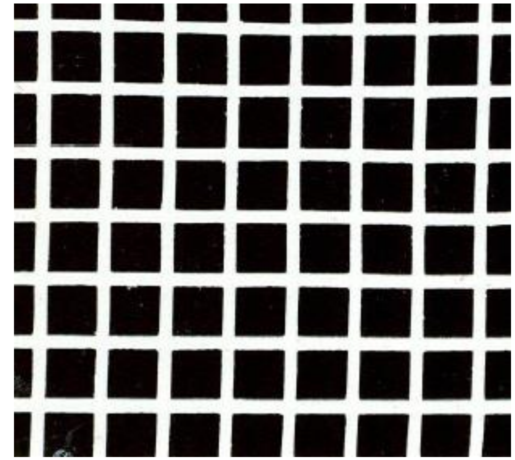
Hexagonal / *Aluminium*

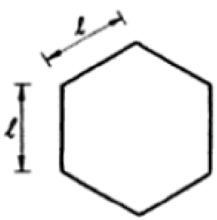


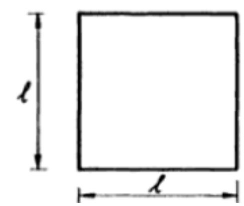
Triangular / *Aluminium*



Cubic / *Ceramic*





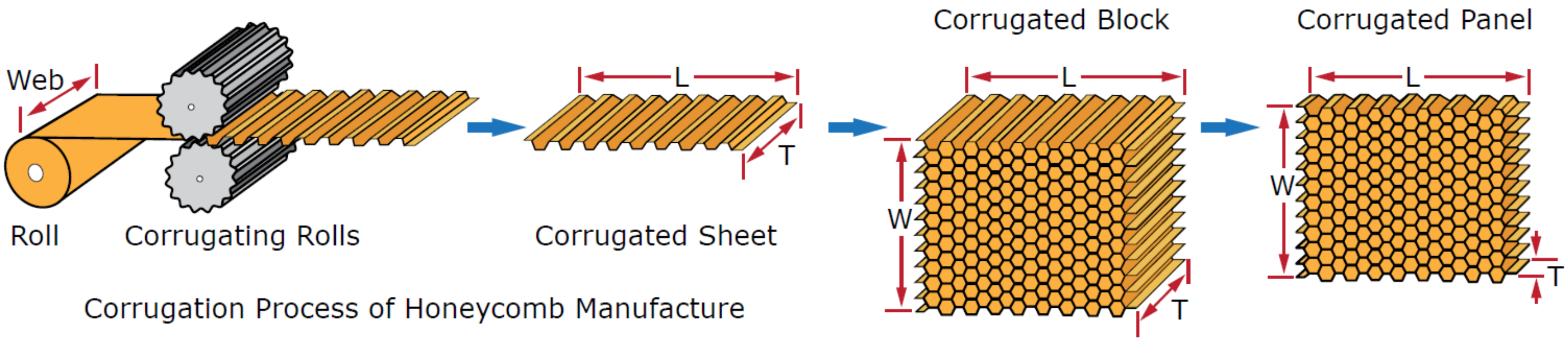


Relative density: $$\phi = \frac{\rho}{\rho_s} = C_1 \frac{t}{l}$$

- t — Walls thickness
- l — Walls length
- C_1 — Constant depending on the cells geometry

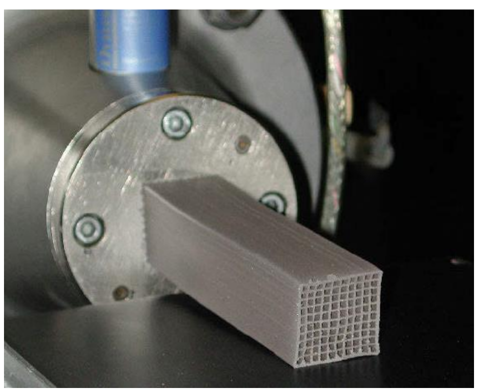
IV. Honeycombs

IV.1. Processing



Corrugation Process of Honeycomb Manufacture

Extrusion

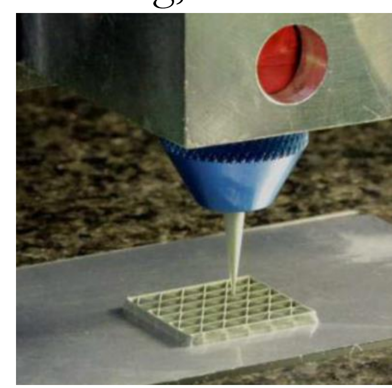


http://ocw.mit.edu/help/faq-fair-use/

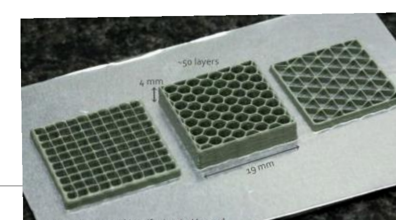
Injection molding

(BMW i3)

Casting, …

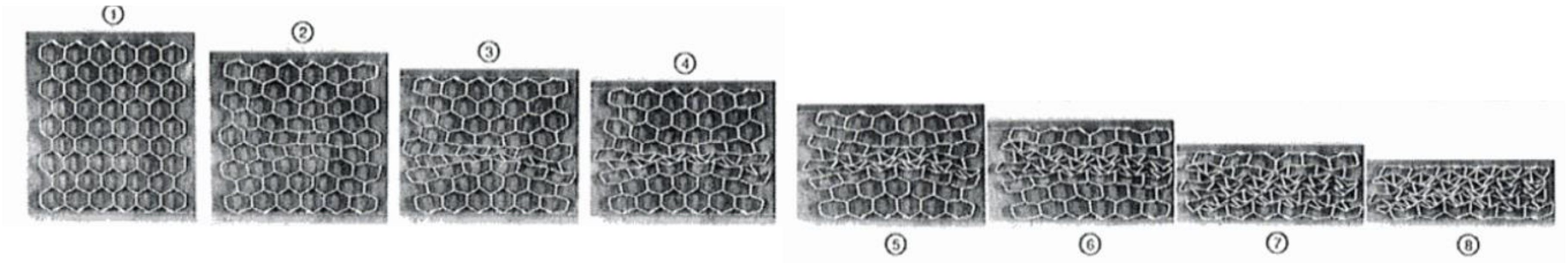


3D printing



IV. Honeycombs

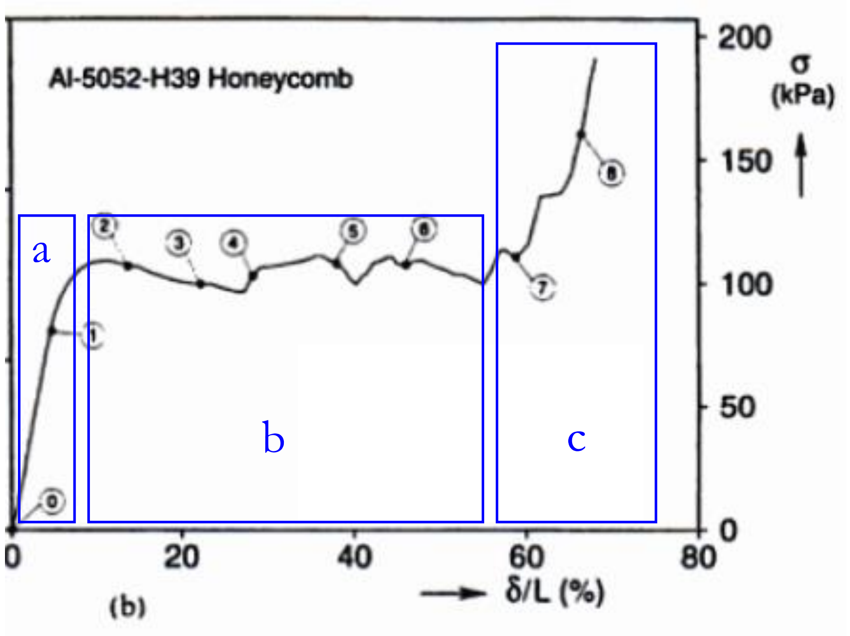
IV.1. Mechanical properties: compression

