The future of architectured materials

Opportunities for innovation and international collaboration

EDTAS Advanced Materials & Manufacturing

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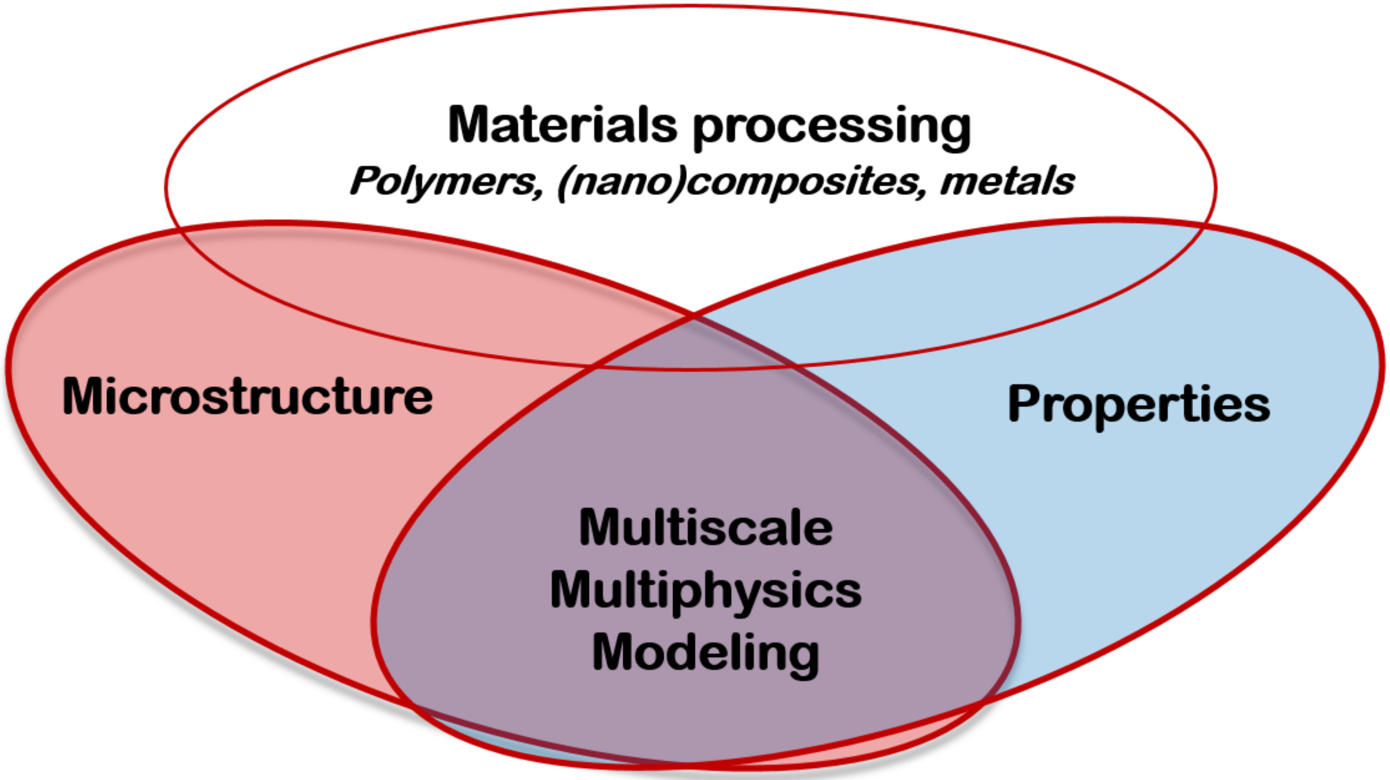

Overview

120 people in 2015 :
- 33 academic staff
- 21 support staff
- 8 adj. researchers
- 3 assist. professors
- 9 postdocs
- 46 PhD candidates

32 collaborative projects between 2009 and 2014

320 papers and 8 patents published between 2009 and 2014

~1M€ of direct industrial contracts per year

4 research groups :

Laser processing
Structural dynamics, systems and control
Behavior and microstructure of metals and alloys
Polymers and composites

PIMM is a member of F2M

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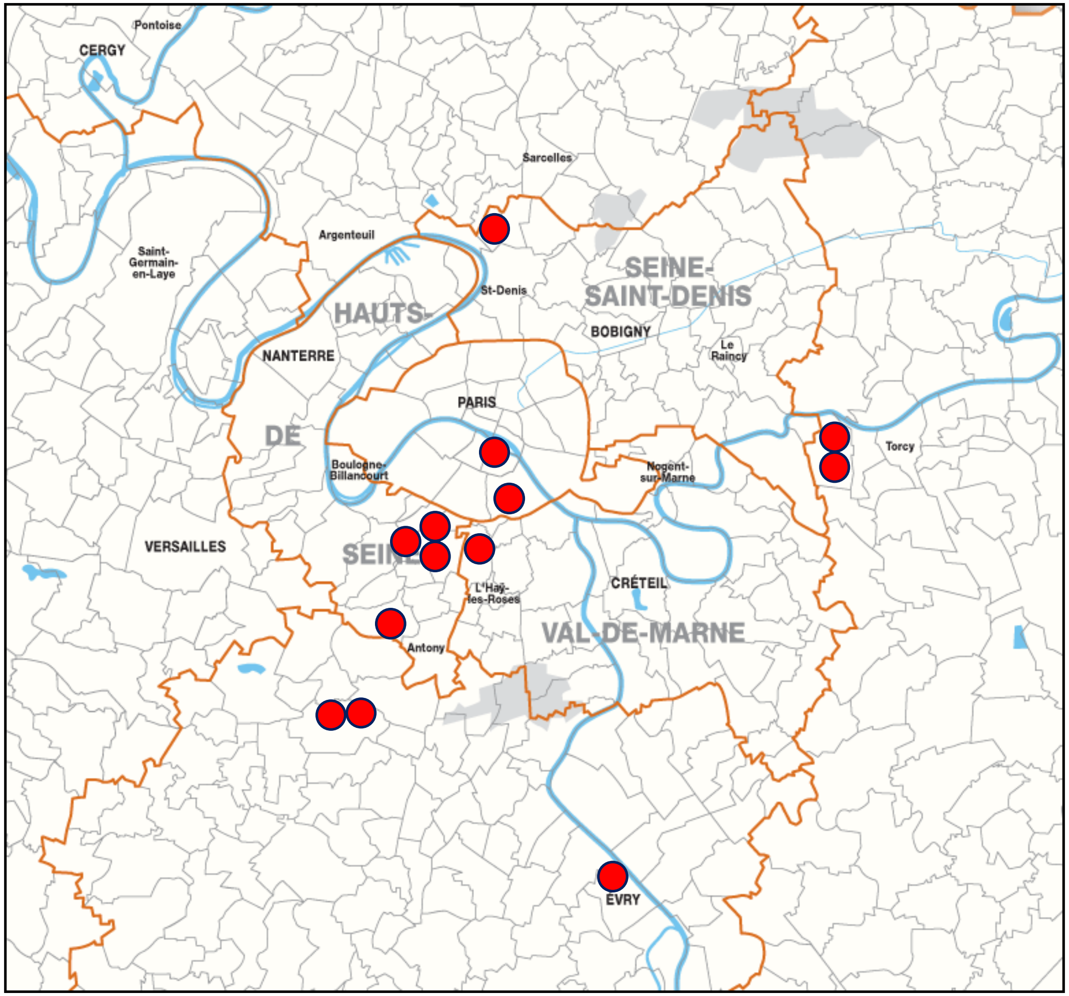

Partners:

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UNIVERSITÉ PARIS-EST

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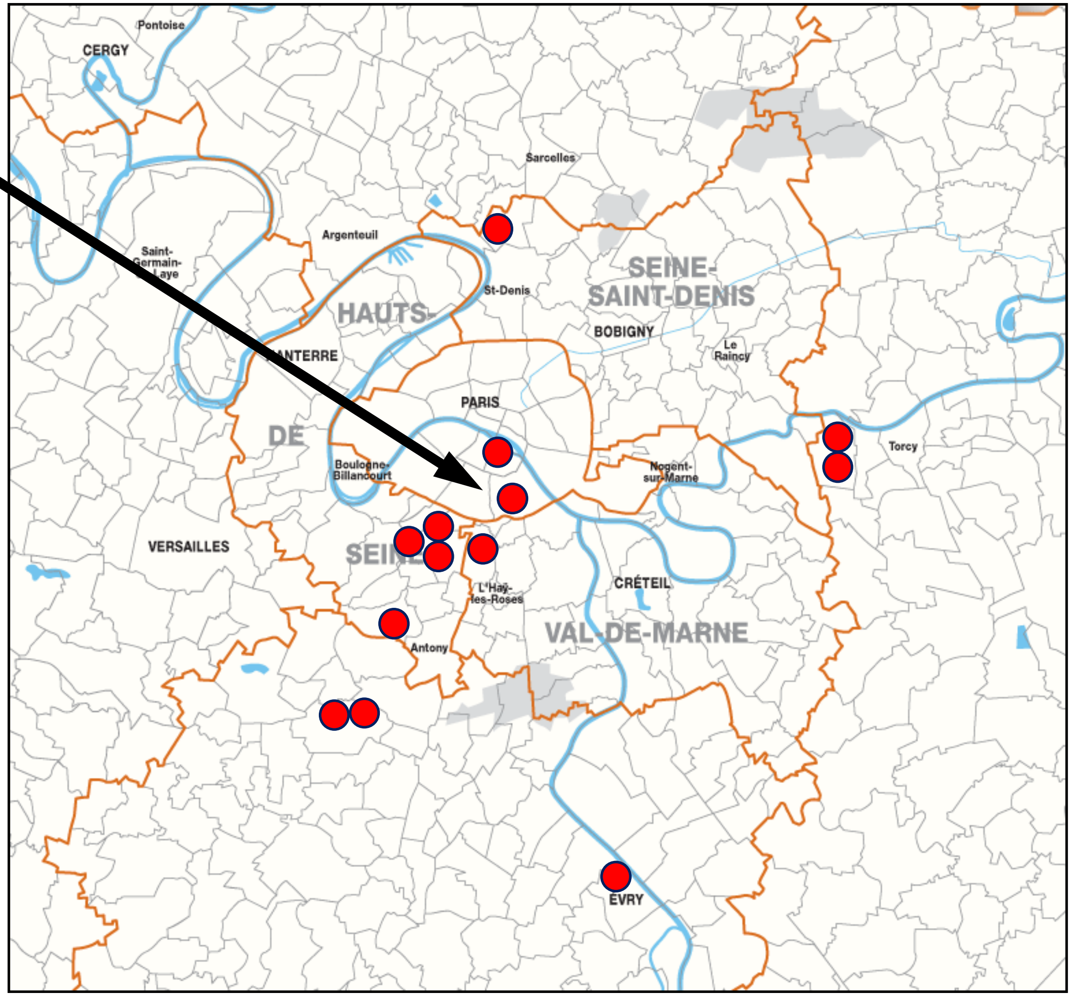

