Controling the propagation of plastic instabilities in planar architectured materials

Justin Dirrenberger
PIMM Lab, Arts et Métiers/Cnam/CNRS – Paris, France
justin.dirrenberger@ensam.eu
@DirrenbergerGrp

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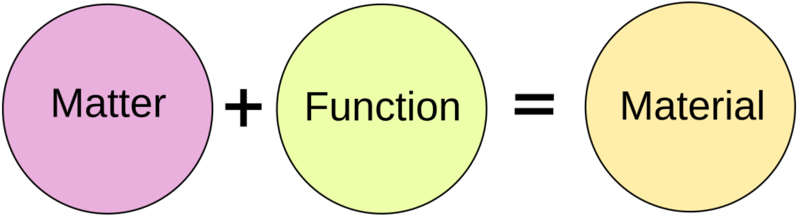
Outline

1. Architectured Materials
    - Introduction to architectured materials
    - Examples
2. Propagating material instabilities
    - Context & motivation
    - Architecture & material instabilities
    - Macroscopic behavior & localisation modes
    - Experimental testing
3. Outlook

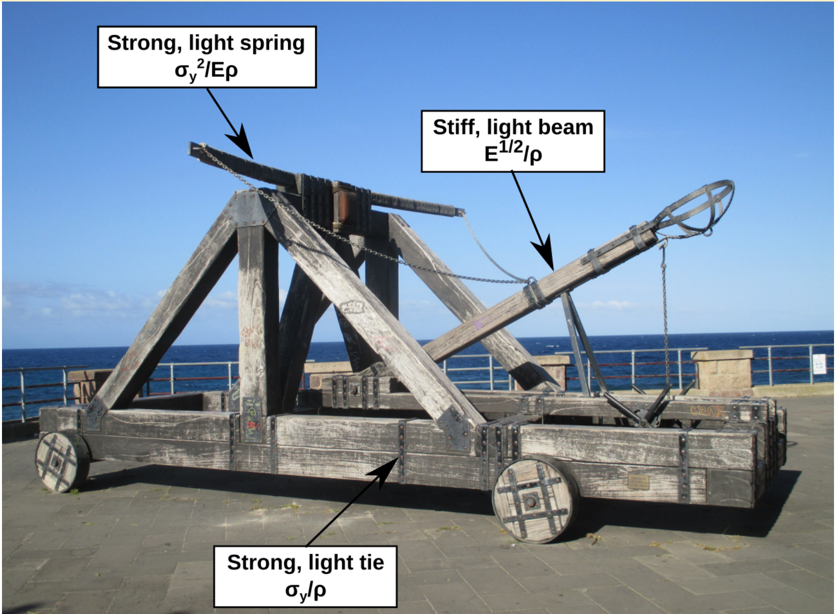
Plan

Plan

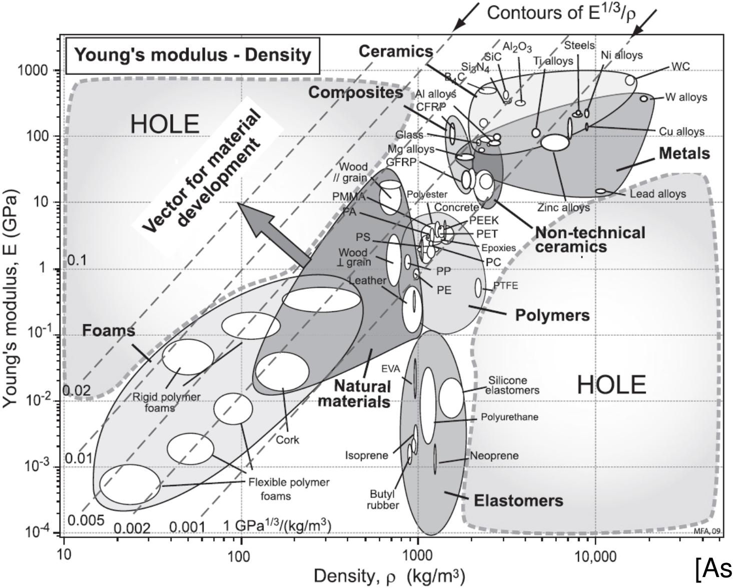
The engineer viewpoint : materials have purpose



Materials function

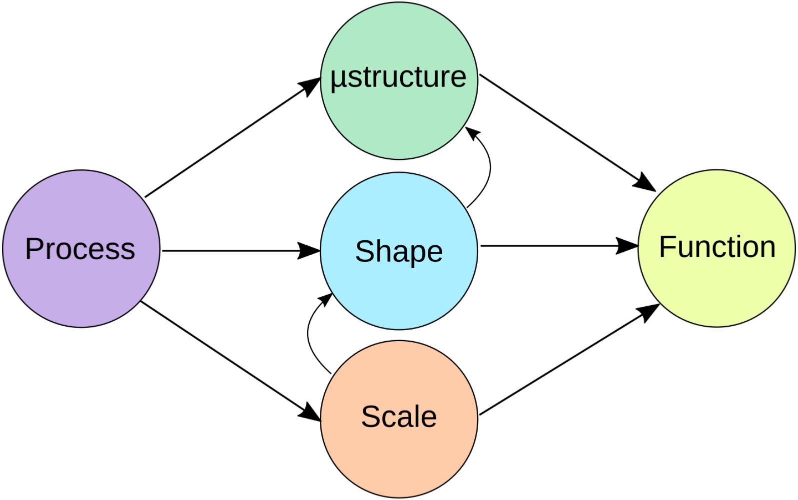


Material performance space

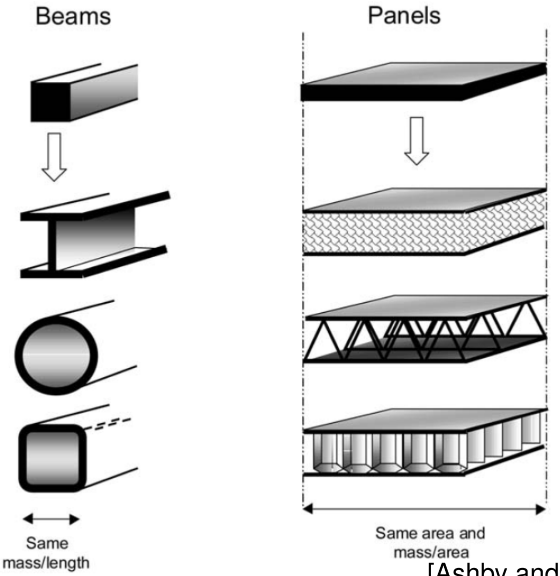


[Ashby, 2013]

But materials need to be processed...