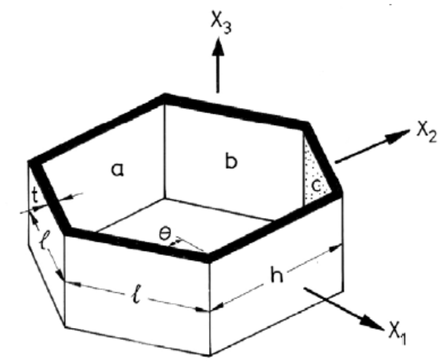


a. Linear regime

b. Plateau regime

c. Densification





$$\frac{E_3}{E_2} \approx \left[\frac{l}{t}\right]^2 \gg 1$$

Pronounced anisotropy

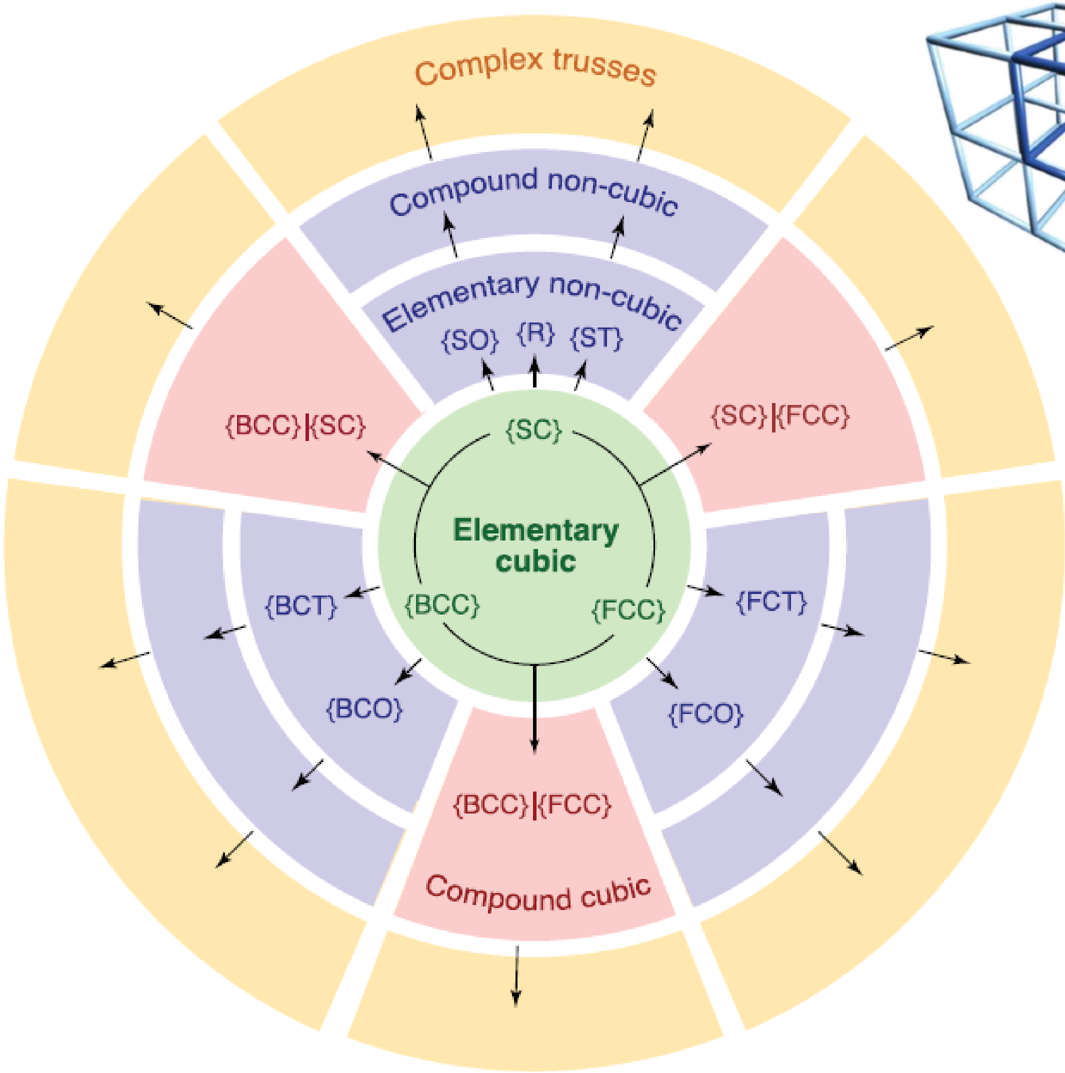
Cellular (solids) materials

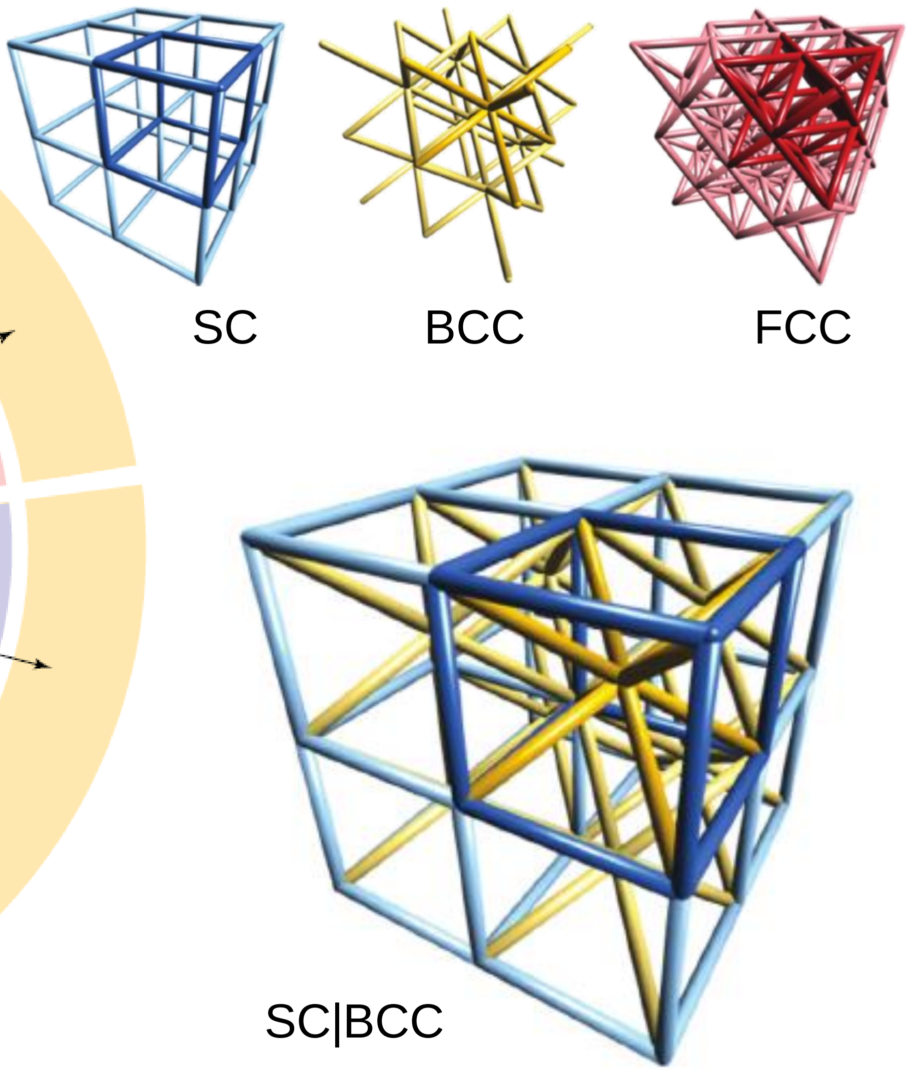
GM5 – CE

V - LATTICES

V. Lattices

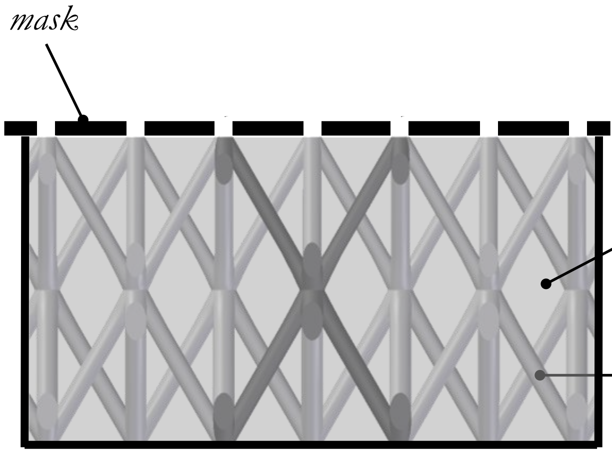
V.1. Taxonomy





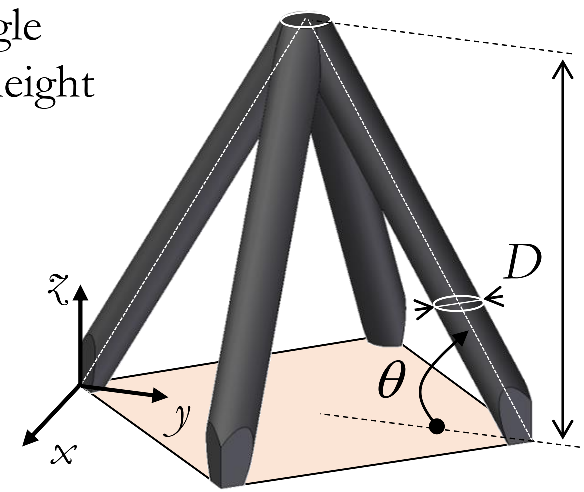
V. Lattices

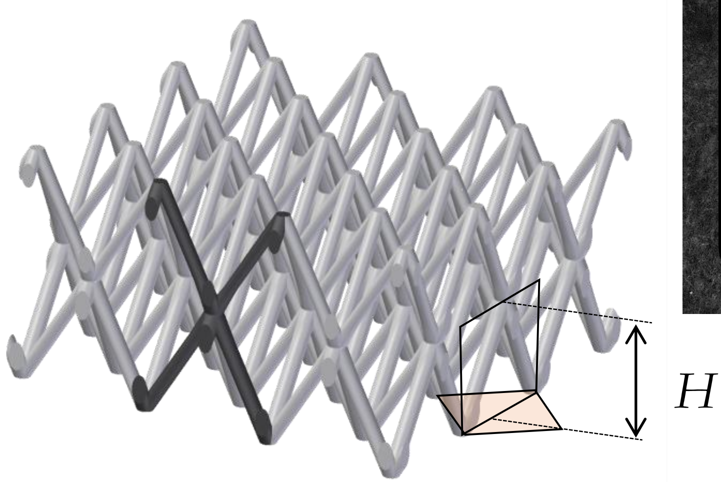
V.2. Materials by design: an example

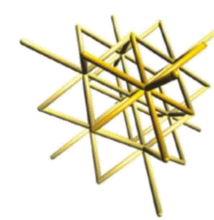


R.V.E.

Mask (apertures, dispersion)
N_l: Number of layers
N_s: Number of merging struts
θ: Strut angle
H: Lattice height