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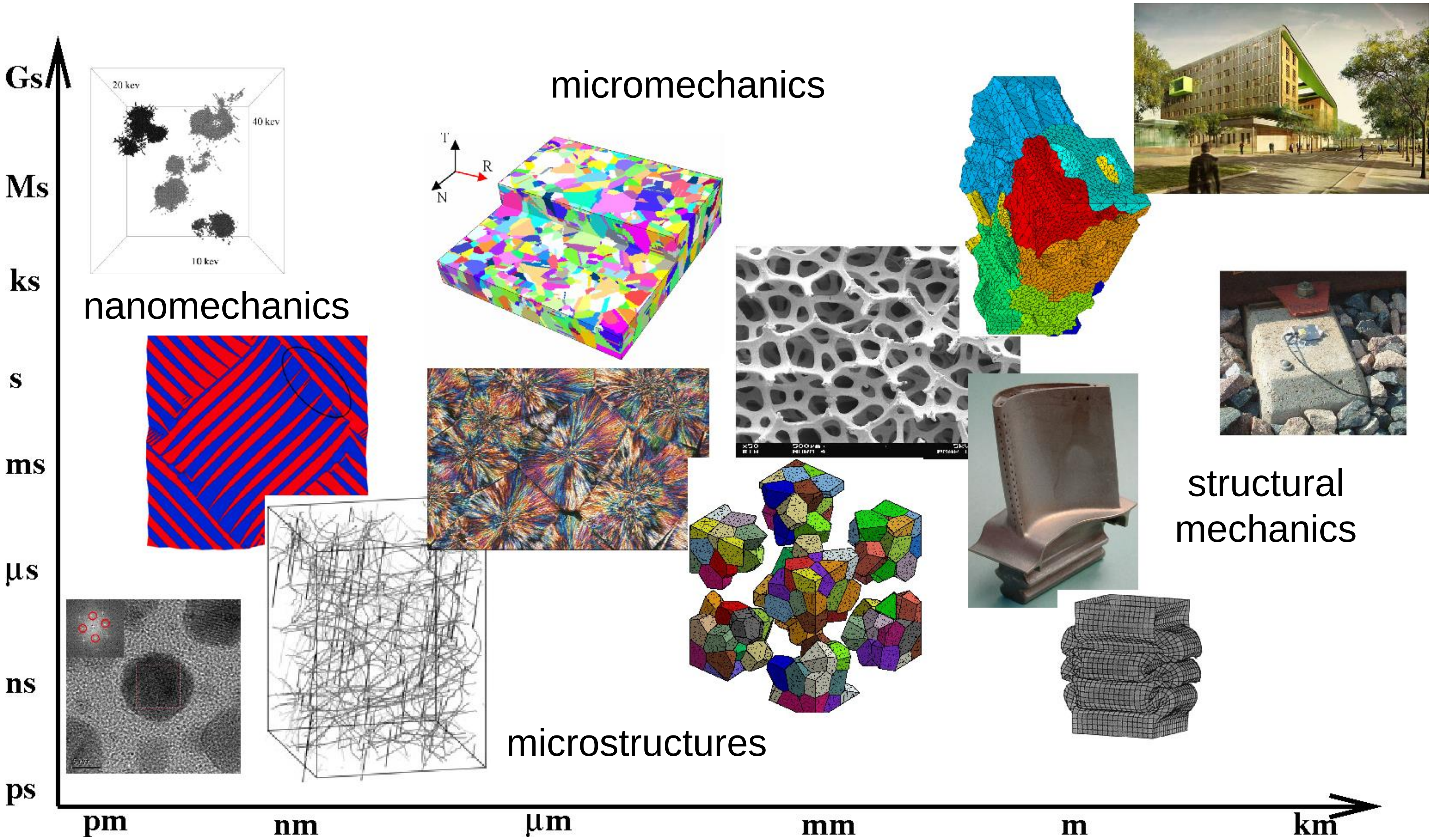
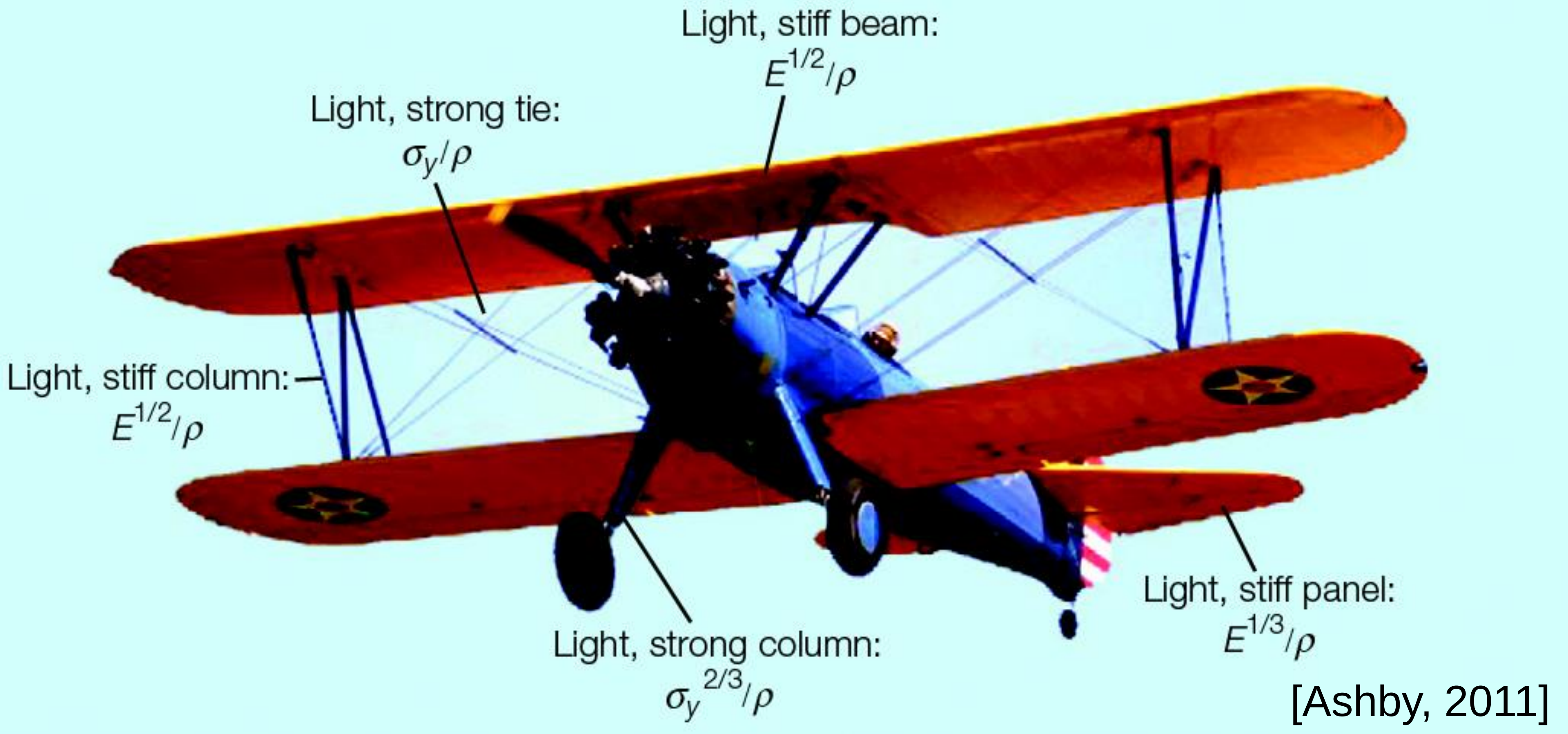
Probing all scales within materials