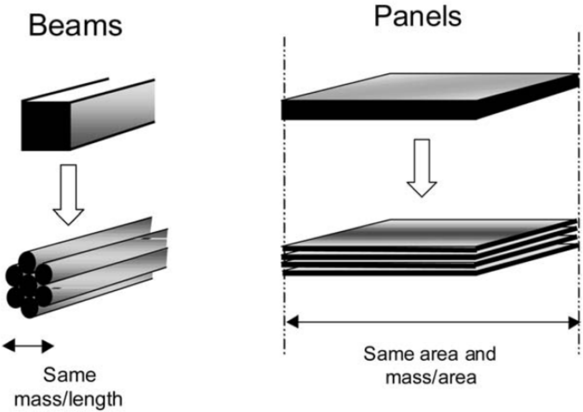


Shape and function : stiffer



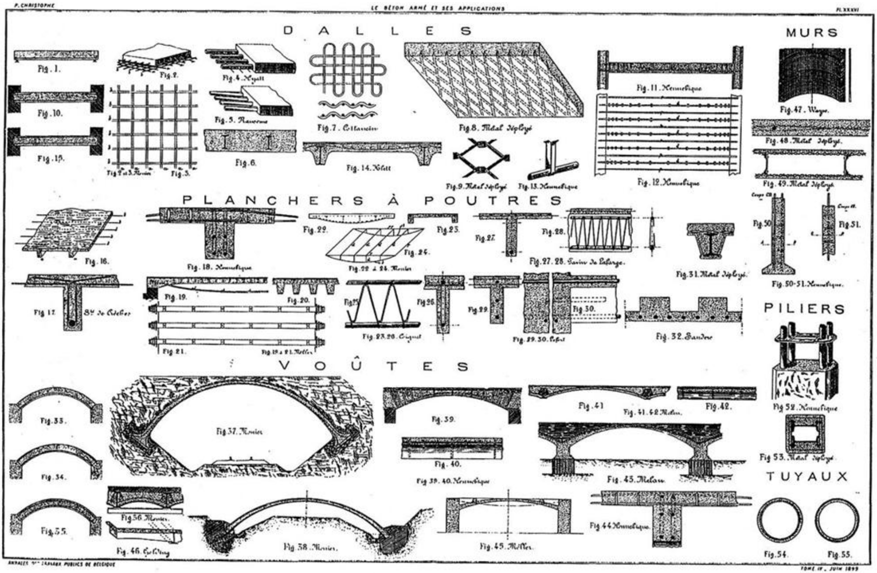
[Ashby and Bréchet, 2003]

Shape and function : more compliant



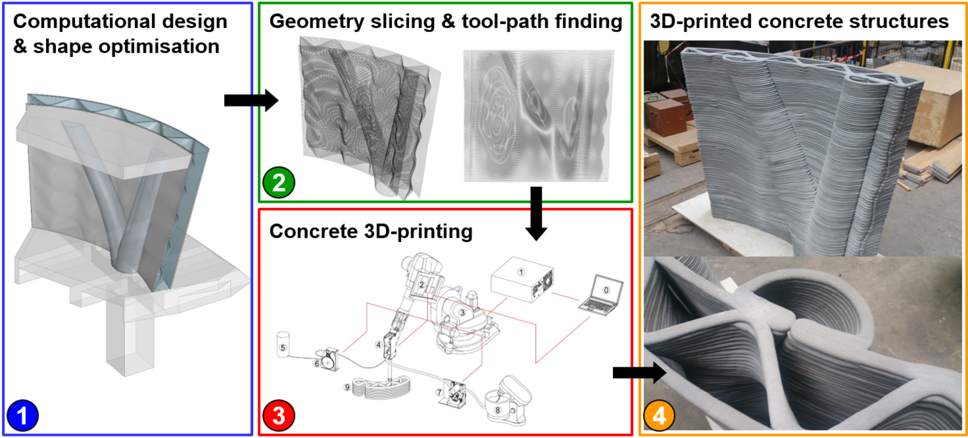
[Ashby and Bréchet, 2003]

Shape and function : taxonomy



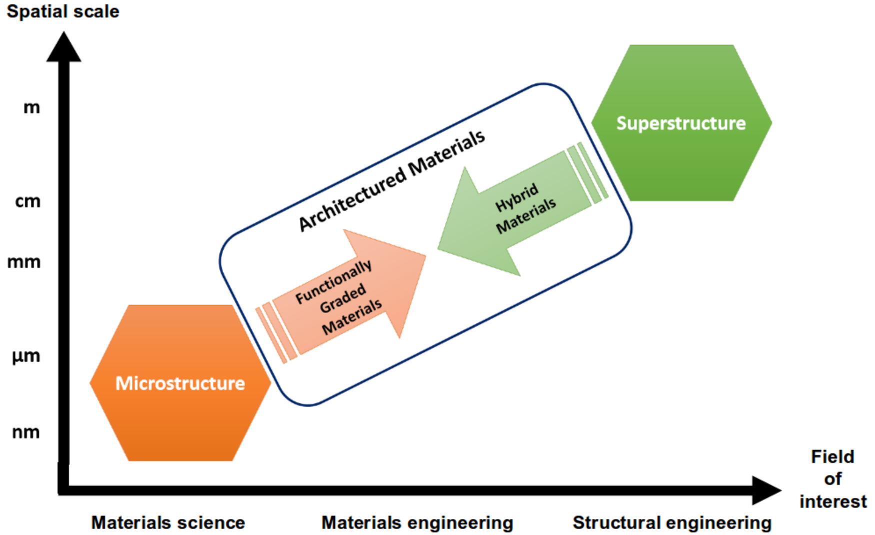
[Christophe, 1899]