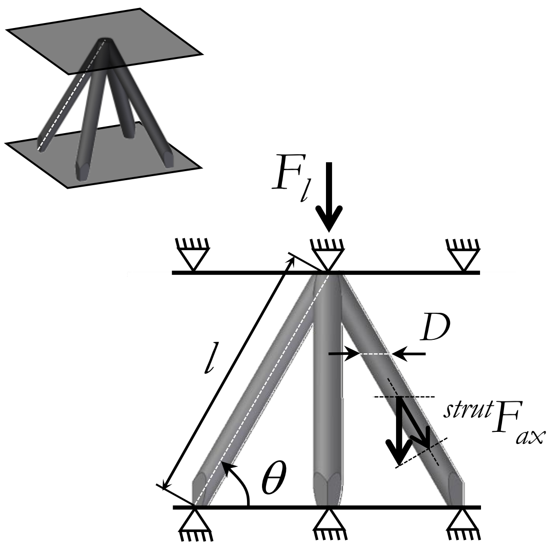






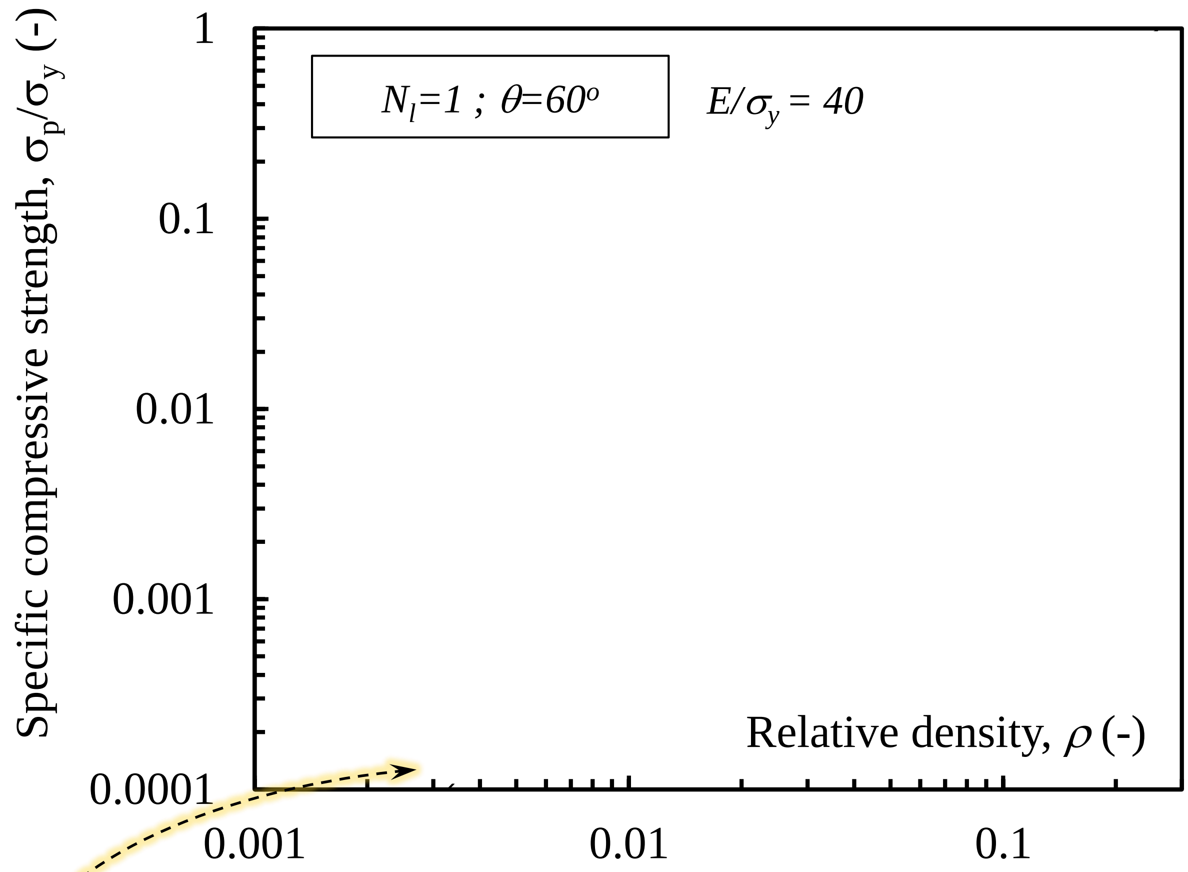
V. Lattices

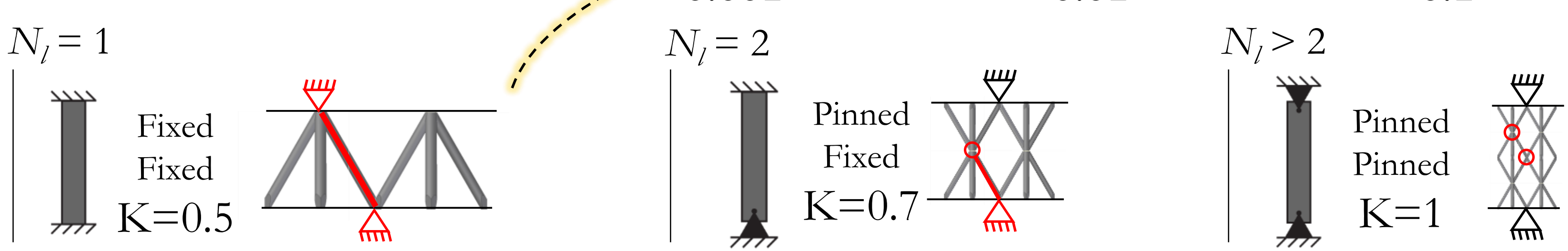
V.2. Materials by design: an example



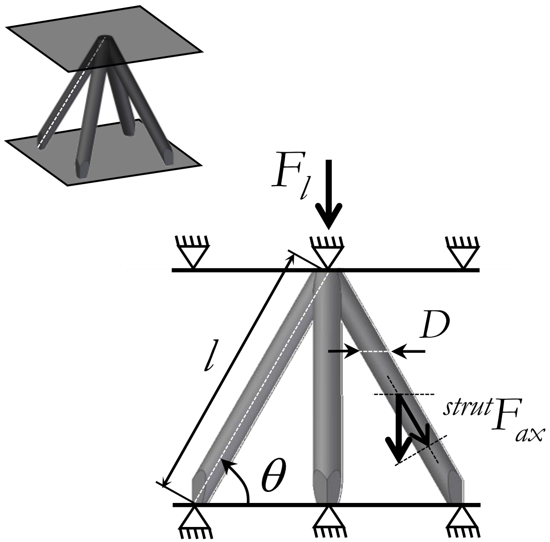
Buckling:

$$^{strut}F_{ax} = \frac{\pi^3 E D^4}{(8Kl)^2 \cos^3\theta}$$





V.2. Materials by design: an example

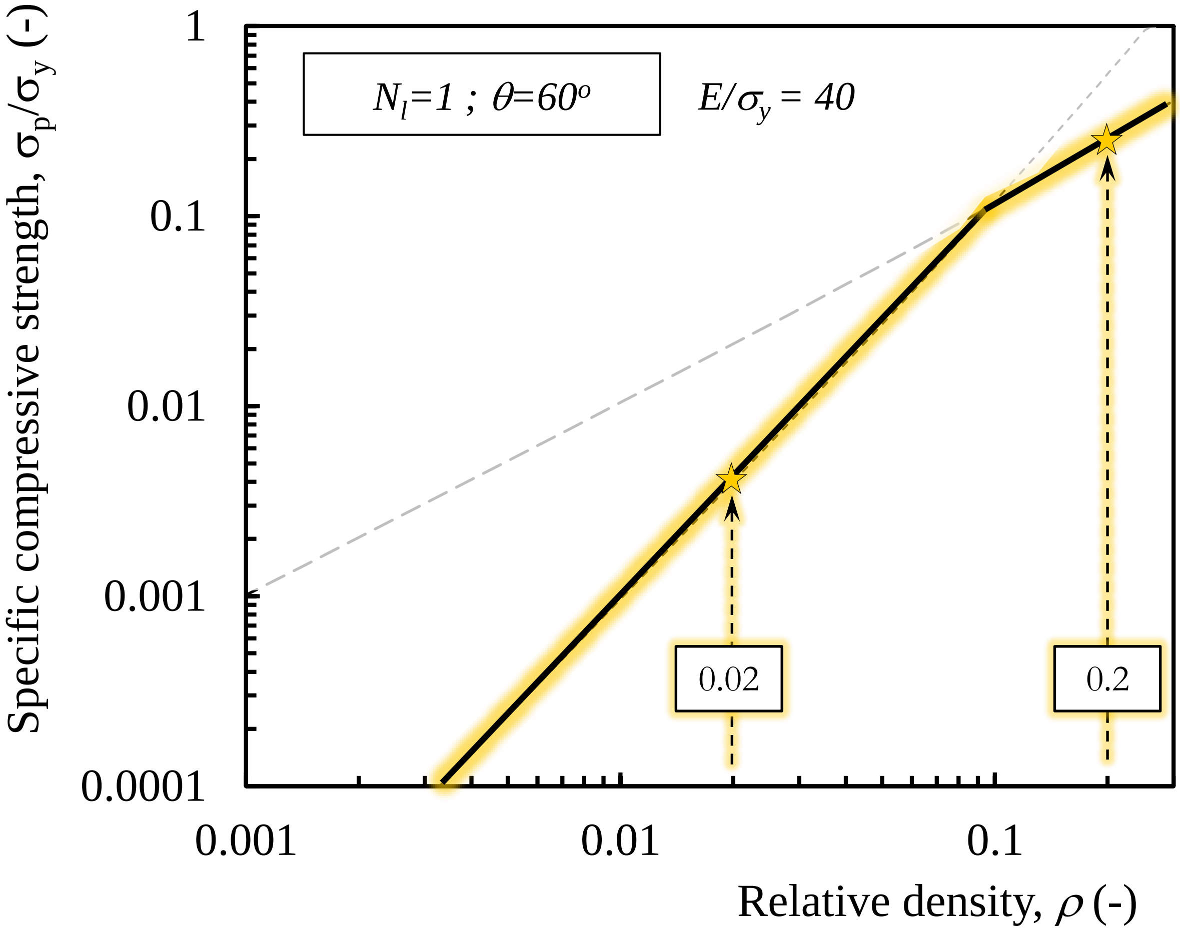


Buckling:

$$^{strut}F_{ax} = \frac{\pi^3 E\, D^4}{(8Kl)^2 \cos^3\theta}$$

Yielding:

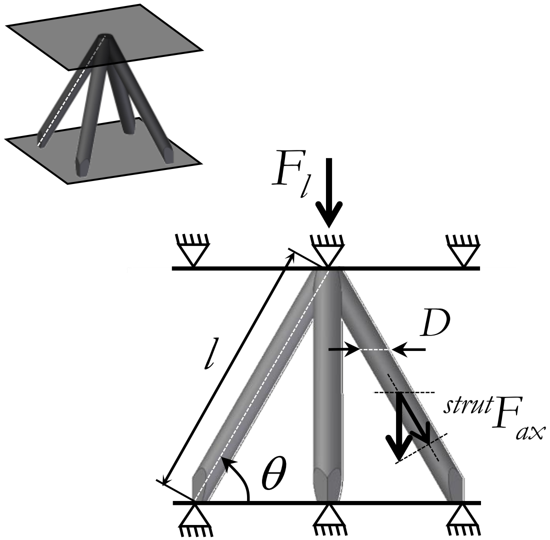
$$^{strut}F_{ax} = \sigma_y \left(\frac{\pi}{4} D^2 \cos\theta \right)$$