Architectured materials in a nutshell

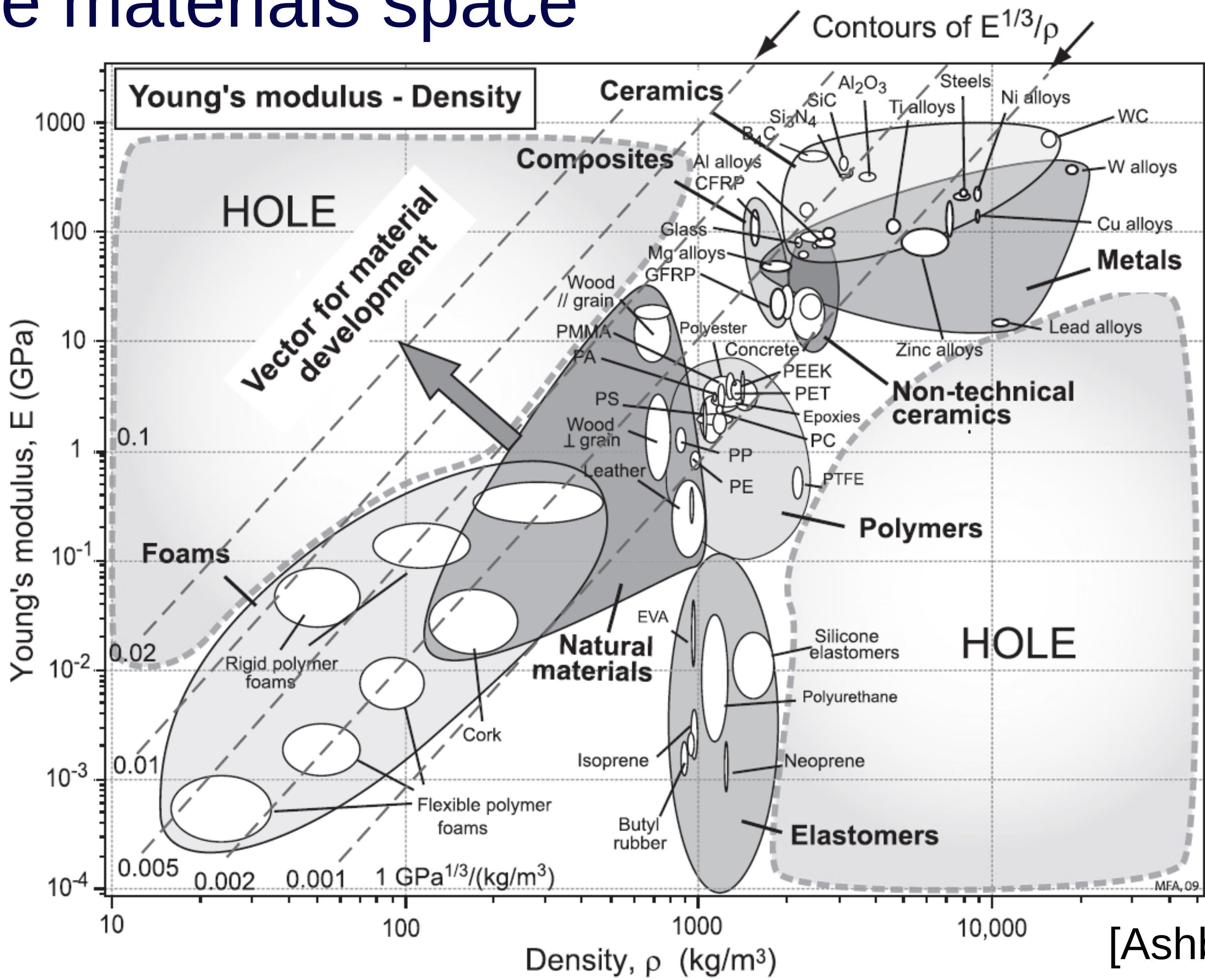
A given material for a given function



[Ashby, 2011]

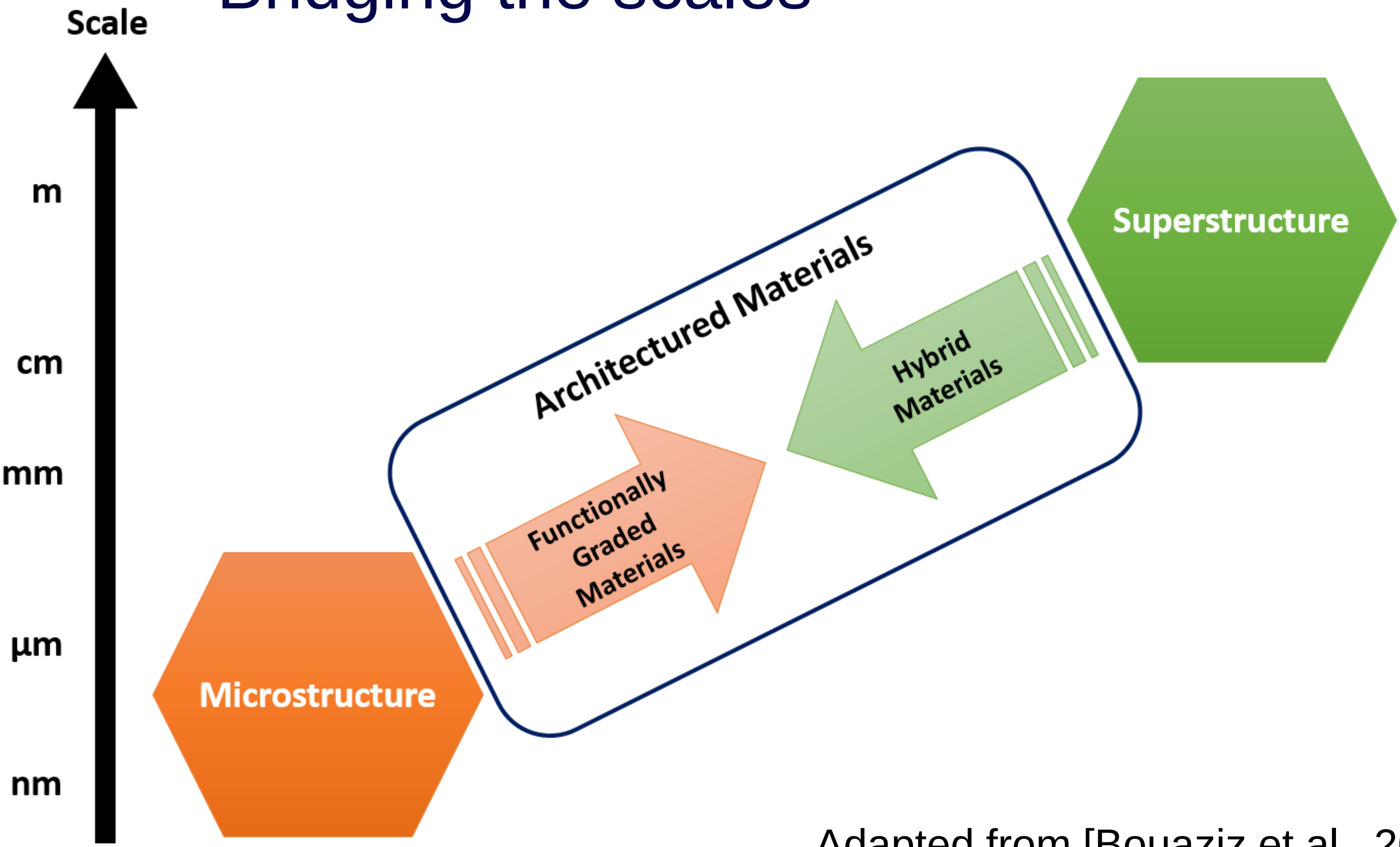
Different function/load ➔ different material optimum

The materials space



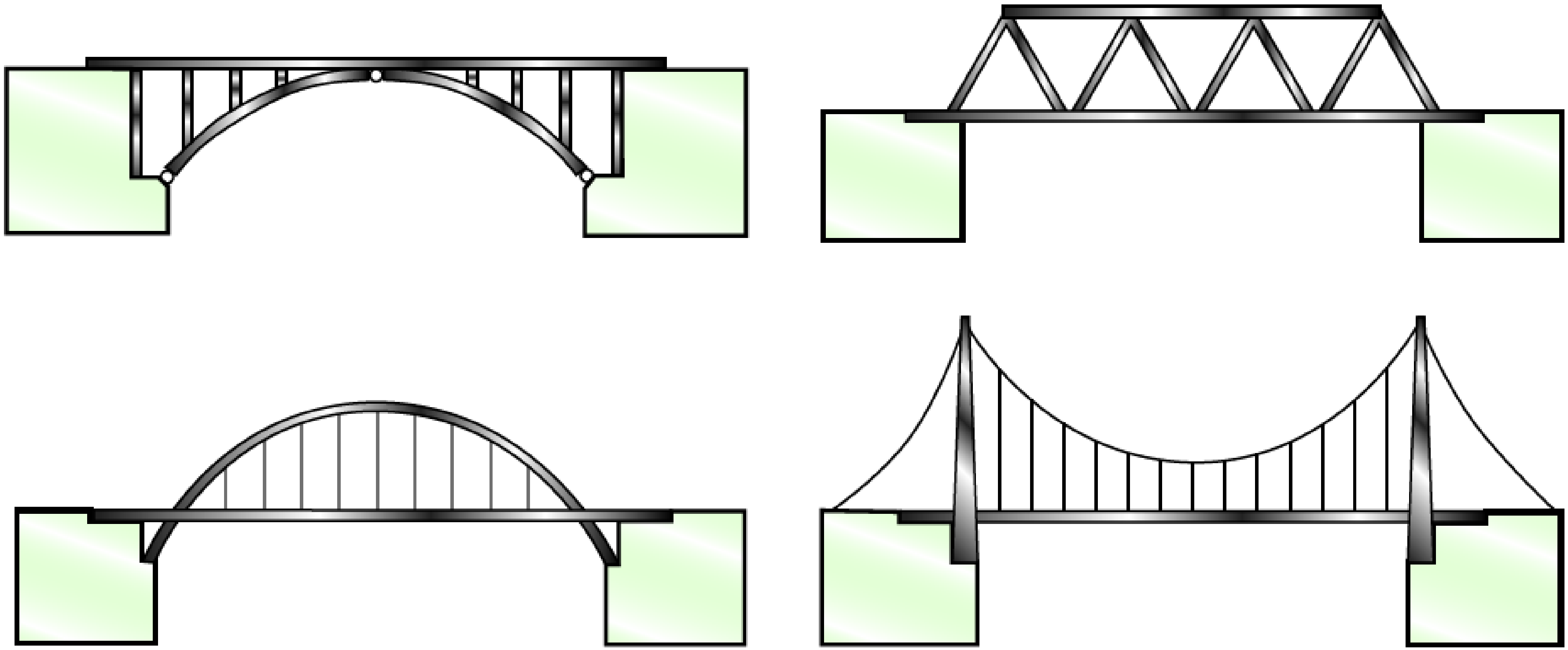
[Ashby, 2013]

Bridging the scales



Adapted from [Bouaziz et al., 2008]