Shape and function : large-scale 3D printing of UHPC



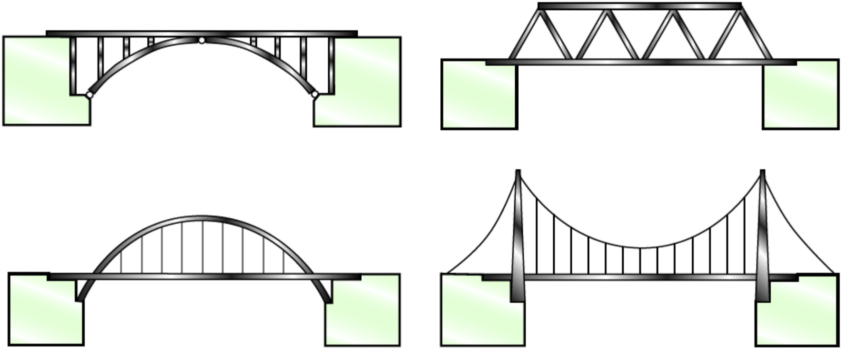
- 1st additively manufactured structural element in France
- Development of tangential continuity slicing [Gosselin et al., 2016]
- Spin-off company created : XtreeE

Spatial scale for architectured materials



Adapted from [Bouaziz et al., 2008]

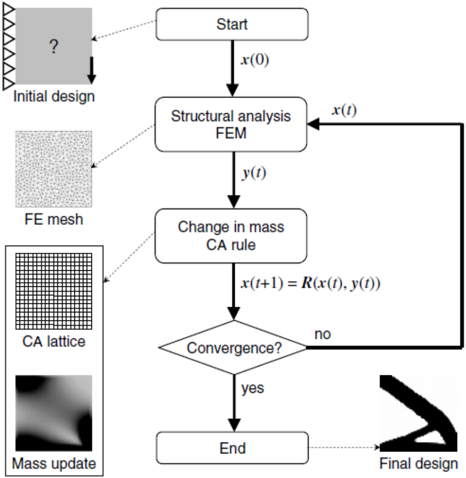
Morphology, not a new idea...

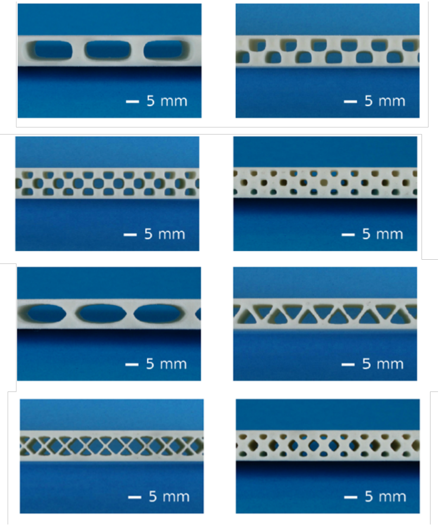


How to use morphology (topology + shape + scale) within architectured materials ?

[Ashby, 2011]

Optimising the morphology





[Tovar et al., 2006]

[Laszczyk, 2011]

Architectured materials

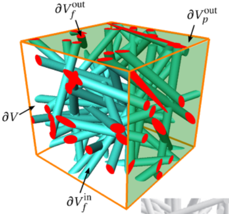
In summary :

- **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.
- This includes any material obtained from a design process aiming at fulfilling a specific set of requirements through a given functionality, behavior, or performance induced by an **engineered morphological arrangement** between multiple material phases .
- The development of architectured materials is **intrinsically transdisciplinary**, on the fringes of materials science, and mechanical engineering, but also biology, mathematical morphology, architecture, design, etc.

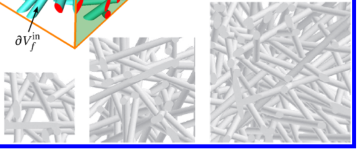
Plan

Example : entangled stochastic fibrous media

Microstructural model definition



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



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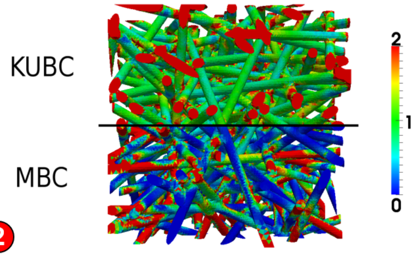
Computational experiments



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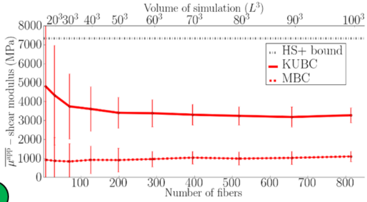
Statistical analysis and size effects



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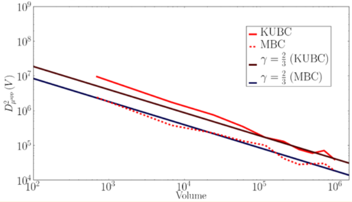
RVE size determination

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

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



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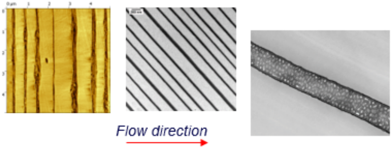
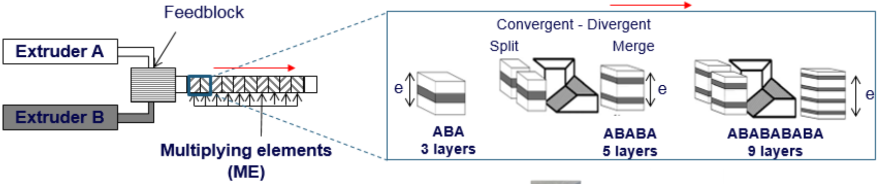
[Dirrenberger et al., 2014]