The failure mode is triggered by the **geometry** of the lattice

V. Lattices

V.2. Materials by design: an example

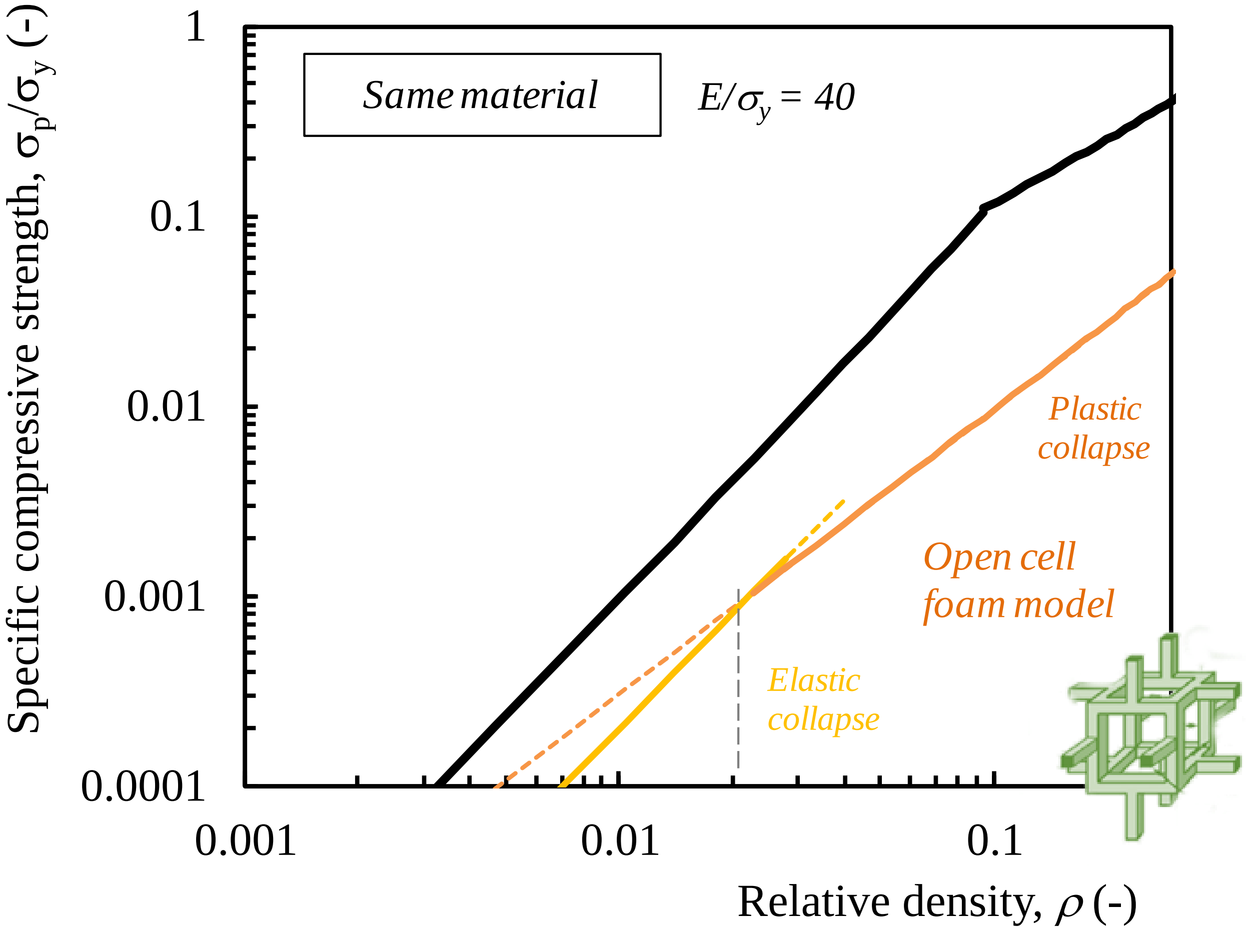


Buckling:

$$^{strut}F_{ax} = \frac{\pi^3 E D^4}{(8Kl)^2 \cos^3\theta}$$

Yielding:

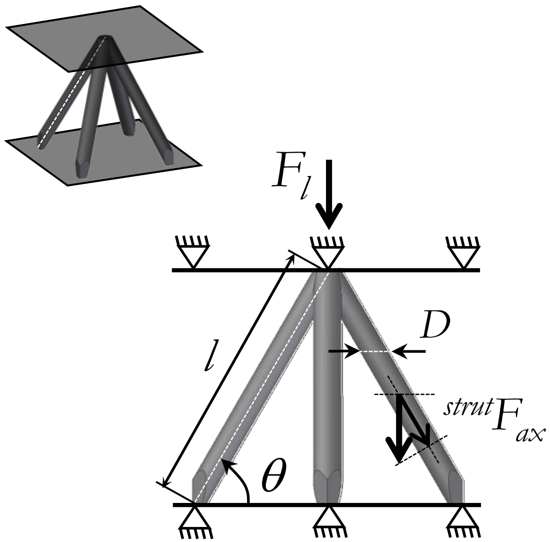
$$^{strut}F_{ax} = \sigma_y \left(\frac{\pi}{4} D^2 \cos\theta \right)$$



The failure mode is triggered by the **geometry** of the lattice

V. Lattices

V.2. Materials by design: an example

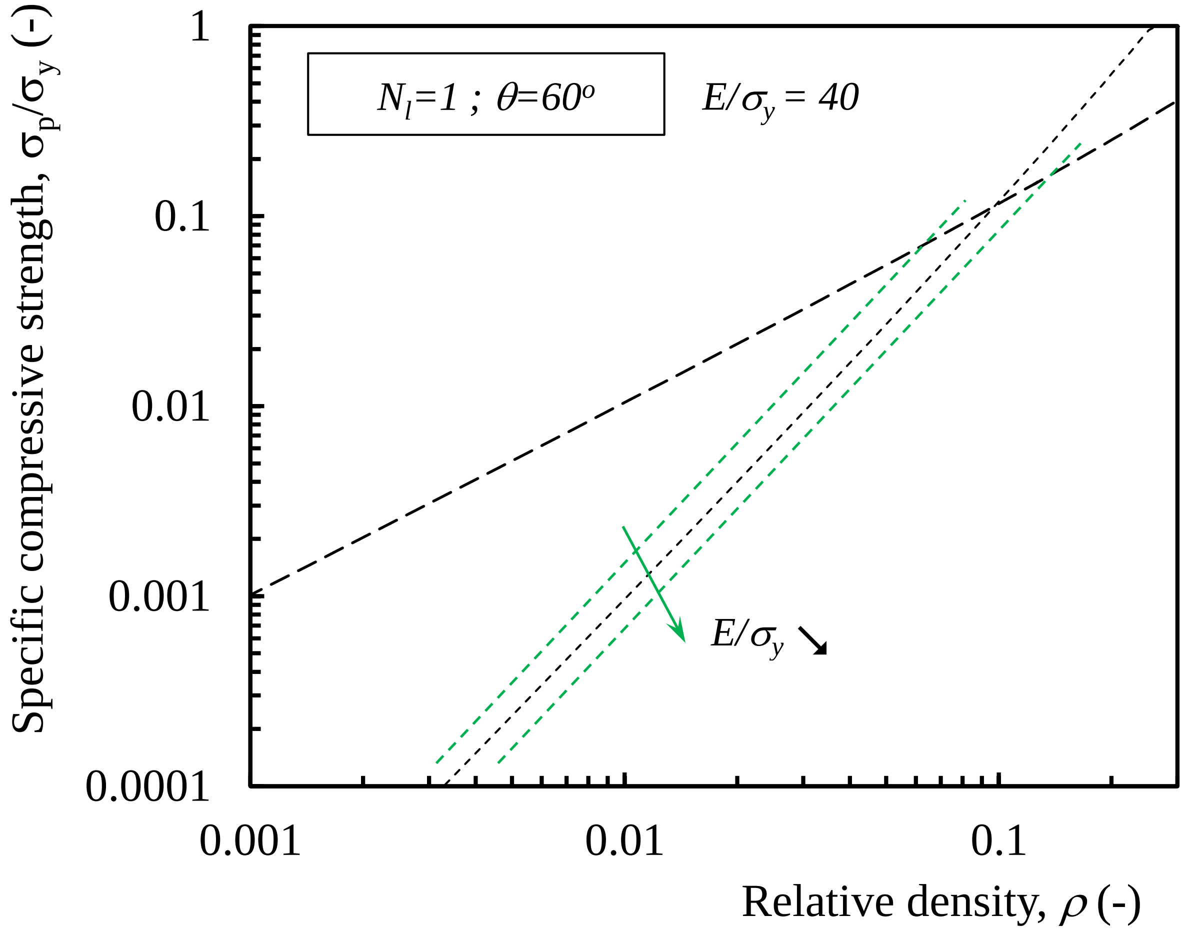


Buckling:

$$ {}^{strut}F_{ax} = \frac{\pi^3 E\, D^4}{(8Kl)^2 \cos^3\theta} $$

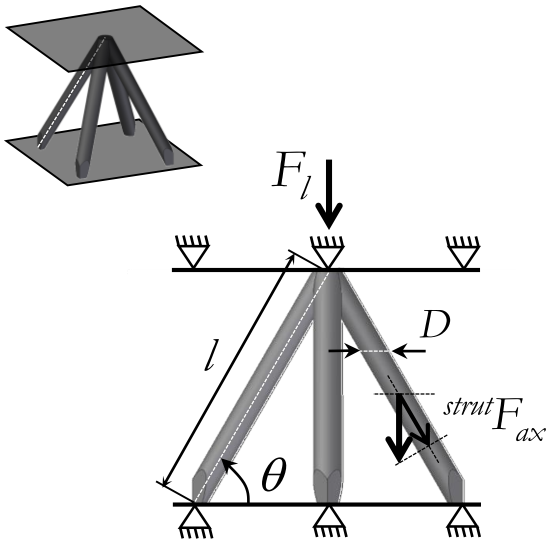
Yielding:

$$ {}^{strut}F_{ax} = \sigma_y \left(\frac{\pi}{4} D^2 \cos\theta \right) $$



The failure mode is triggered by the parent **material properties** (and its sensitivities)

V.2. Materials by design: an example

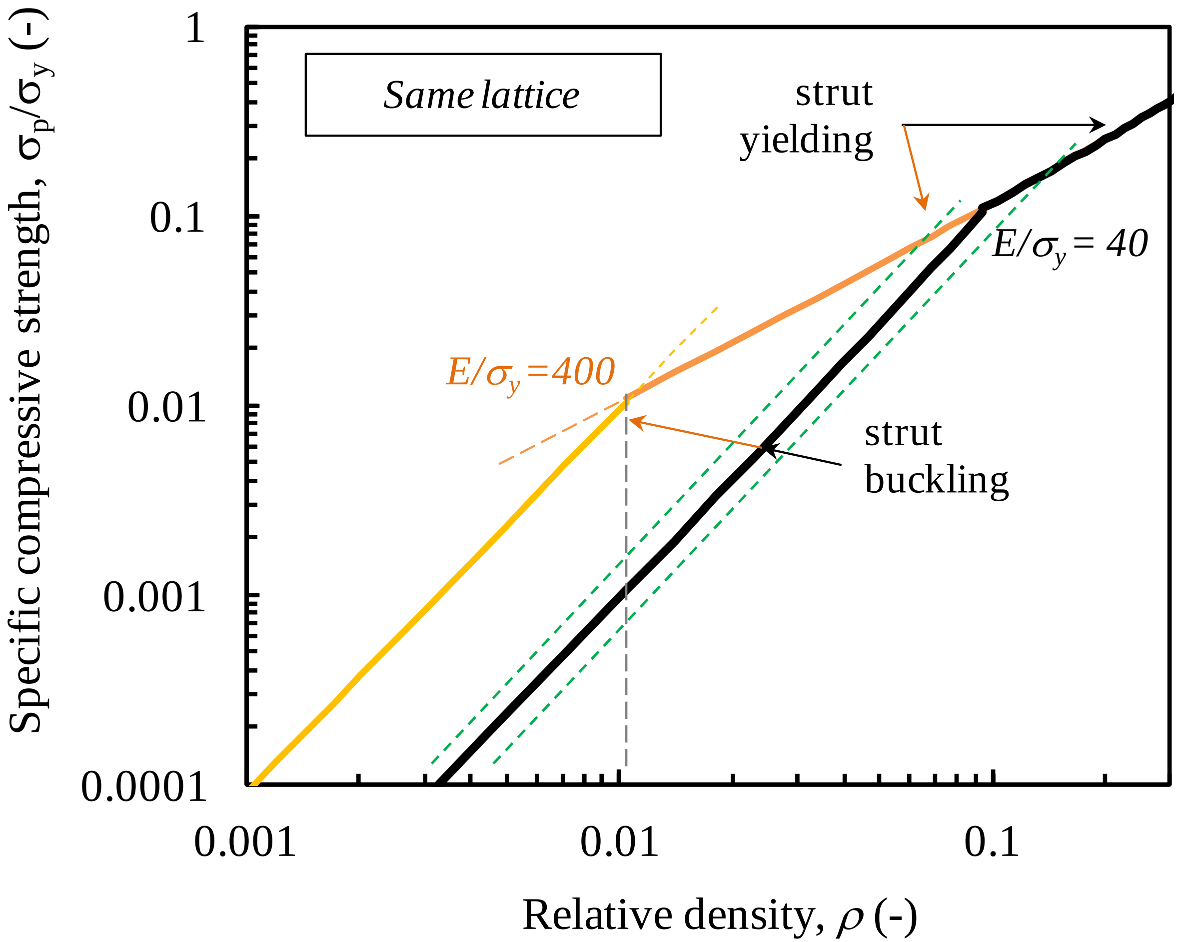


Buckling:

$$^{strut}F_{ax} = \frac{\pi^3 E\, D^4}{(8Kl)^2 \cos^3\theta}$$

Yielding:

$$^{strut}F_{ax} = \sigma_y \left(\frac{\pi}{4} D^2 \cos\theta\right)$$

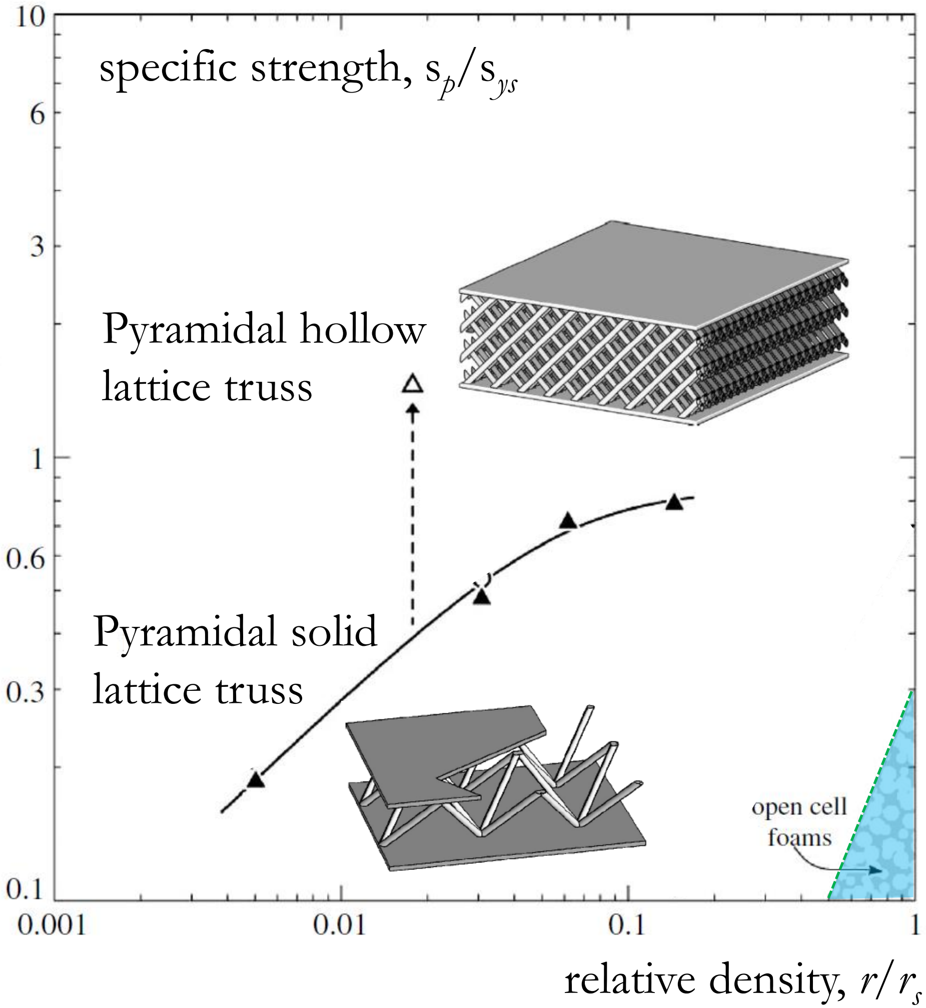


The failure mode is triggered by the parent **material properties** (and its sensitivities)

glassy polymer *vs* conventional metal

V. Lattices

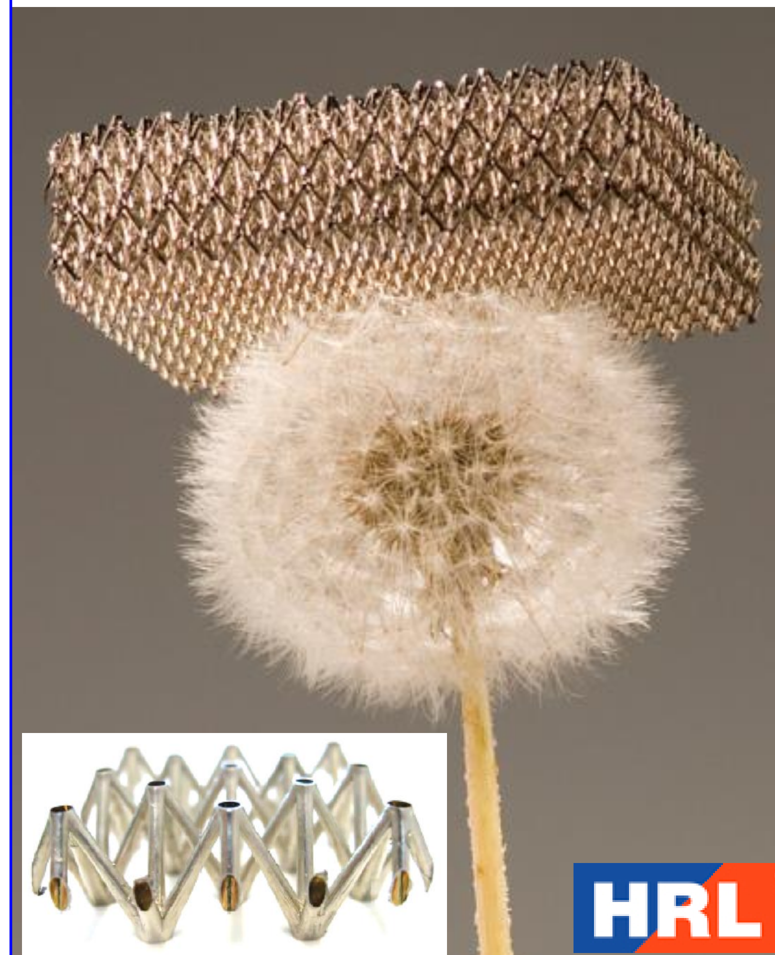
V.2. Materials by design: an example



A.G. Evans. Int. J. Impact Eng. (2010)

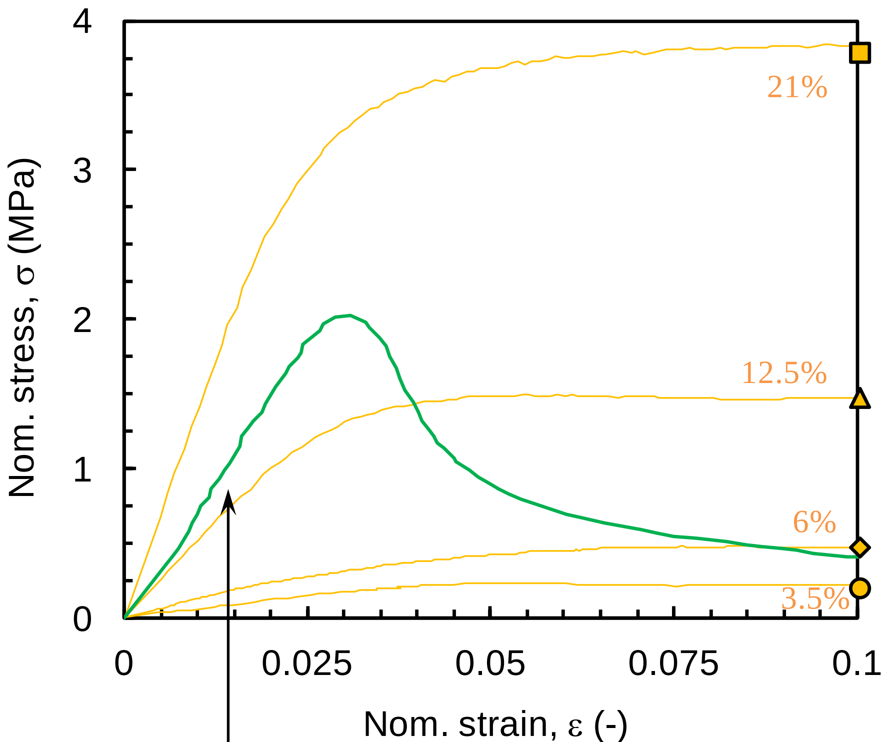
Absolute & Specific strength enhancement