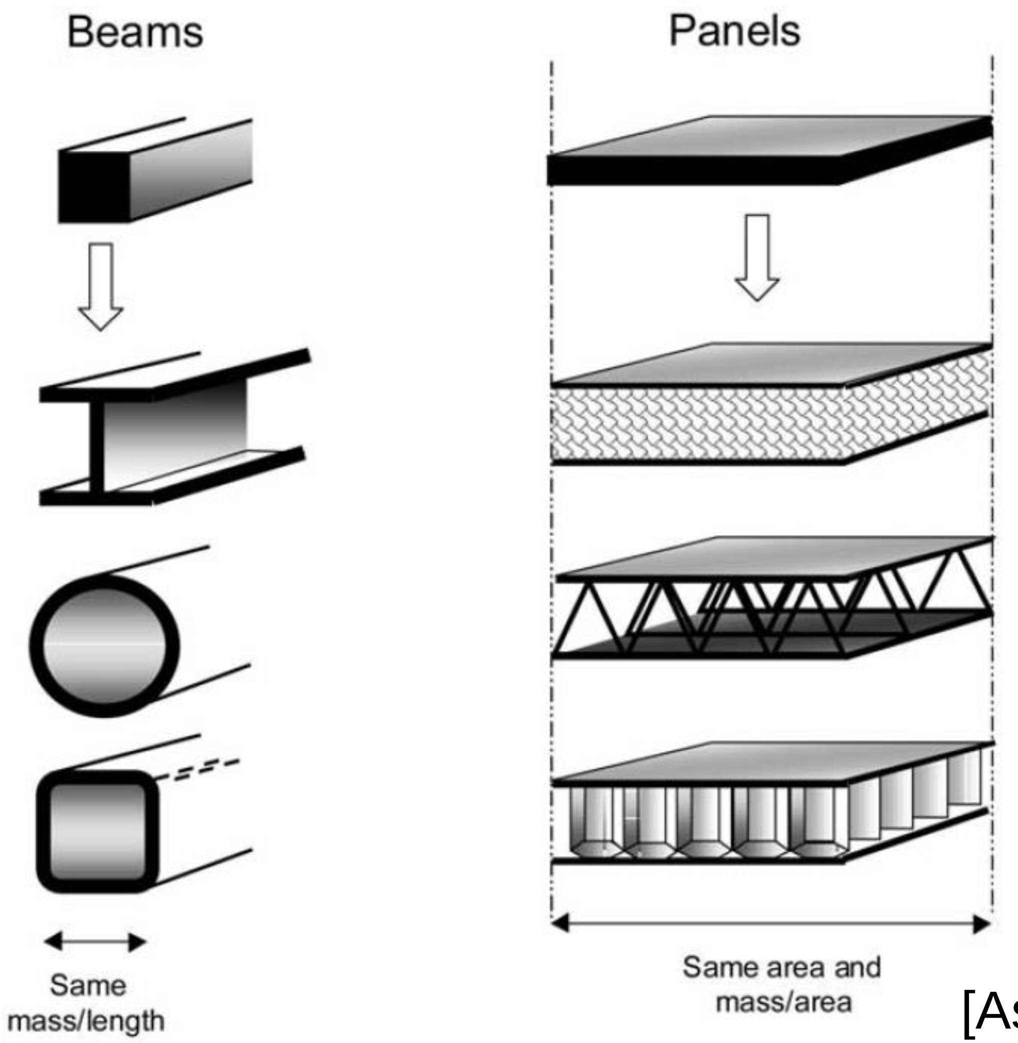
Geometry, not a new idea…



[Ashby, 2011]

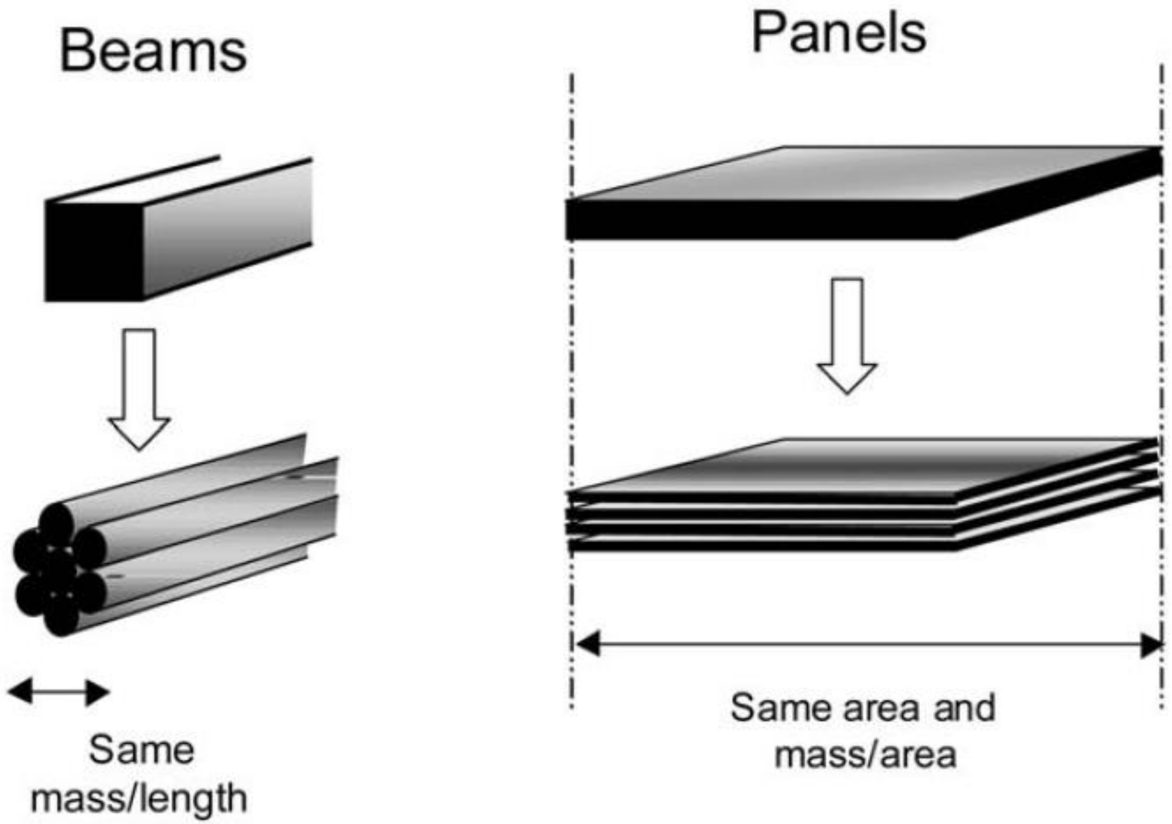
Same function ➔ different structural designs

Changing the topology – more rigid



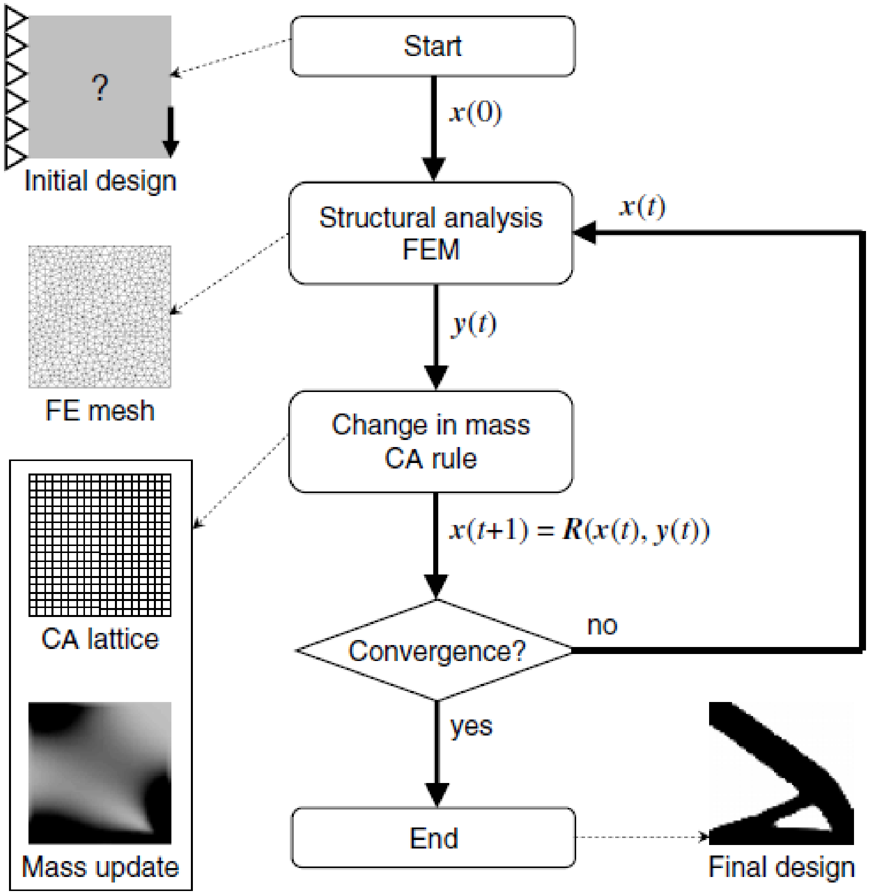
[Ashby & Bréchet, 2003]