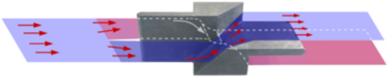
Example : nanolayered coextruded polymers

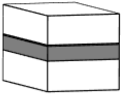
- Nanocomposites processing
- Confined polymer systems
- Forced-assembly / self-assembly materials





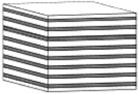
- Section area: 10 x 10 mm²
- Up to 13 ME in series





→ $2^{n+1} + 1$ layers

n : number of ME

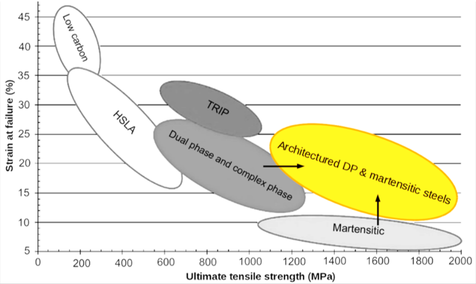


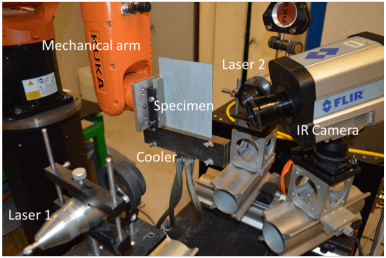
n = 10 → 2049 layers
n = 11 → 4097 layers
n = 12 → 8193 layers
n = 13 → 16385 layers

Nanoscale thickness

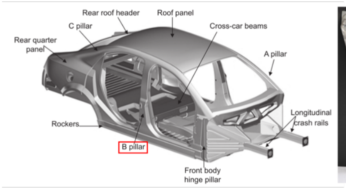
[Bironeau et al., 2016, Bironeau et al., 2017, Messin et al., 2017]

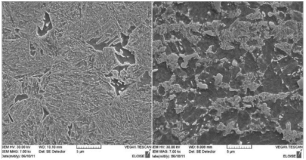
Example : laser-architectured metal sheets (1/2)



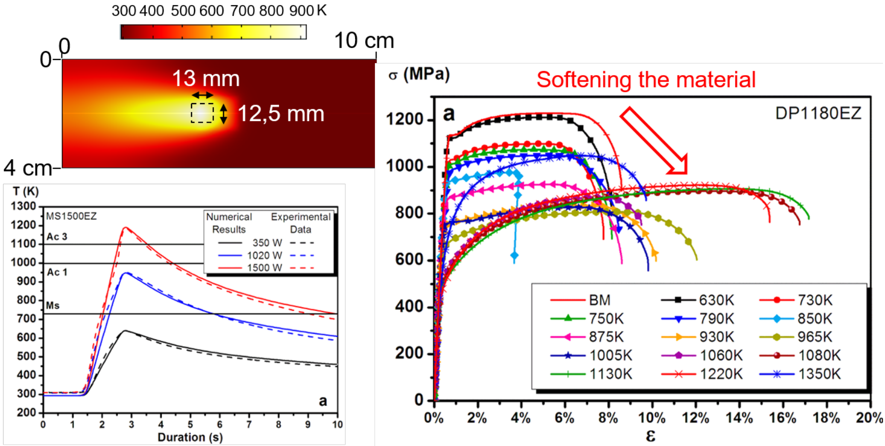


Laser heat-treatment





Example : laser-architectured metal sheets (2/2)

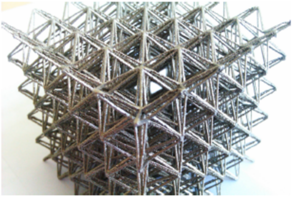


Pierre Lapouge's postdoc (2017-2019)
Zhige Wang's PhD thesis (2019-)

[Lapouge et al., 2019]

Example : elastoplastic auxetic lattices

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

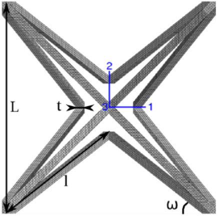
Elastoplasticity

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

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

$$R = R_o + Hp$$

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

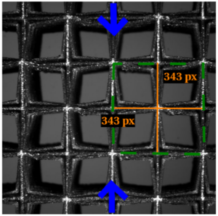


Unit-cell for the hexachiral lattice.

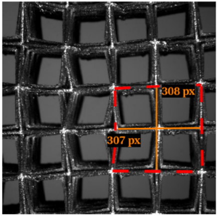
2

Experimental validation

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



Initial state

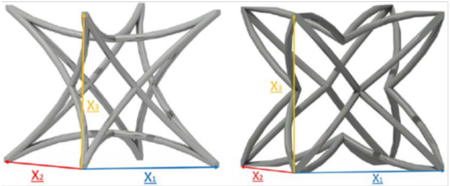


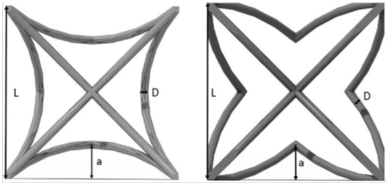
Deformed state

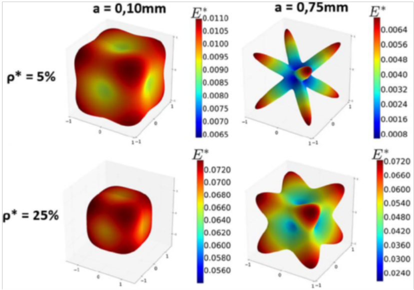
3

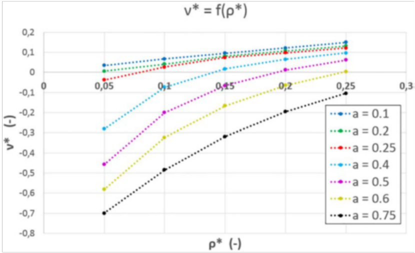
[Dirrenberger et al., 2011, Dirrenberger et al., 2012, Dirrenberger et al., 2013]