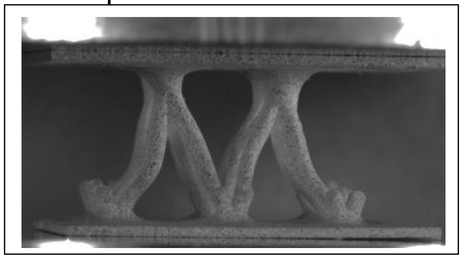
coat and burn

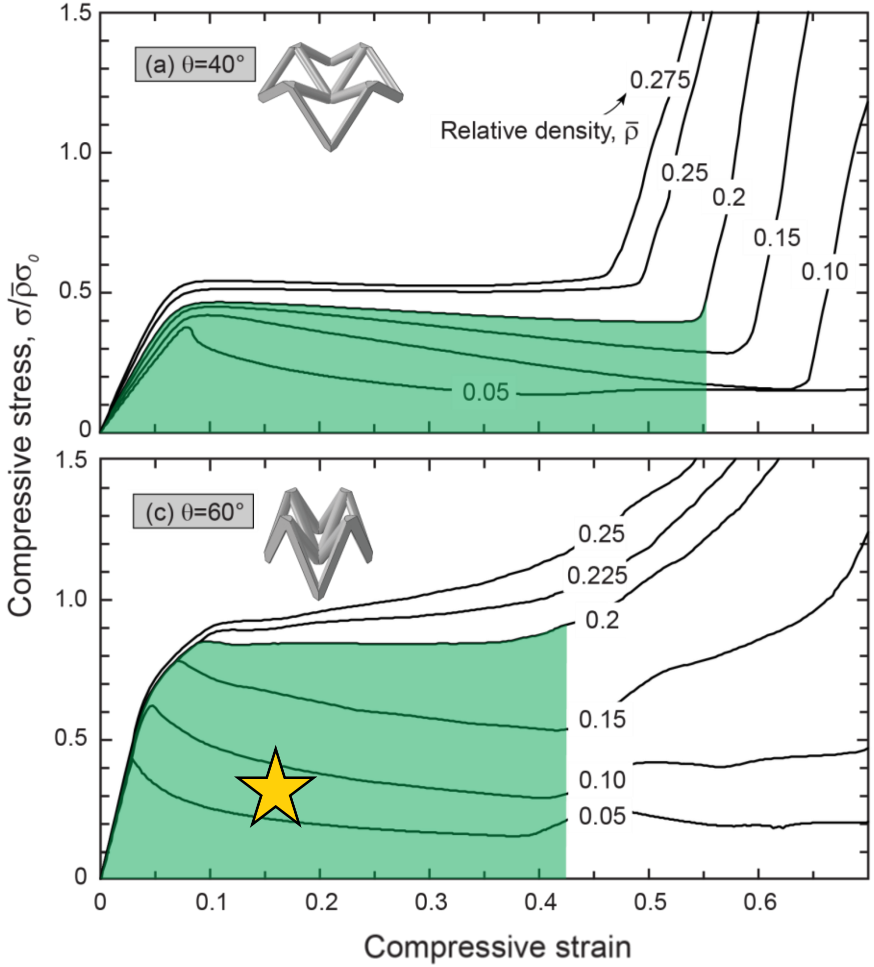


T.A. Schaedler. Science (2011)