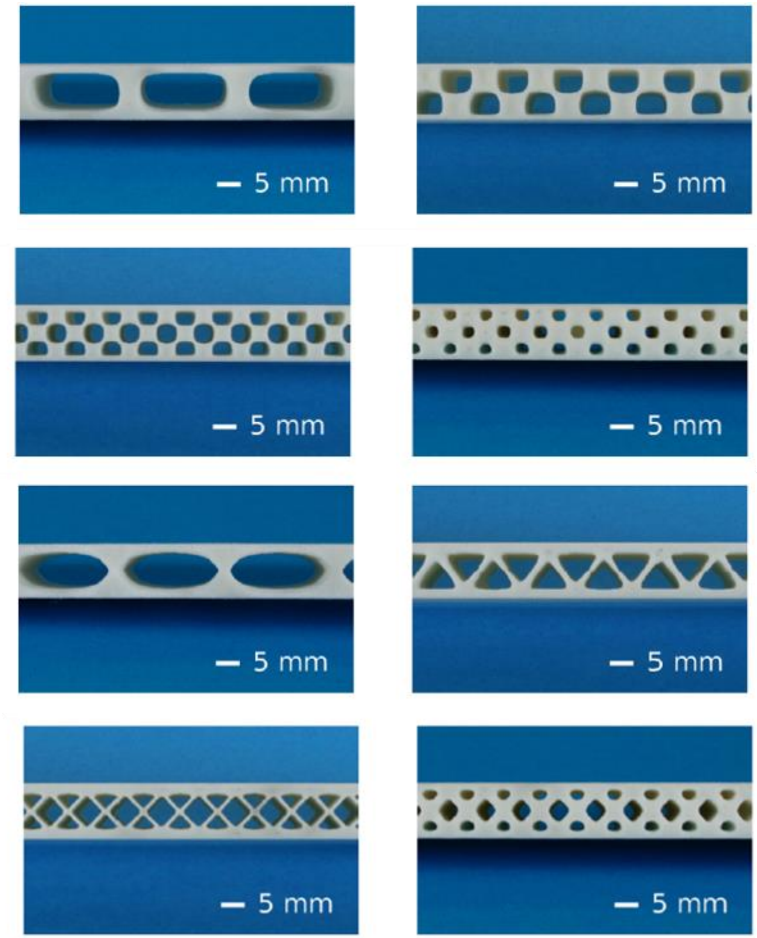
Changing the topology – more compliant



[Ashby & Bréchet, 2003]

Optimising the topology





[Tovar et al., 2006]

[Laszczyk, 2011]

In summary

- **Architectured materials** are a rising class of materials that bring new possibilities in terms of functional properties, filling the gaps within the materials performance space.

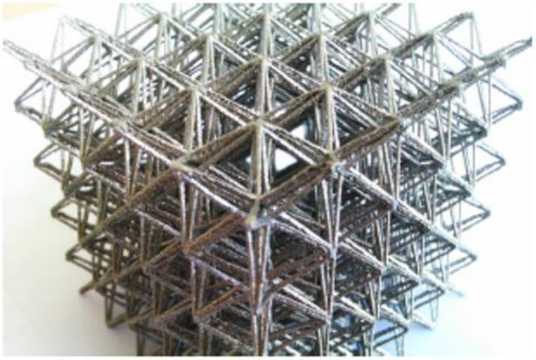
- They include any material that has been **morphologically engineered** such that some of its properties have been enhanced in comparison to the bulk monolithic material, due to both structure and composite effects, which depend on the multiphase morphology, i.e. the topological arrangement of each phase.

- The development of architectured materials is **intrinsically transdisciplinary**, on the fringes of physics, chemistry, and mechanical engineering, but also biology, computer science, architecture, design, etc.

Some examples

Lattices with negative Poisson's ratio

Computational homogenization



Cubic auxetic microstructure proposed by [Dirrenberger et al., 2013].

Elastic moduli are computed using FEM.

Zebulon Non-linear finite element solver

$$[\underset{\approx}{C}] = \begin{bmatrix} 307 & 81 & 81 & 0 & 0 & 0 \\ 81 & 307 & 81 & 0 & 0 & 0 \\ 81 & 81 & 307 & 0 & 0 & 0 \\ 0 & 0 & 0 & 11342 & 0 & 0 \\ 0 & 0 & 0 & 0 & 11342 & 0 \\ 0 & 0 & 0 & 0 & 0 & 11342 \end{bmatrix}$$

Cubic elasticity

1

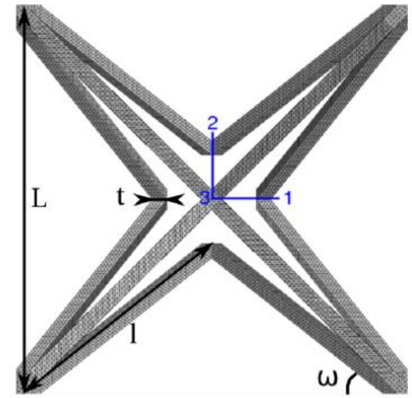
Elastoplasticity

$$f(\underset{\sim}{\sigma}) = \sigma^{eq} - R$$

$$\sigma^{eq} = \sqrt{\frac{3}{2}\underset{\sim}{\sigma}^{dev} : \underset{\sim}{\sigma}^{dev}}$$

$$R = R_0 + Hp$$

Young's modulus (GPa)	210
Poisson's ratio	0.3
Yield stress (MPa)	100
Isotropic hardening (MPa)	1000
Volume fraction	2.0%

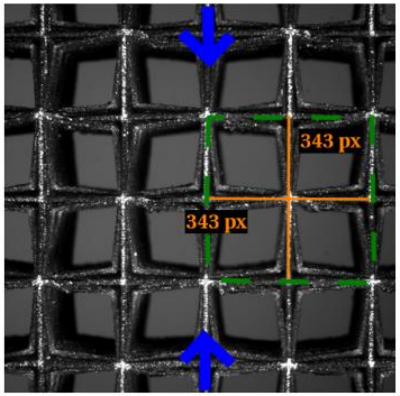


Unit-cell for the hexachiral lattice.

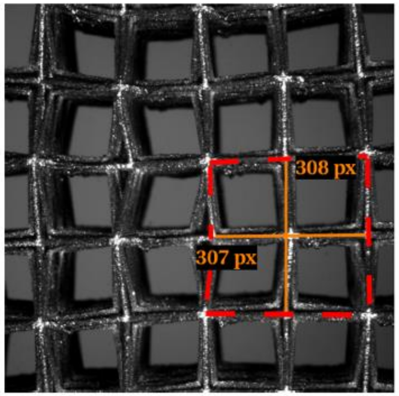
2

Experimental validation

$\nu^{app} = -0.6 \pm 0.4$ (min-max)



Initial state



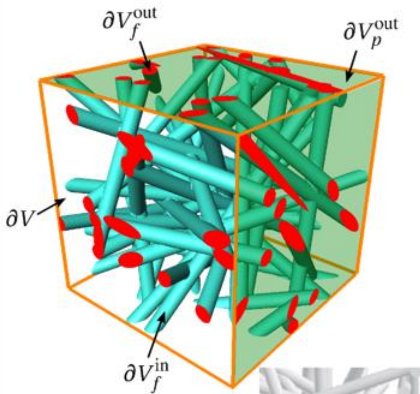
Deformed state

3

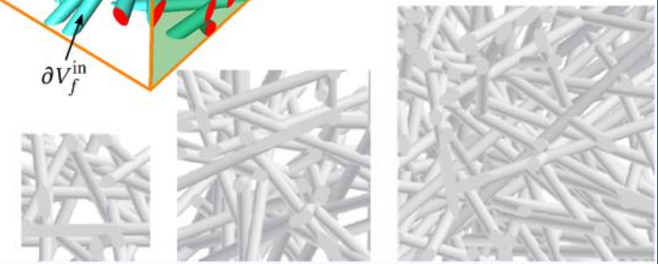
[Dirrenberger et al., 2011, 2012, 2013]