Example : 3D pre-buckled auxetic lattices









[Albertini et al., 2019]

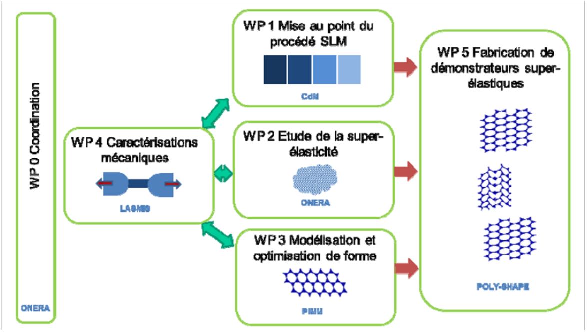
Frédéric Albertini's PhD thesis (2017-)

Plan

Plan

Context : ALMARIS ANR-funded project

Développement de matériaux architecturés superélastiques par fabrication additive (alliage NiTi), pour cahier des charges en tenue structurelle, absorption de chocs et actuation, dans le domaine aéronautique.



Antoine-Emmanuel Viard's PhD thesis (2017-)

Goals

Goals : Provide numerical tools for the design of architectured materials exploiting material instabilities.

- Computational modelling of the material instabilities
- Determine the effect of geometry on the onset of material instabilities
- Harness instabilities through architecture

Hypothesis on material instability modelling

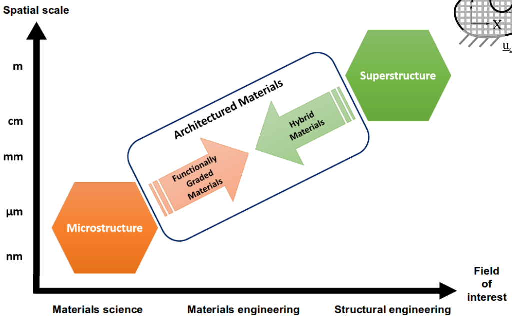
Analogue propagation is assumed for martensitic transformation front in SMA and plasticity front in low carbon steel (Piobert-Lüders phenomenon).

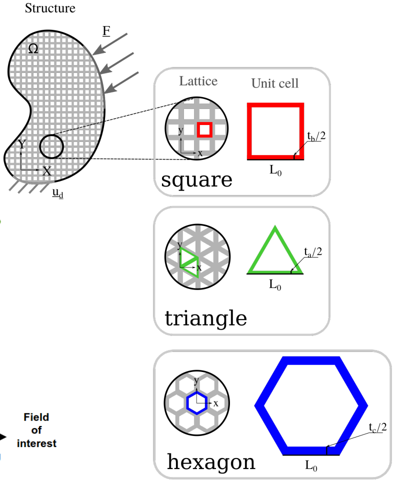
Plan

From the structure to the unit cell

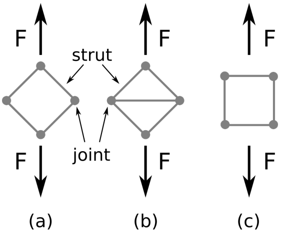
Lattice materials

- intermediate length scale
- periodic unit-cell repeated





Mechanical behavior of lattices

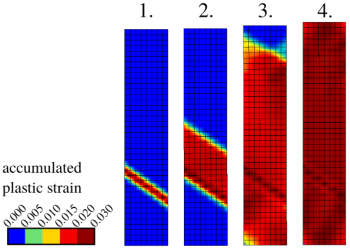


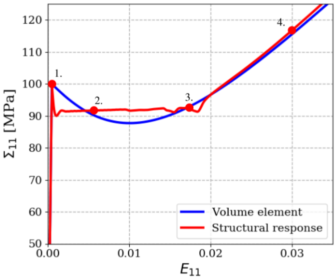
(a) mechanism ; (b) structure ; (c) selfstressed mechanism

Figure adapted from [Deshpande et al., 2001]

Triangular lattice	Hexagonal lattice	Square lattice
Stretch-dominated	Bending-dominated	Stretch-dom. bending-dom.

Phenomenological model





Nonlinear isotropic work-hardening function

$$R(p) = R_0 + Q_1(1 - e^{-b_1 p}) + Q_2(1 - e^{-b_2 p}) + Q_3(1 - e^{-b_3 p})$$

R_0	Q_1	b_1	Q_2	b_2	Q_3	b_3
100	-100	80	400	10	5	500

[Tsukahara and Iung, 1998, Mazière and Forest, 2015]

Problem statement

Architecture

- Choice of geometry (lattice...)
- Macroscopic behavior

Material

- Plastic strain instability
- Localisation and propagation

Problem

How do instabilities propagate in periodic media ?

Plan

Computational homogenization

Macroscopic constitutive equation

$$\underset{\sim}{\boldsymbol{\Sigma}} = \langle \underset{\sim}{\boldsymbol{\sigma}} \rangle \Longleftrightarrow \underset{\sim}{\boldsymbol{E}} = \langle \underset{\sim}{\varepsilon} \rangle$$

$$\underset{\sim}{\boldsymbol{\Sigma}} = \underset{\approx}{\boldsymbol{C}} : \underset{\sim}{\boldsymbol{E}}$$

$$\underset{\sim}{\boldsymbol{\sigma}}(\underline{\boldsymbol{x}}) = \underset{\approx}{\boldsymbol{c}}(\underline{\boldsymbol{x}}) : \underset{\sim}{\varepsilon}(\underline{\boldsymbol{x}})$$

$$\underset{\sim}{\boldsymbol{\sigma}}(\underline{\boldsymbol{x}}) \Longleftrightarrow \underset{\sim}{\varepsilon}(\underline{\boldsymbol{x}})$$

Microscopic constitutive equation

Computational homogenization

$$\underset{\sim}{\boldsymbol{\Sigma}} = \langle \underset{\sim}{\boldsymbol{\sigma}} \rangle \quad \Longleftrightarrow \quad \underset{\sim}{\boldsymbol{E}} = \langle \underset{\sim}{\boldsymbol{\varepsilon}} \rangle$$