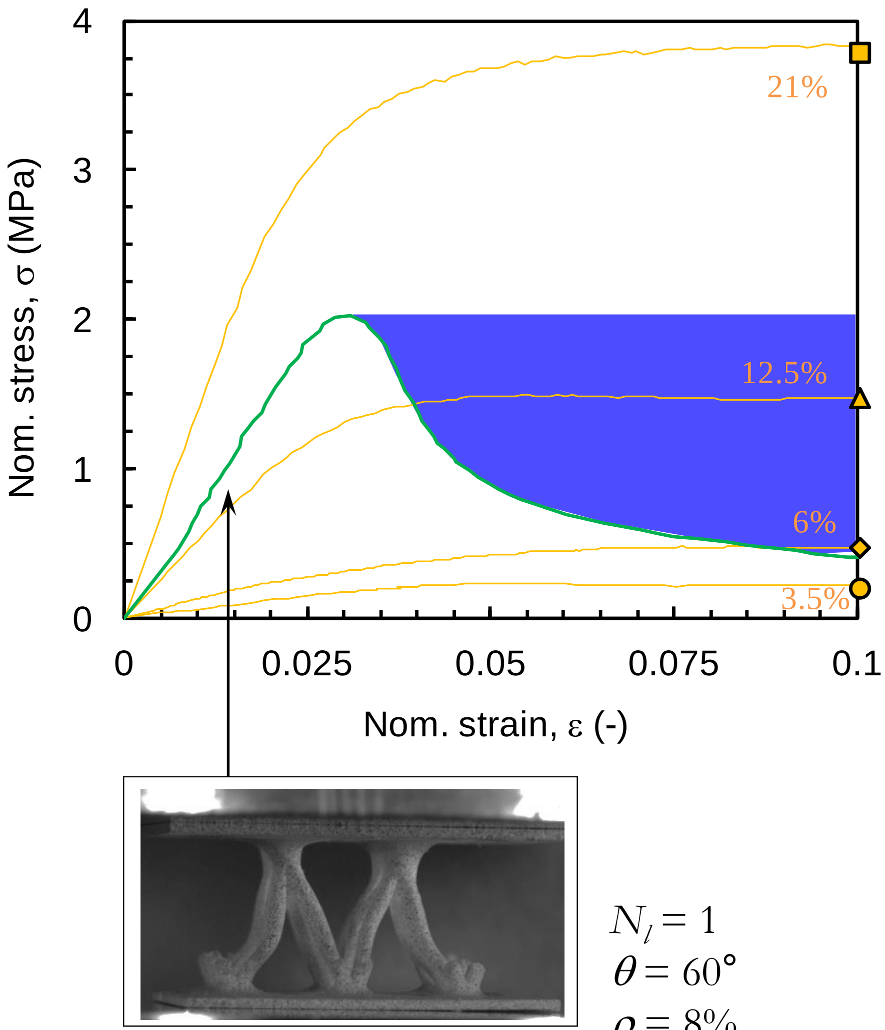
V.2. Materials by design: an example



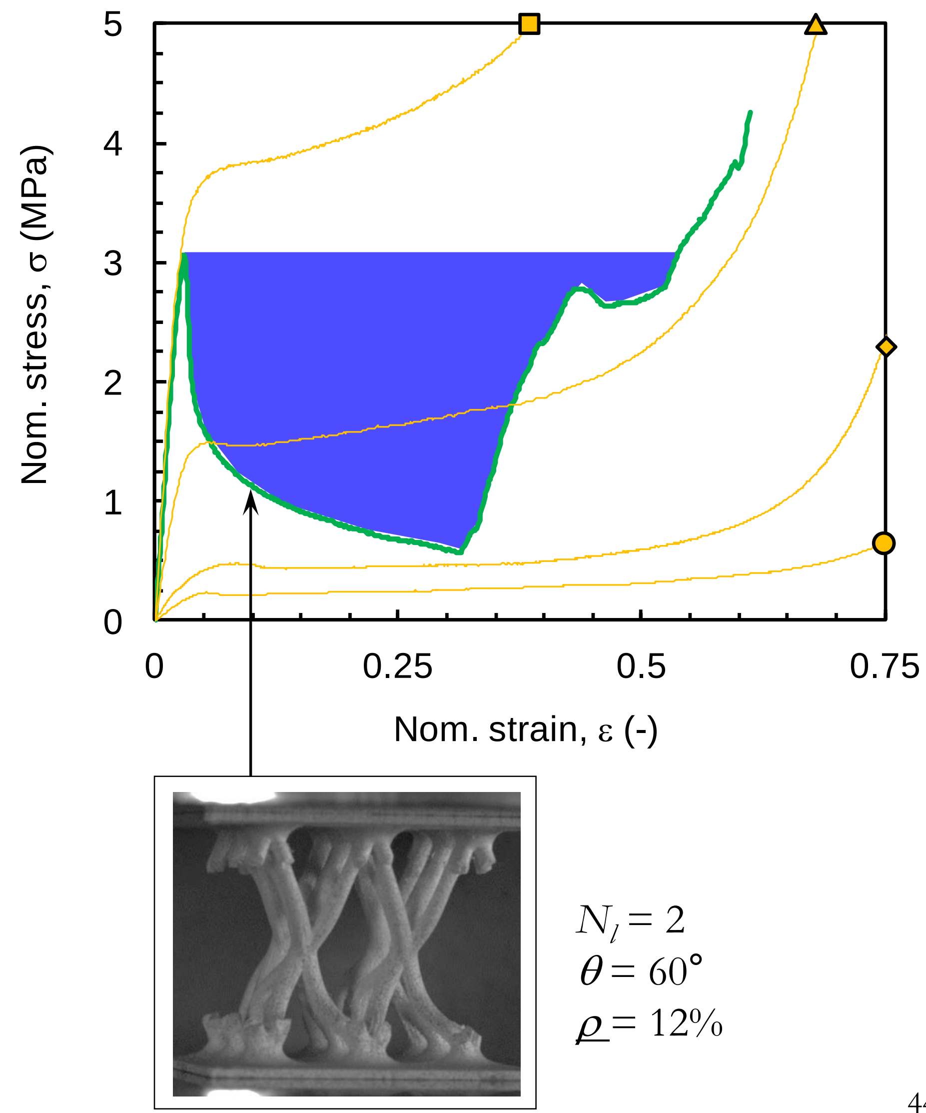




V.2. Materials by design: an example



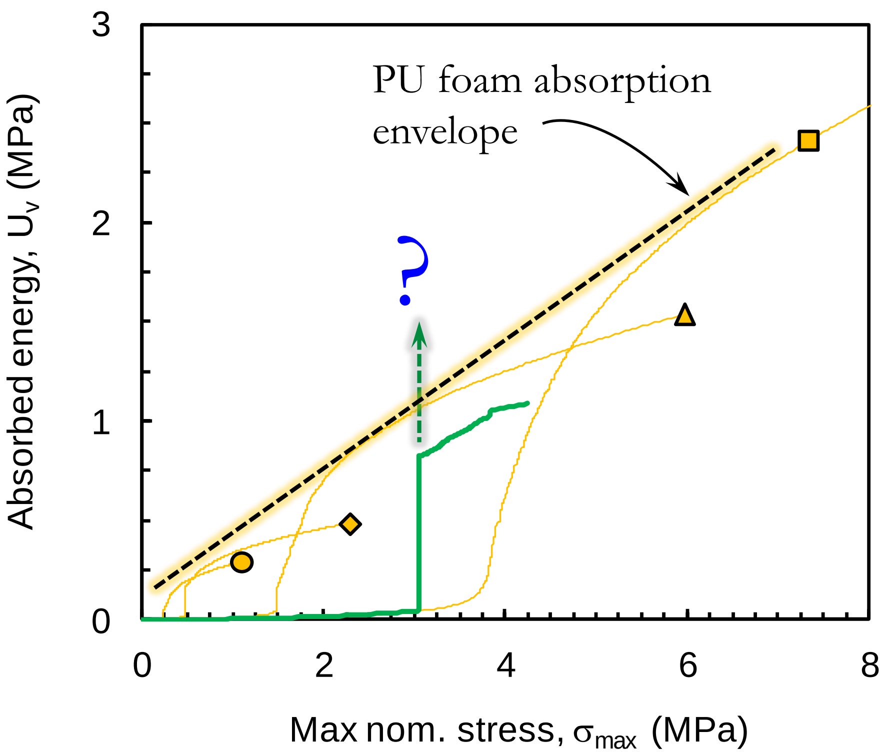
$N_l = 1$
$\theta = 60°$
$\rho = 8\%$

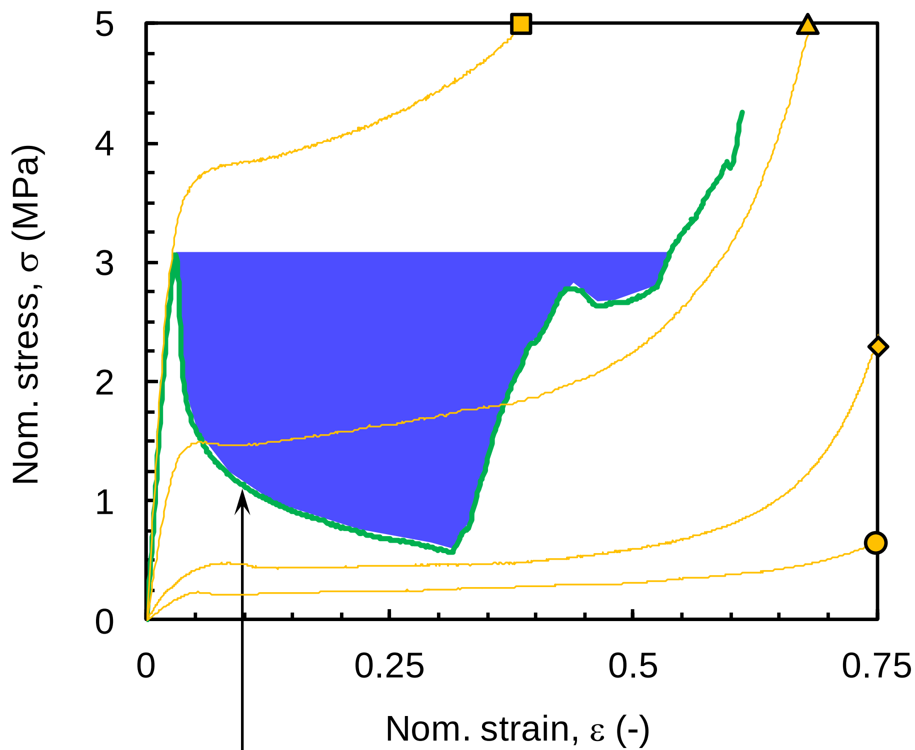


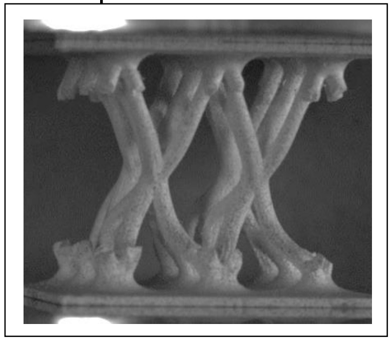
$N_l = 2$
$\theta = 60°$
$\rho = 12\%$

V. Lattices

V.2. Materials by design: an example





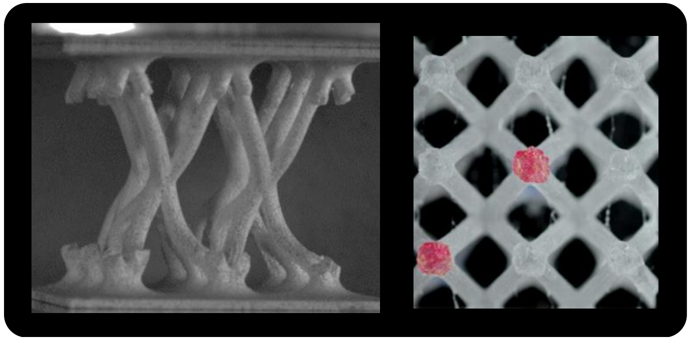


$N_l = 2$
$\theta = 60°$
$\underline{\rho} = 12\%$

Exploring the possible adjustments to enhance the energy absorption capability of pyramidal lattice systems

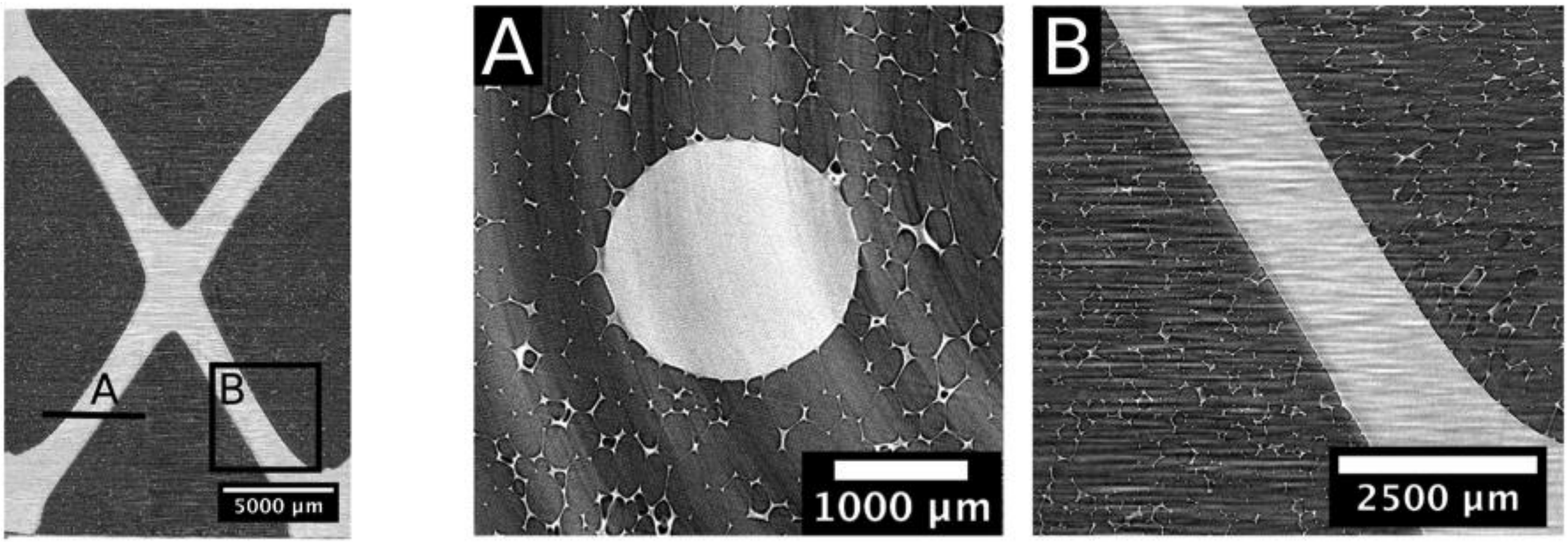
V. Lattices

V.2. Materials by design: an example



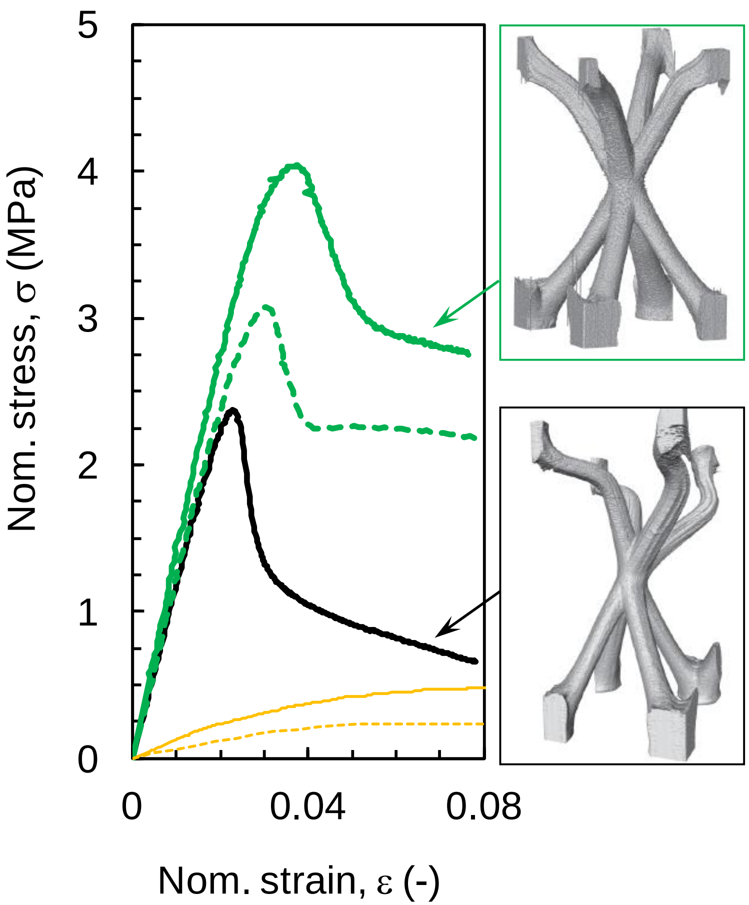
Macro-lattice

Foamed macro-lattice



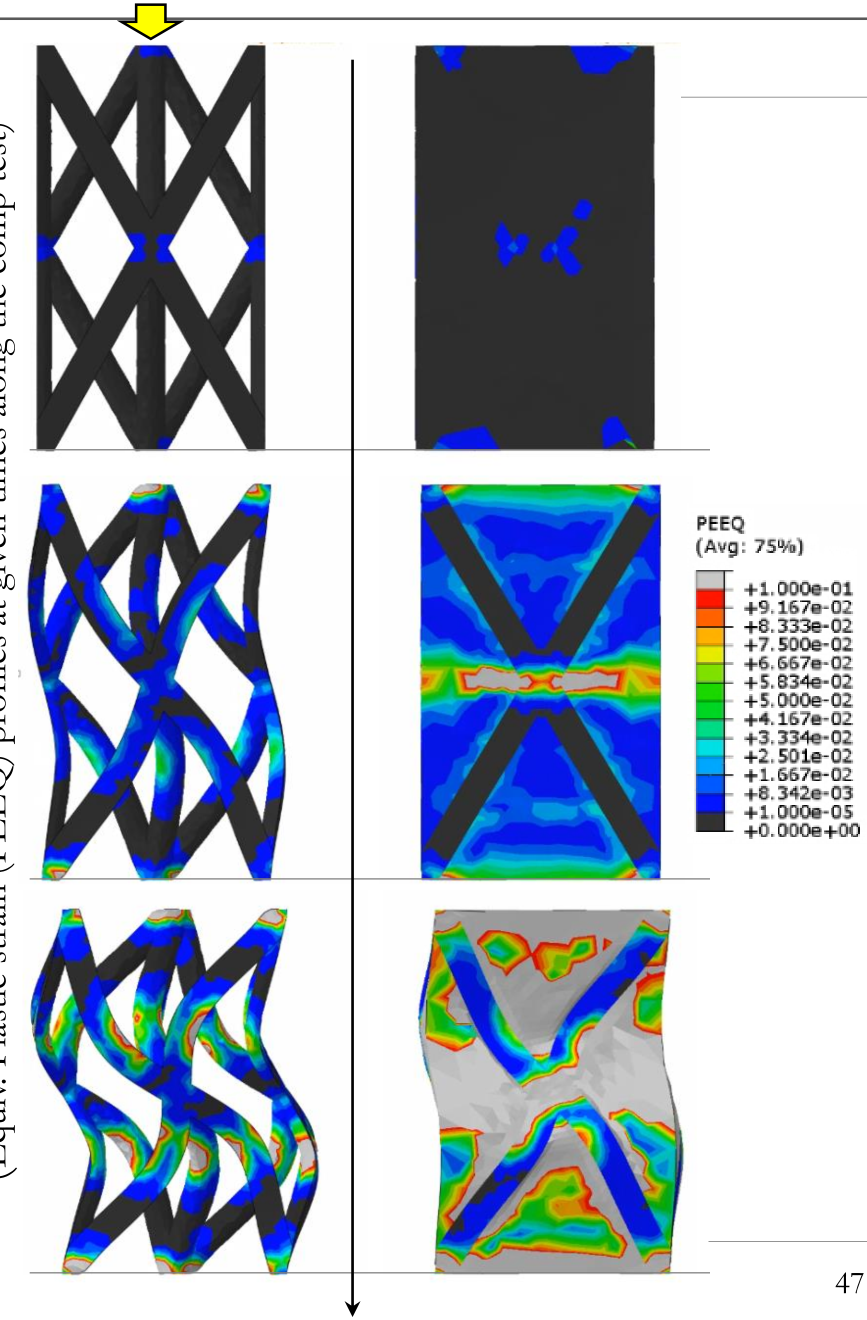
V.2. Materials by design: an example

Experiments (μ-CT characterization)