Architectured stochastic fibrous materials

Microstructural model definition

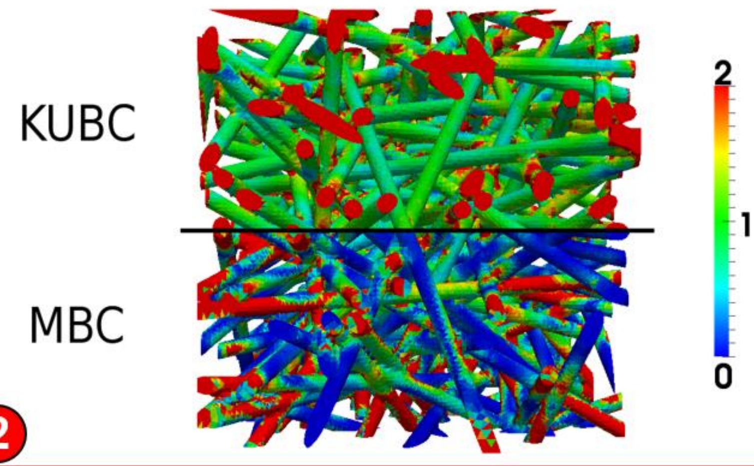


$$\theta = \frac{-\ln(1 - V_V^f)}{\pi^2 R^2}$$



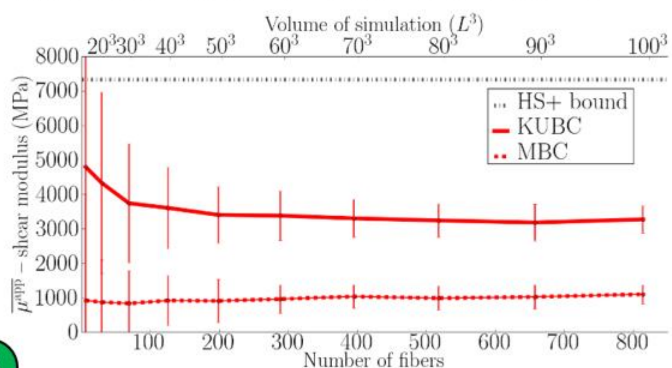
1

Computational experiments



2

Statistical analysis and size effects



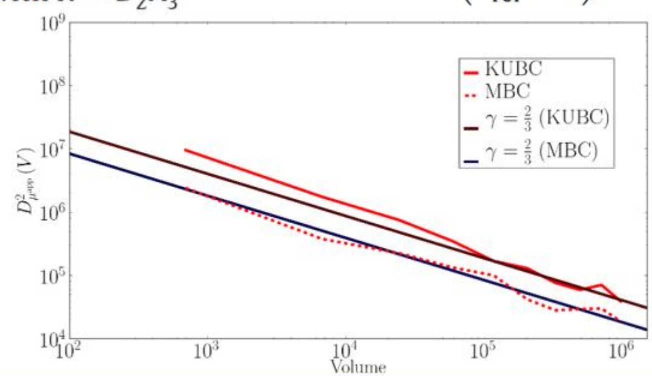
3

RVE size determination

$$D_Z^2(V) = KV^{-\gamma}$$

with $K = D_Z^2 A_3^{*\gamma}$

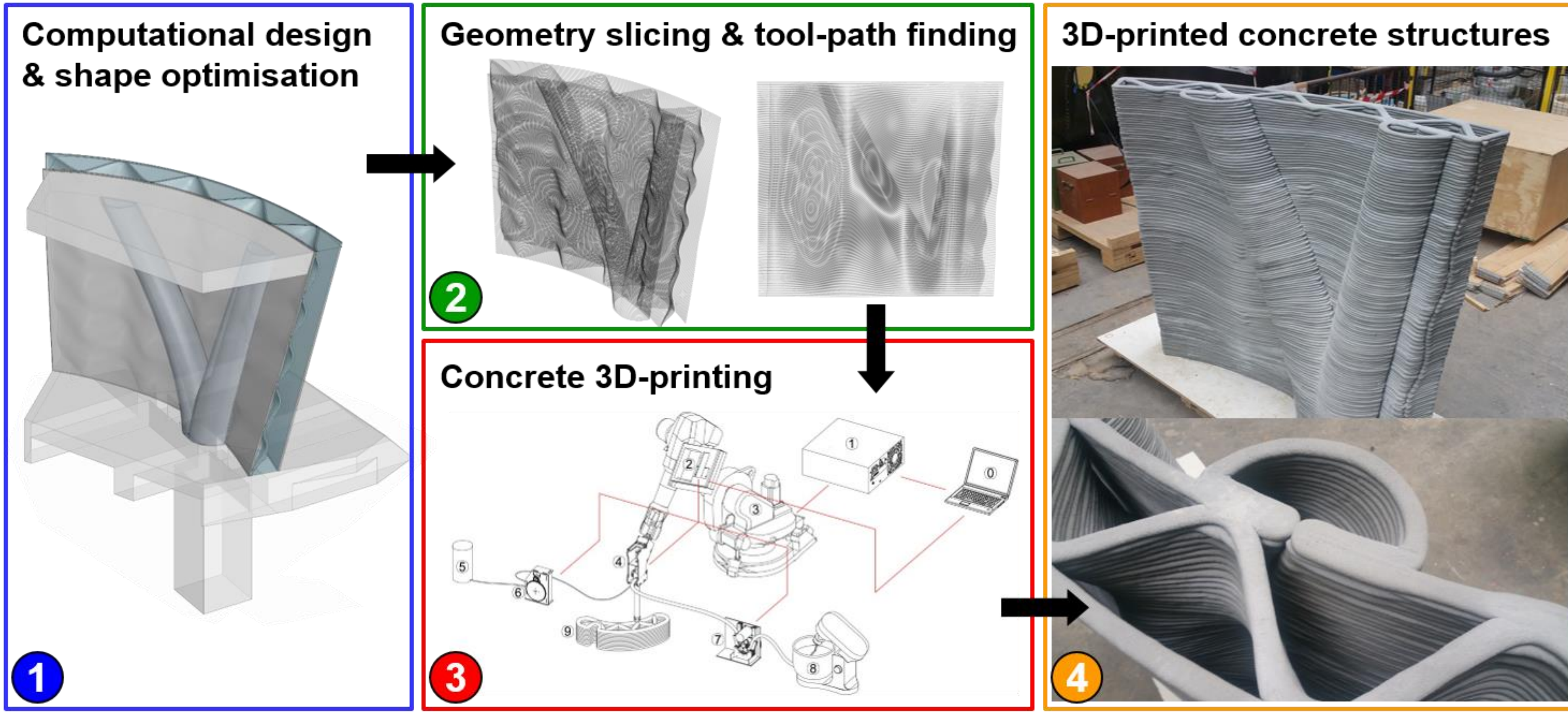
$$V_{\mathrm{RVE}} = A_3^* \left(\frac{4D_Z^2}{\epsilon_{\mathrm{rel}}^2 \overline{Z}^2 n} \right)^{\frac{1}{\gamma}}$$



4

[Dirrenberger et al., 2014]

Large-scale additive manufacturing

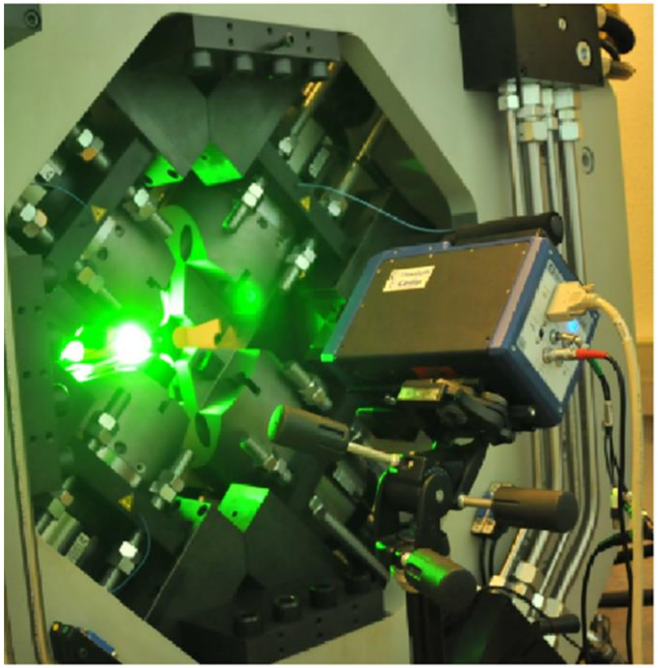


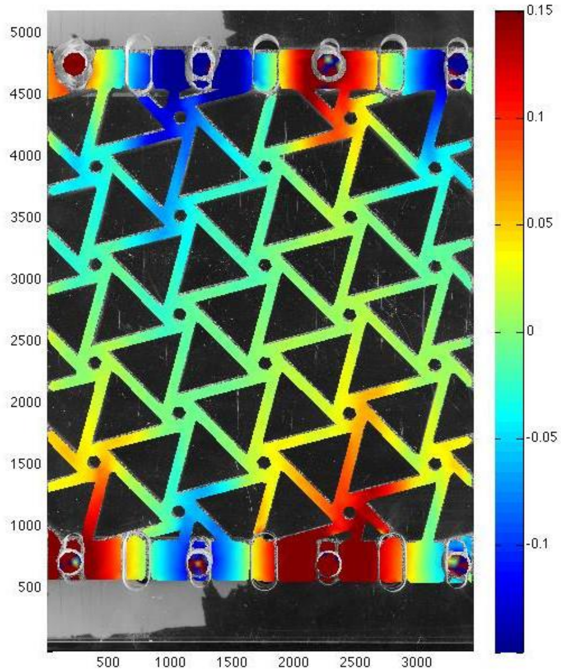
- 1st additively manufactured structural element in France
- Spin-off company created : XtreeE

[Gosselin et al., 2016; Dirrenberger, 2016; Duballet et al., 2017; Duballet et al., 2018]

3D printed architectured wall

Architectured lattice metamaterials

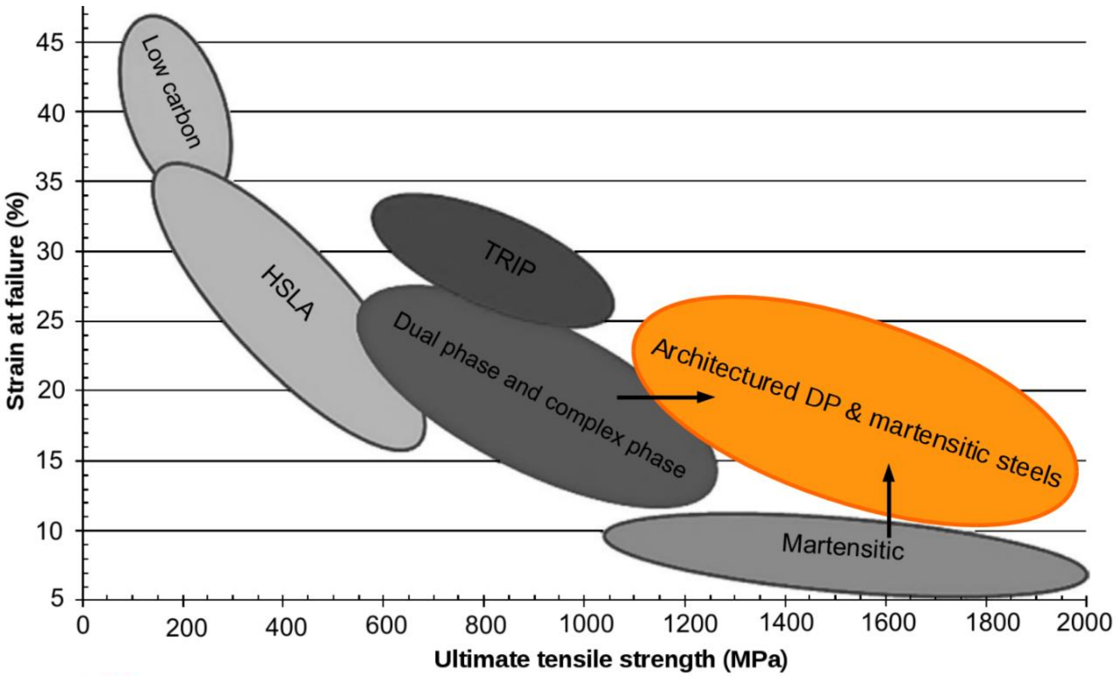




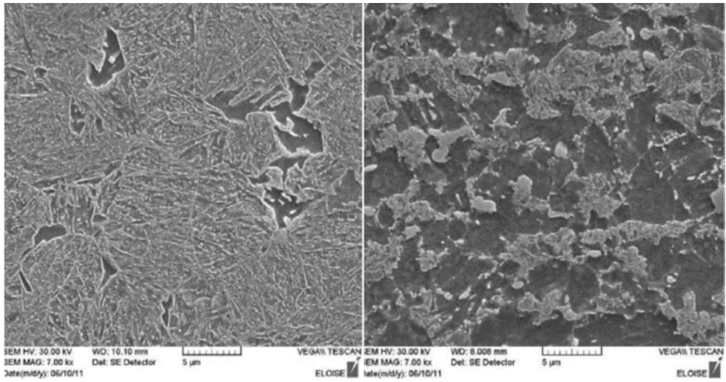
- Multiaxial mechanical loading
- Non-homogeneous boundary conditions
- Architectured materials necessitate new methods of characterisation