Macroscopic constitutive equation

$$\underset{\sim}{\boldsymbol{\Sigma}} = \underset{\approx}{\boldsymbol{C}} : \underset{\sim}{\boldsymbol{E}}$$

Localization

$$\underset{\sim}{\boldsymbol{\varepsilon}}(\underline{\boldsymbol{x}}) = \underset{\approx}{\boldsymbol{A}}(\underline{\boldsymbol{x}}) : \underset{\sim}{\boldsymbol{E}}$$

$$\underset{\sim}{\boldsymbol{\sigma}}(\underline{\boldsymbol{x}}) = \underset{\approx}{\boldsymbol{c}}(\underline{\boldsymbol{x}}) : \underset{\sim}{\boldsymbol{\varepsilon}}(\underline{\boldsymbol{x}})$$

$$\underset{\sim}{\boldsymbol{\sigma}}(\underline{\boldsymbol{x}}) = \underset{\approx}{\boldsymbol{c}} : \underset{\approx}{\boldsymbol{A}} : \underset{\sim}{\boldsymbol{E}} \quad \Longleftrightarrow \quad \underset{\sim}{\boldsymbol{\varepsilon}}(\underline{\boldsymbol{x}}) = \underset{\approx}{\boldsymbol{A}}(\underline{\boldsymbol{x}}) : \underset{\sim}{\boldsymbol{E}}$$

Microscopic constitutive equation

Computational homogenization

Macroscopic constitutive equation

$\underset{\sim}{\boldsymbol{\Sigma}} = \langle \underset{\sim}{\sigma} \rangle \longleftrightarrow \underset{\sim}{\boldsymbol{E}} = \langle \underset{\sim}{\varepsilon} \rangle$

$$\underset{\sim}{\boldsymbol{\Sigma}} = \underset{\approx}{\boldsymbol{C}} : \underset{\sim}{\boldsymbol{E}}$$

Homogenization ↑

Localization ↓

$$\underset{\sim}{\sigma}(\underline{\boldsymbol{x}}) = \underset{\approx}{\boldsymbol{c}}(\underline{\boldsymbol{x}}) : \underset{\sim}{\varepsilon}(\underline{\boldsymbol{x}})$$

$\underset{\sim}{\sigma}(\underline{\boldsymbol{x}}) = \underset{\approx}{\boldsymbol{c}} : \underset{\approx}{\boldsymbol{A}} : \underset{\sim}{\boldsymbol{E}} \longleftrightarrow \underset{\sim}{\varepsilon}(\underline{\boldsymbol{x}}) = \underset{\approx}{\boldsymbol{A}}(\underline{\boldsymbol{x}}) : \underset{\sim}{\boldsymbol{E}}$

Microscopic constitutive equation

Computational homogenization

Macroscopic constitutive equation

$$\underset{\sim}{\Sigma} = \langle \underset{\sim}{\sigma} \rangle \quad \longleftrightarrow \quad \underset{\sim}{E} = \langle \underset{\sim}{\varepsilon} \rangle$$

$$\underset{\sim}{\Sigma} = \underset{\approx}{C} : \underset{\sim}{E}$$

Homogenization ↑ Localization ↓

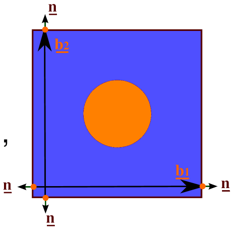
$$\underset{\sim}{\sigma}(\underline{x}) = \underset{\approx}{c}(\underline{x}) : \underset{\sim}{\varepsilon}(\underline{x})$$

$$\underset{\sim}{\sigma}(\underline{x}) = \underset{\approx}{c} : \underset{\approx}{A} : \underset{\sim}{E} \quad \longleftrightarrow \quad \underset{\sim}{\varepsilon}(\underline{x}) = \underset{\approx}{A}(\underline{x}) : \underset{\sim}{E}$$

Microscopic constitutive equation

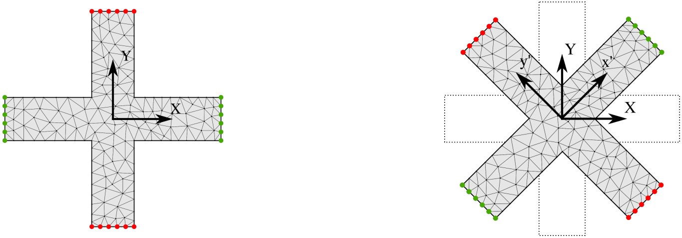
Use of periodic boundary conditions (PBC)

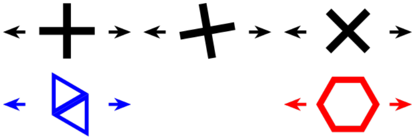
$$\begin{cases} \underline{u} = \underset{\sim}{E}.\underline{x} + \underline{v} \quad \forall \underline{x} \in V & \text{with } \underline{v}\ \# \text{ on } \partial V \text{ and,} \\ \underline{t} = \underset{\sim}{\sigma}.\underline{n} \quad \forall \underline{x} \in \partial V & \text{with } \underline{t} - \# \text{ on } \partial V \end{cases}$$