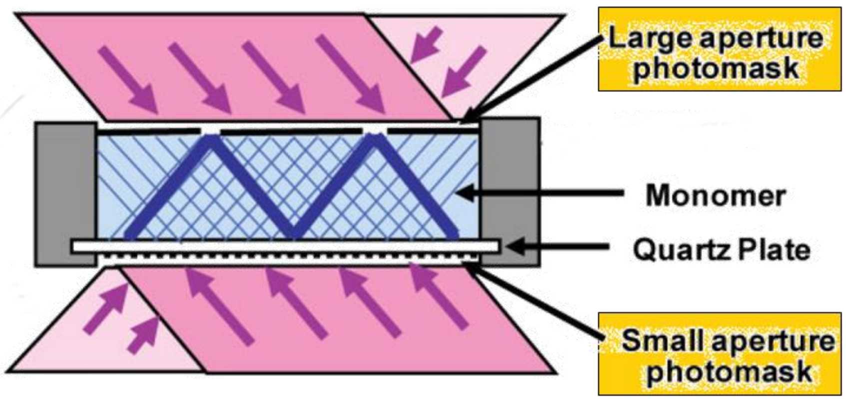


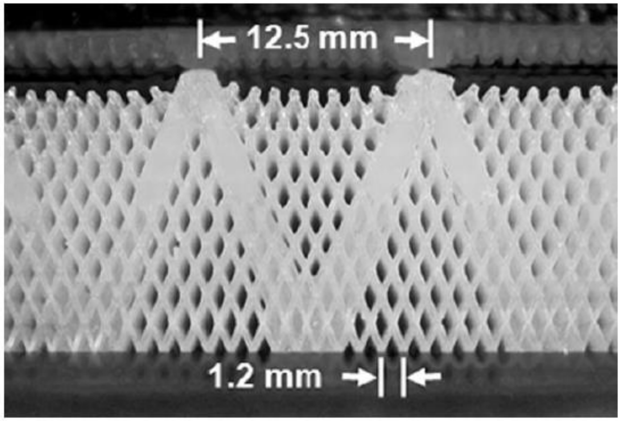
F.E. simulations

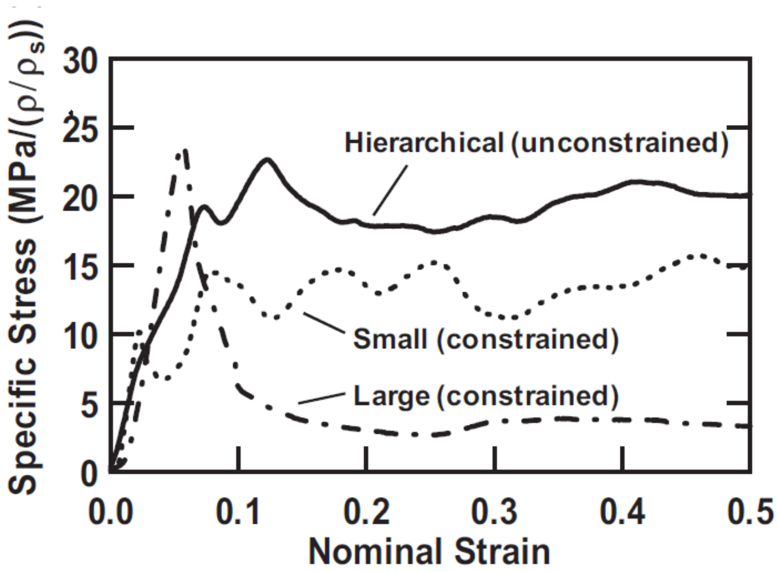
(Equiv. Plastic strain (PEEQ) profiles at given times along the comp test)



V.2. Materials by design: an example



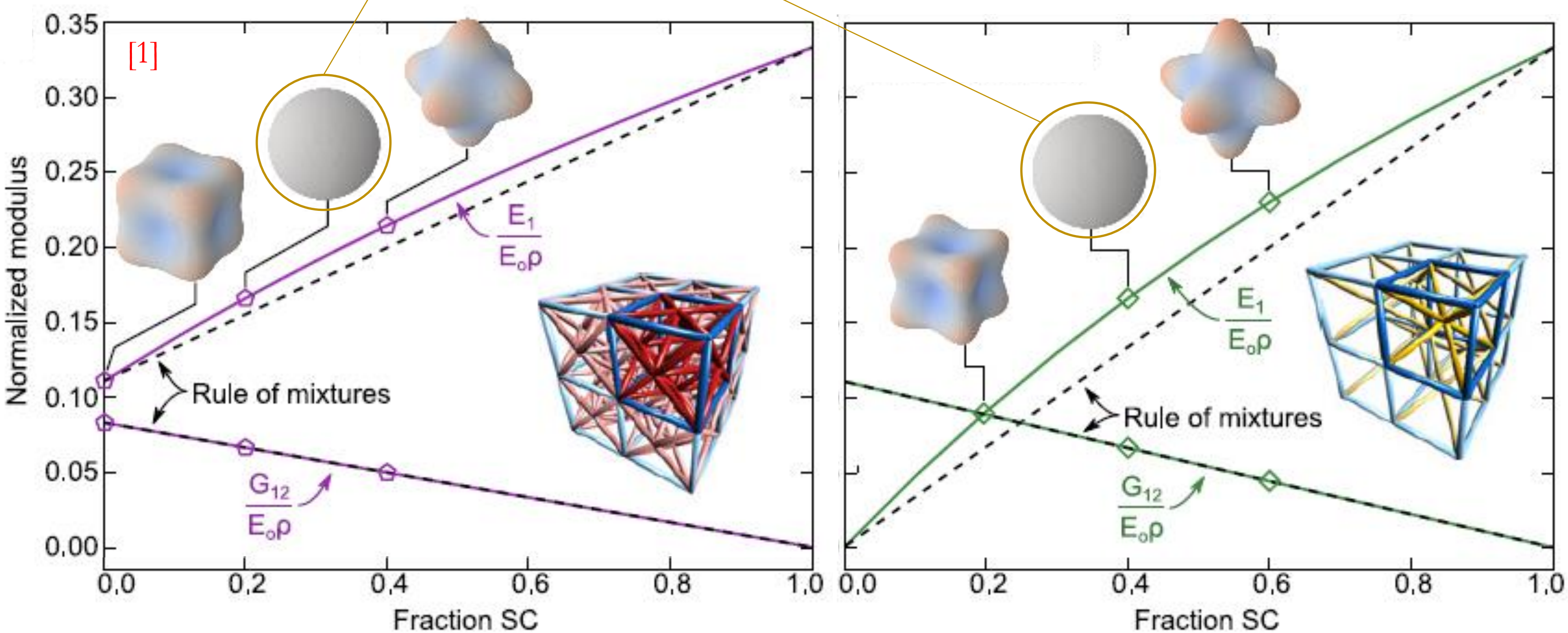




V.3. Materials by design: Enhancement / Optimization

Polar plots of axial stiffness
(isotropic lattice materials)

[2] $$\frac{1}{E_{ijk}} = \frac{1}{E_1} - 2\left(\alpha^2\beta^2 + \beta^2\gamma^2 + \alpha^2\gamma^2\right)\left(\frac{1}{E_1} - \frac{1}{2G_{12}} - \frac{\nu_{12}}{E_1}\right)$$

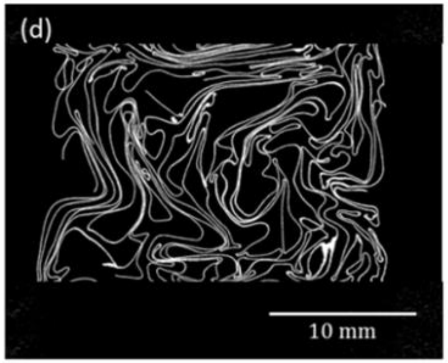


$\{11FCC\}^3|\{11SC\}^3$ $\{11BCC\}^3|\{11SC\}^3$

Binary
compound
truss

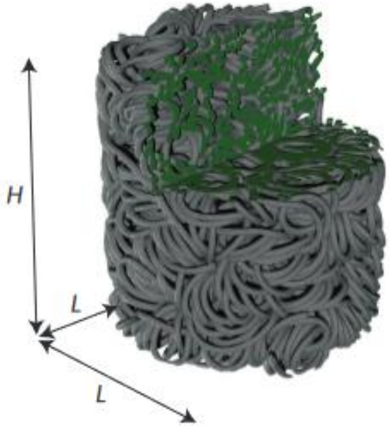
Conclusion: Limited limitations

Crumpled material



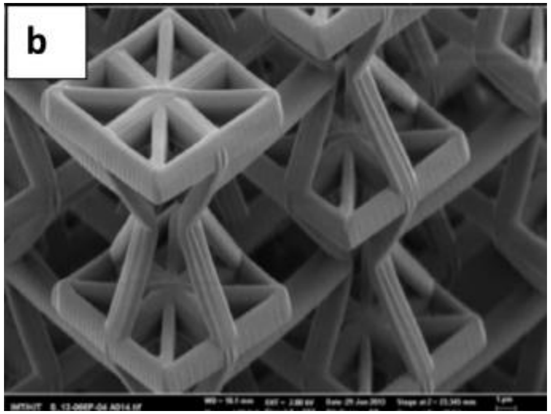
Martoïa et al., Mater&Design, 2017

Entangled monofilament



Rodney et al., Nature Materials, 2016

Auxetic materials



Saxena et al., Adv. Eng. Mater., 2016