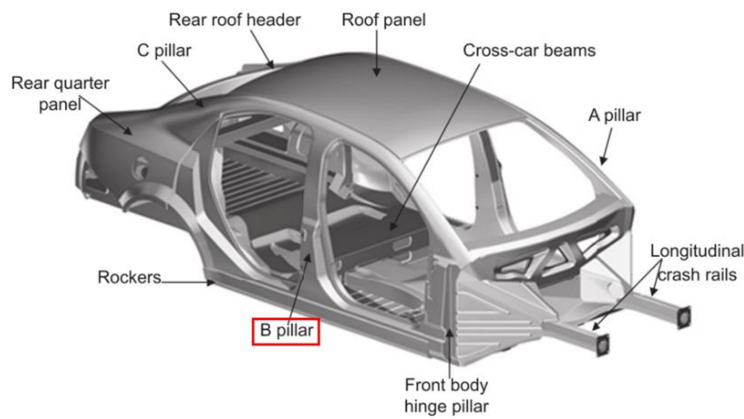
[Auffray et al., 2015; Rosi & Auffray, 2016]

Laser-architectured metal sheets



Laser heat-treatment





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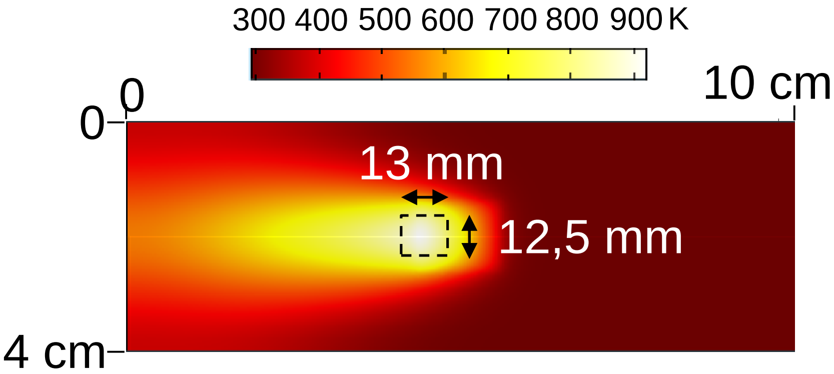
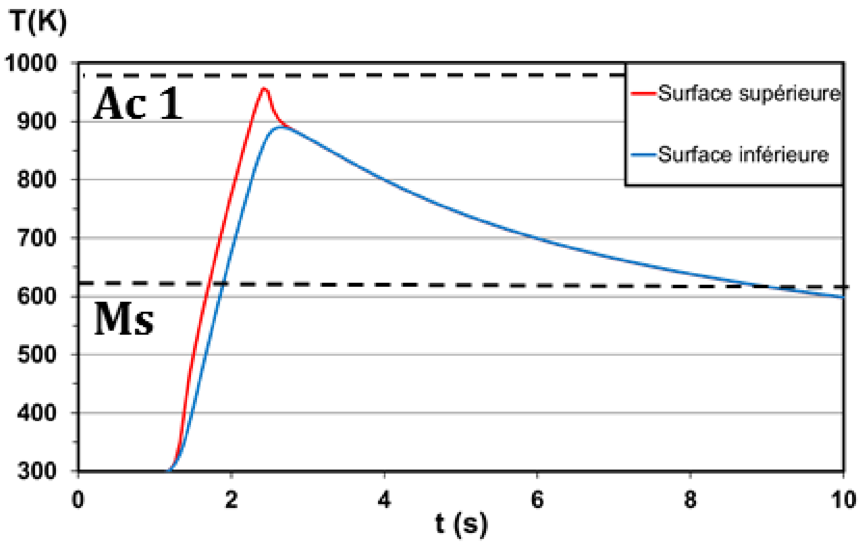
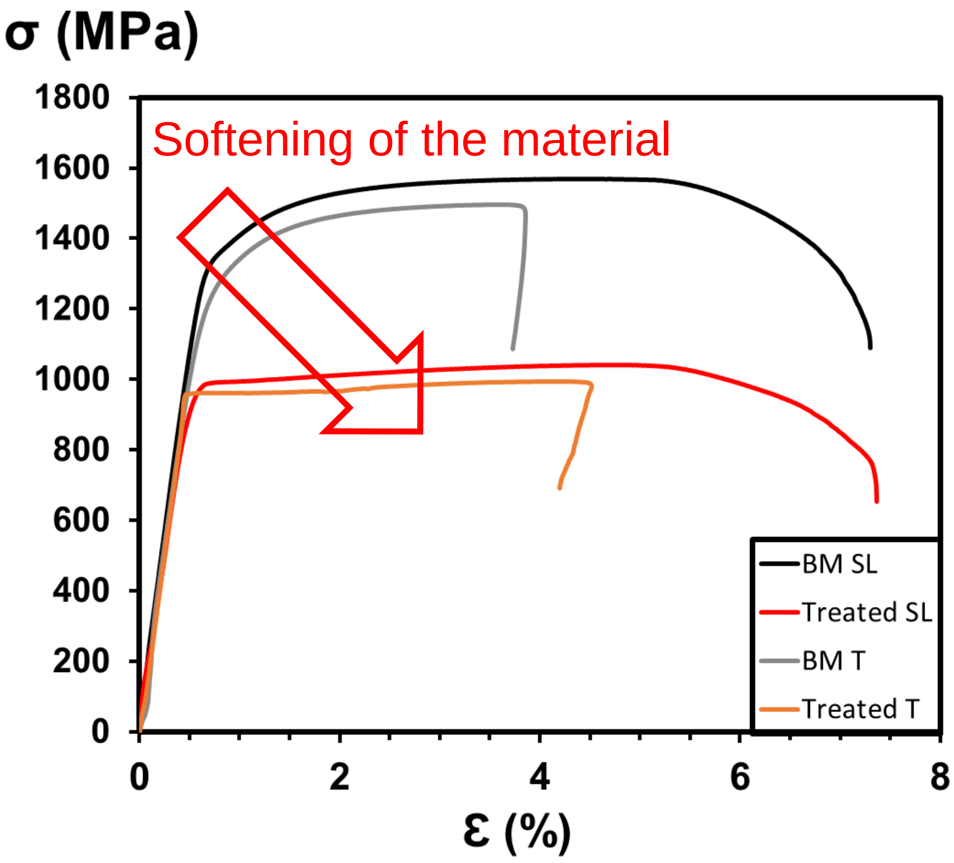
Laser-architectured metal sheets





ArcelorMittal



Prospective topics of interest for international collaboration

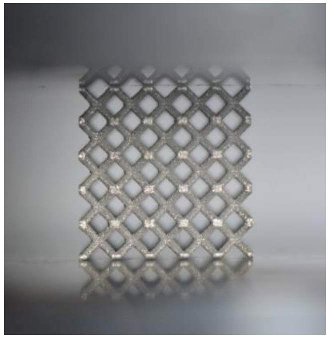
Prospective research topics

- Hybrid architectured materials
- Multiphysics computationally-efficient modelling tools
- Innovative material processing (not just additive manufacturing!)
- Materials science through machine learning
- Cradle-to-cradle design of structures

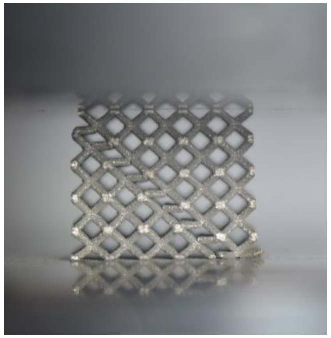
Hybrid architectured materials

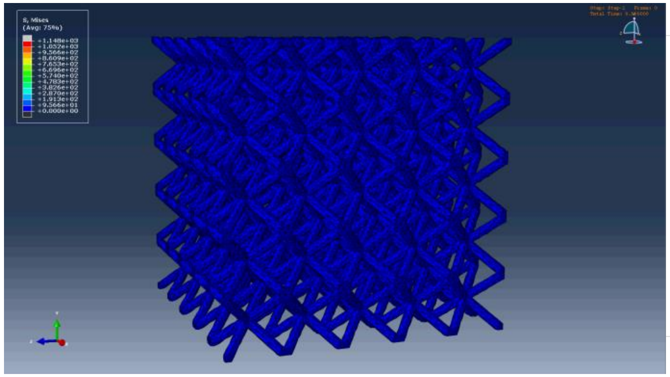
- Mitigating the surface defects of lattice structures
- Stabilising the lattice, delaying the collapse
- Hyperelastic/viscoelastic behaviour for dissipation

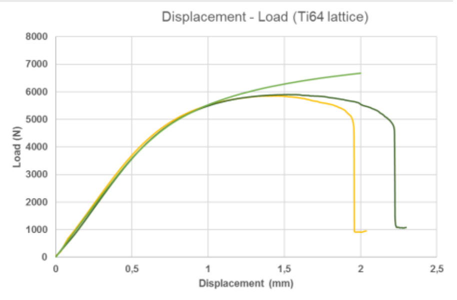
Ti64 initial configuration



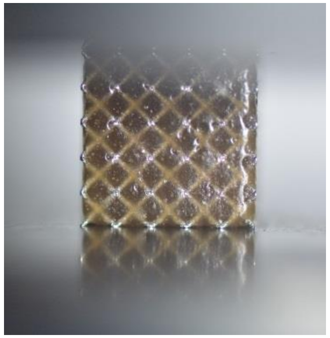
Localisation and fracture (13%)