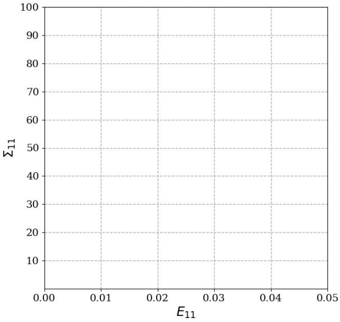
Numerical framework

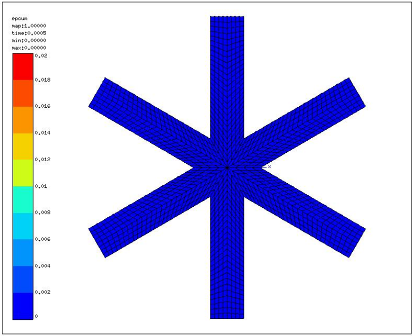
PBC





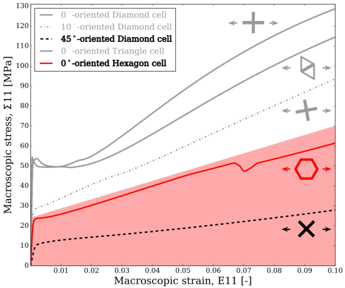
Simulation of the triangle lattice





Two types of response

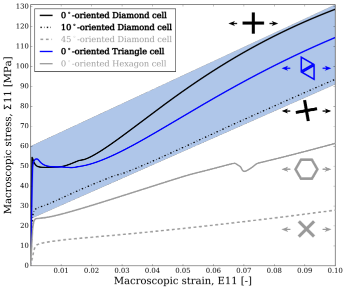
Bending-dominated lattices



Low stiffness - Neither peak nor plateau stress

► Non propagating behavior for Lüders instabilities

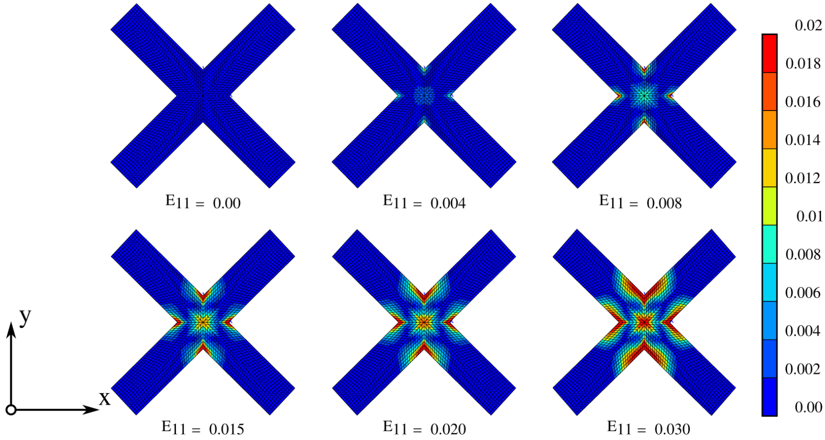
Stretch-dominated lattices



High stiffness - Both peak and plateau stress

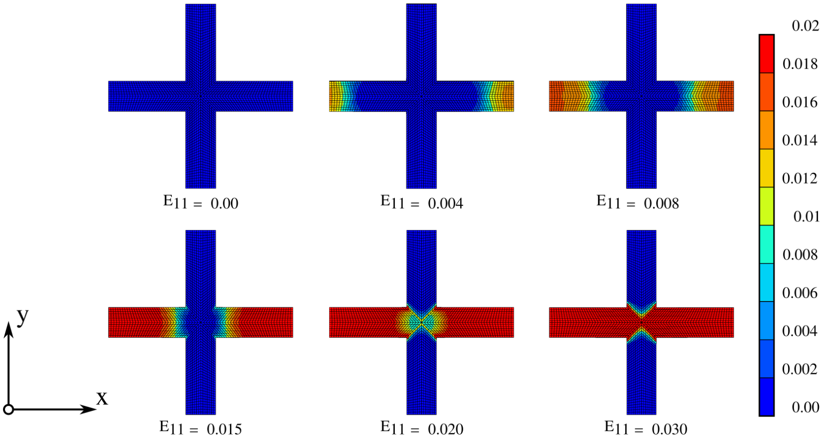
► Propagating behavior for Lüders instabilities

1. Non propagating instabilities



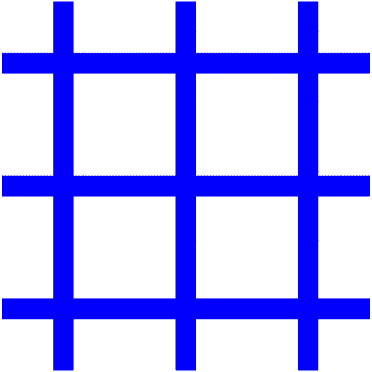
Cumulated plastic strain for bending-dominated lattices tension in horizontal direction.

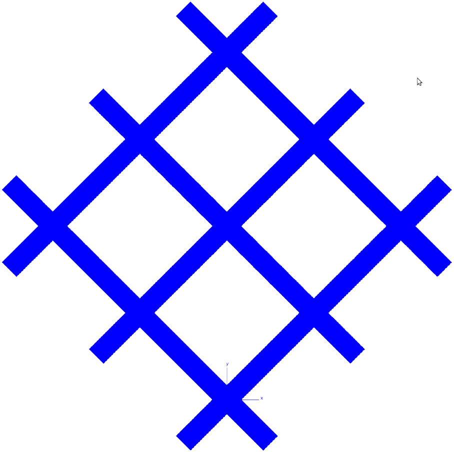
2. Propagating instabilities



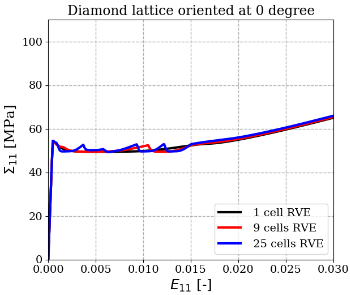
Cumulated plastic strain for stretch-dominated lattices tension in horizontal direction.

RVE size : square lattice

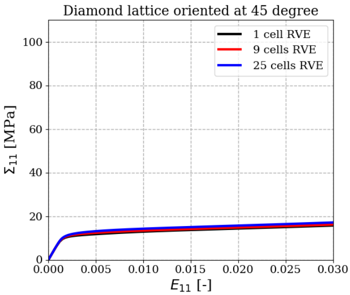




Macroscopic behavior for several unit cells



Square oriented at 0 deg w.r.t. the tensile direction.