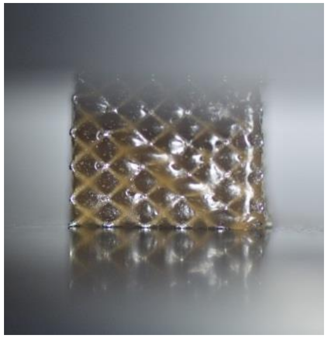


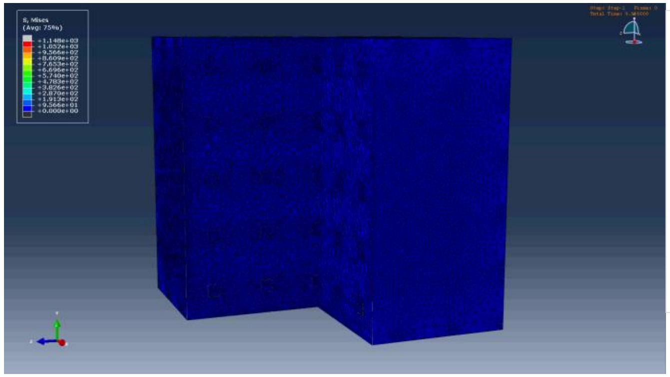


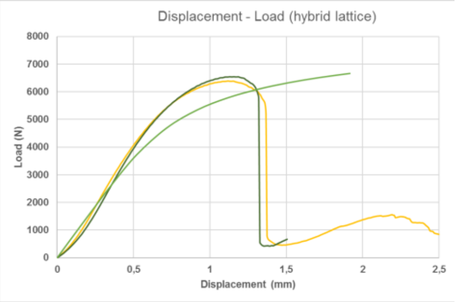
Hybrid initial configuration



Localisation and fracture (10%)



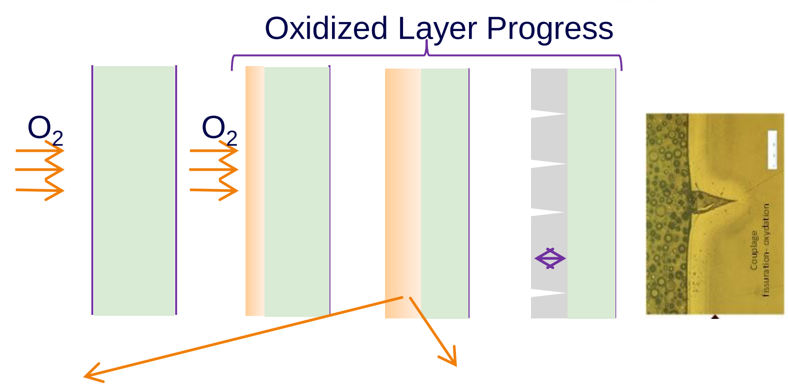




[Dirrenberger & Molotnikov, 2017]

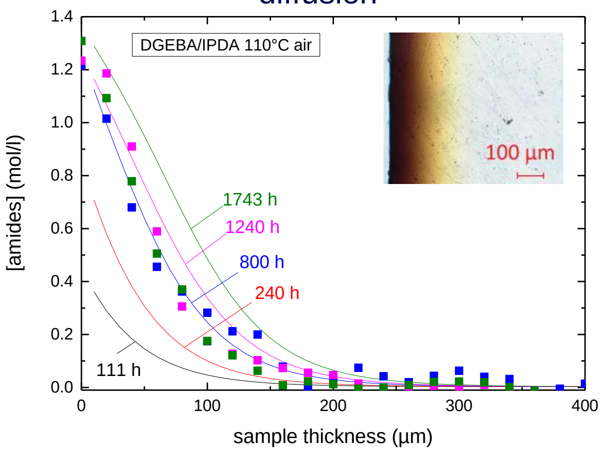
Durability of polymers and composites

- How to predict lifetime of polymers in use conditions?
- Main ageing mechanism: oxidation
- How to simulate the stress-strain state in the oxidized layer in order to assess the time when spontaneous cracking occurs

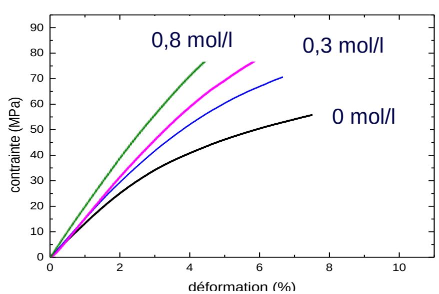


METHODOLOGY:

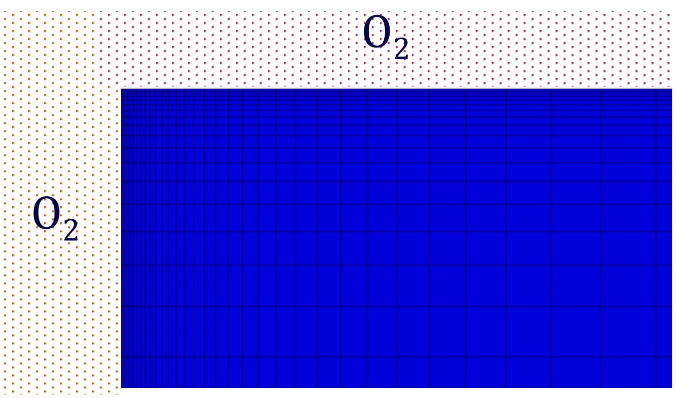
1. Kinetic modelling molecular tracer by coupling oxidation mechanism et oxygen diffusion



2. Assessment of relationships between tracer and shrinkage/mechanical behaviour changes



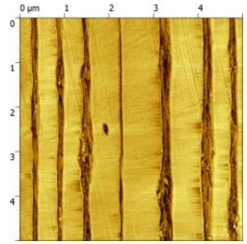
3. Simulation of oxidation-induced strain

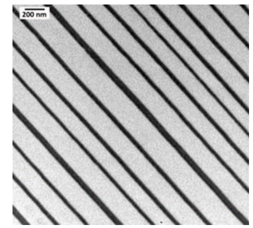


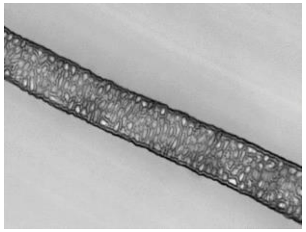
[Ernault et al., 2017]

Multilayer coextrusion

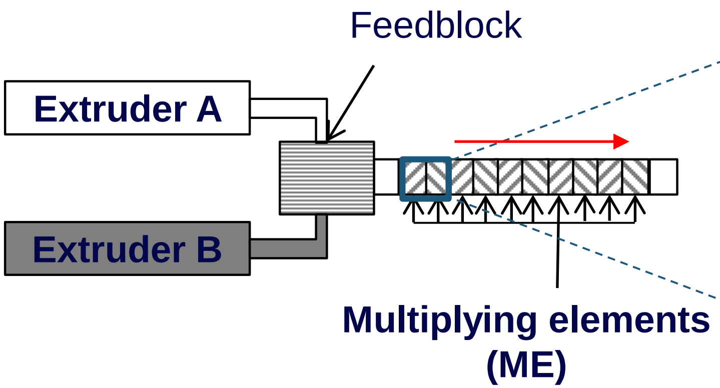
- Nanocomposites processing
- Confined polymer systems
- Forced-assembly / self-assembly materials

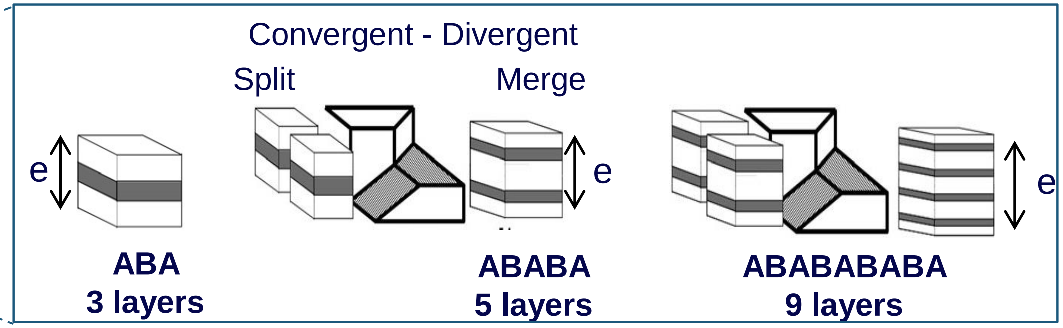




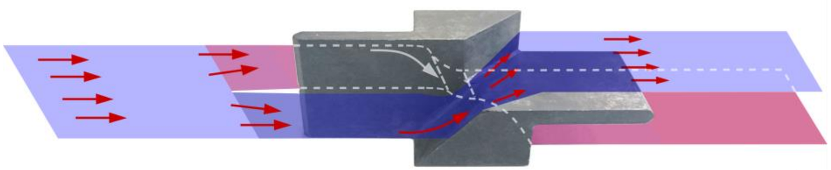


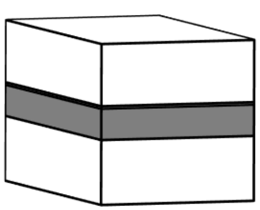
Flow direction





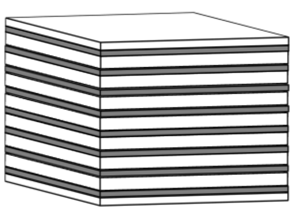
- Section area: 10 x 10 mm²
- Up to 13 ME in series





$= 2^{n+1} + 1$

n : number of ME



n = 10 → 2049 layers
n = 11 → 4097 layers
n = 12 → 8193 layers
n = 13 → 16385 layers

Nanoscale thickness

[Messin et al., 2017; Bironeau et al., 2017; Bironeau et al., 2016]

Outlook

- Many scientific questions remain (durability, processing, modelling…)
- Most industrial sectors have applications for architectured materials: biomedical, aerospace, energy, automotive, defence…
- We need more international collaboration in order to tackle the scientific challenges involved in materials engineering, and foster innovation.

Thank you!

Dr. Justin DIRRENBERGER

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