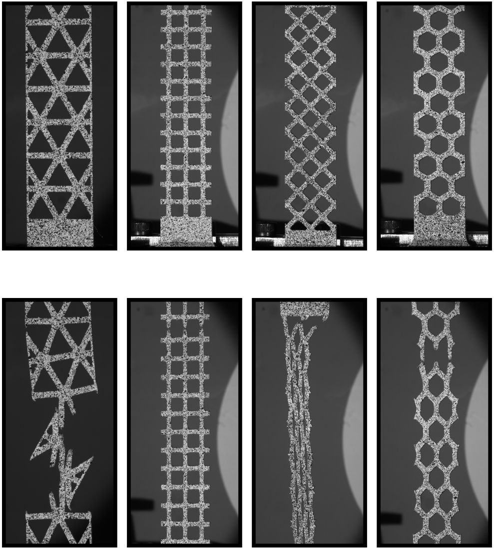


Square oriented at 45 deg w.r.t. the tensile direction.

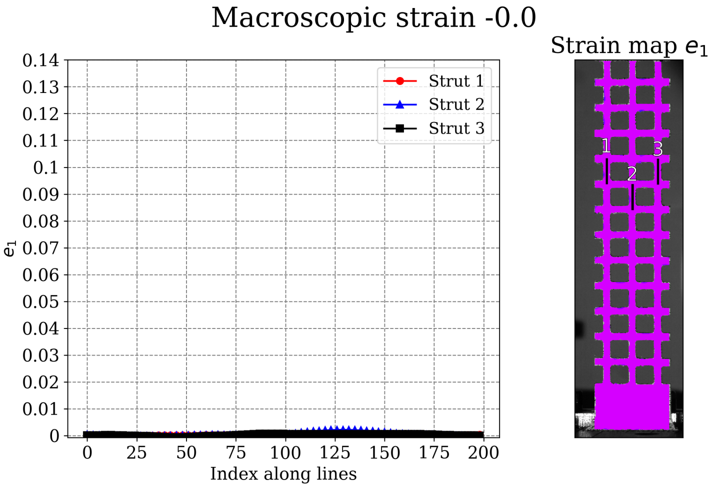
- What definition for the RVE in case of instabilities ?

Plan

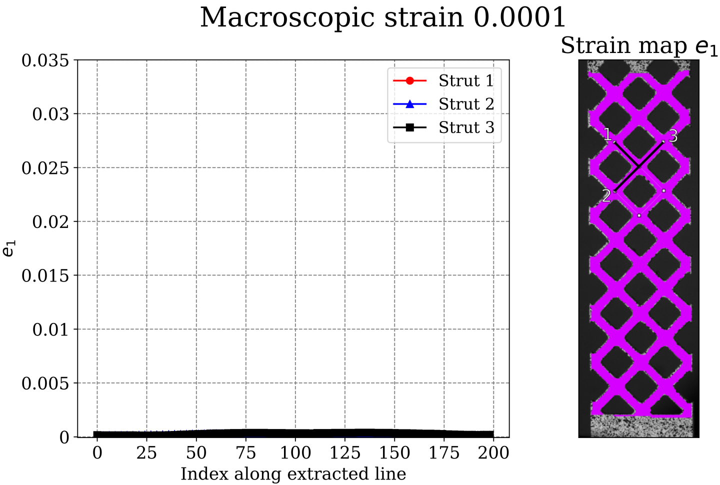
Architectured samples



Stretch-dominated structure



Bending-dominated structure

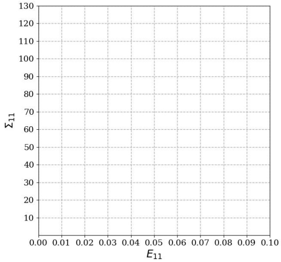


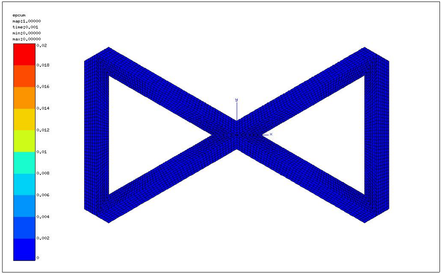
Conclusions & perspectives

Conclusions [Viard et al., 2020]

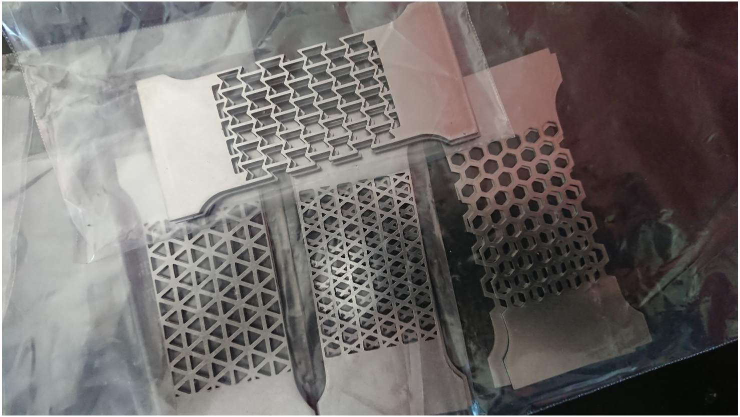
- Interactions between architecture and material instabilities
- Specific behavior identified for each geometry
- Qualitative experimental validation of the computation

Perspectives





Conclusions & perspectives



Plan

1. Architectured Materials
   - Introduction to architectured materials
   - Examples
2. Propagating material instabilities
   - Context & motivation
   - Architecture & material instabilities
   - Macroscopic behavior & localisation modes
   - Experimental testing
3. Outlook

Finally...

Conclusions & outlook

- The emergence of architectured materials is fostered by the development of advanced manufacturing techniques. Localised material processing allows for intricate architecturation, enabling new possibilities in terms of material properties.
- Controling the propagation of plastic instabilities, or phase transformation front, through architecture seems like a promising approach to develop new actuating or adaptive material systems.
- Developing architectured materials necessitates a transdisciplinary approach, please get in touch if you would like to collaborate with our group ! We'll welcome you in Paris, once COVID is over...

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