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Effective properties of architected materials

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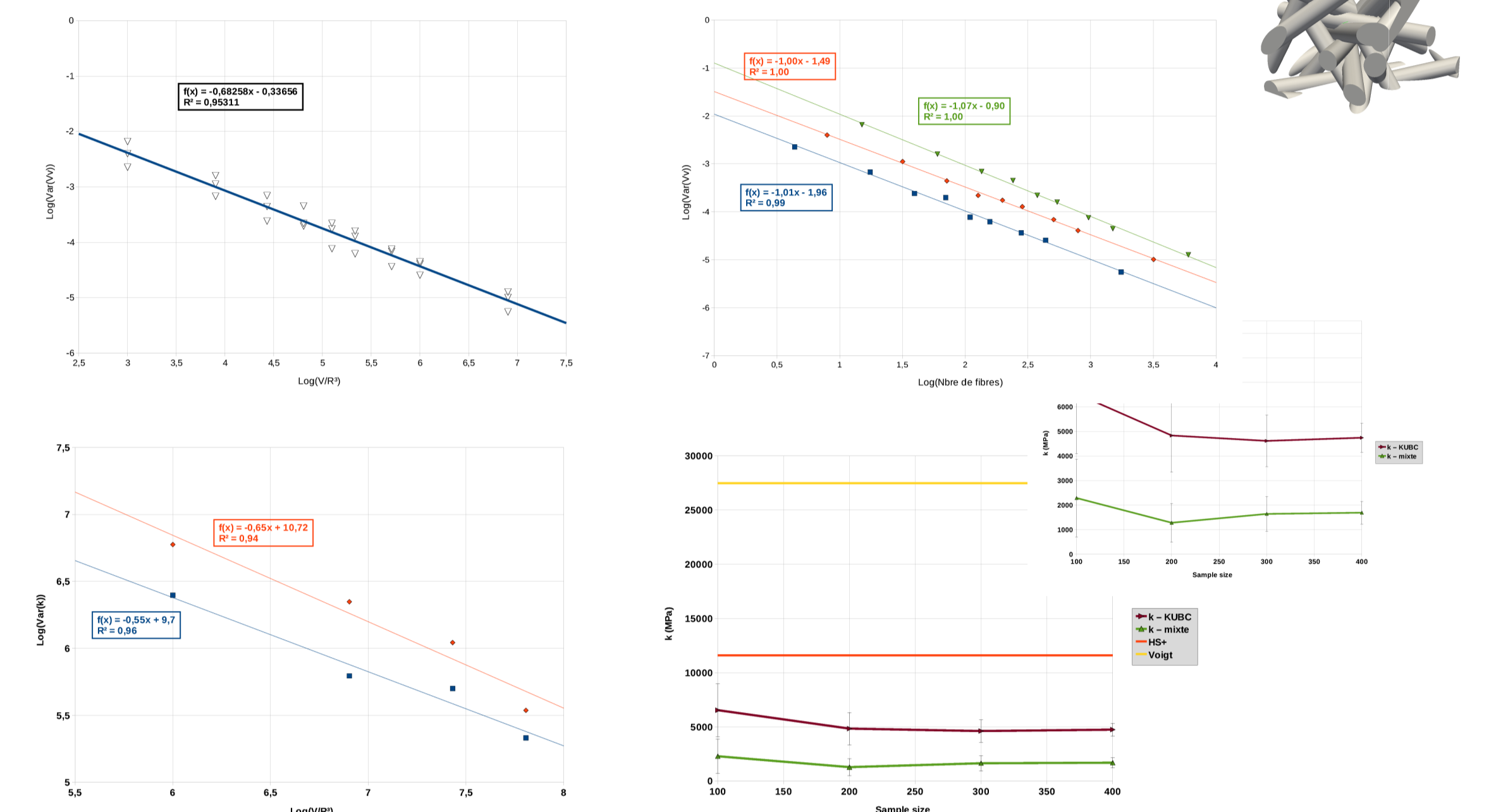
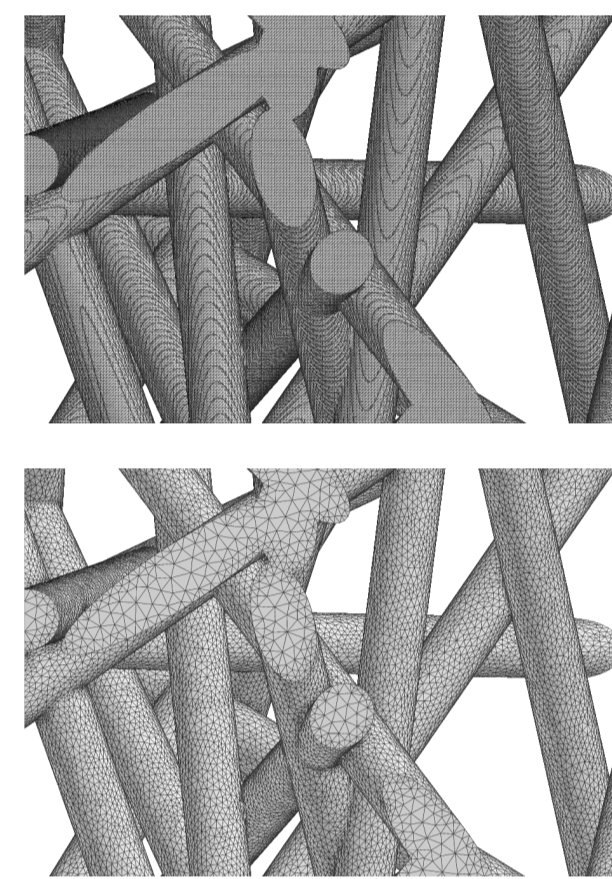
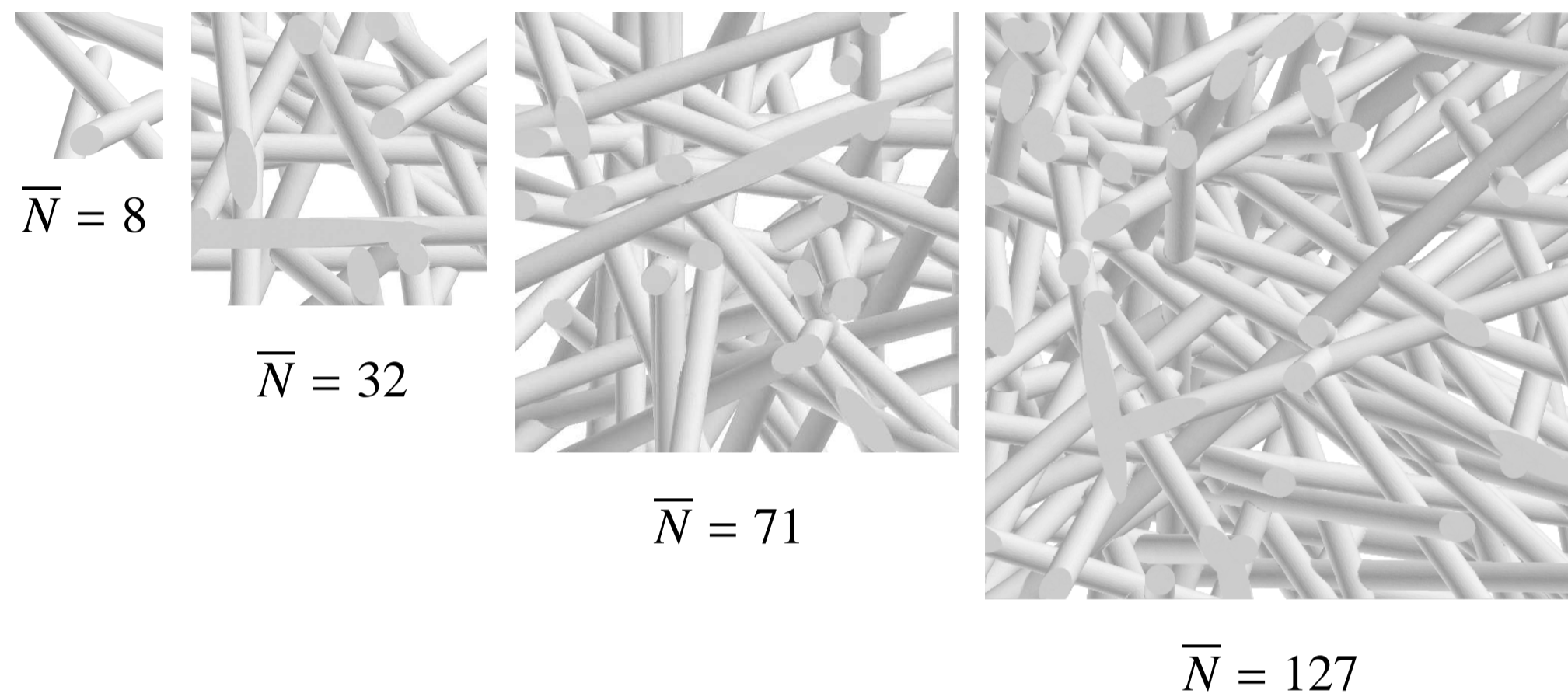
Introduction

The MANSART project, for "architected sandwich materials", aims at developing innovative **architected materials**, exhibiting **improved functional properties** in comparison with traditional composites. Our contribution is focused on **modeling** and **simulation** of architected microstructures, prediction of their **effective properties** using **numerical homogenization** implemented with finite elements (Z-set software). **Rapid prototyping** using selective laser melting allows us to fabricate samples and validate the numerical prediction. Two types of morphologies have been identified: randomly distributed **entangled Poisson's fibres** and **auxetic periodic lattices**. Effective properties of Poisson's fibres is investigated although estimation is challenging since statistical **representative volume element (RVE)** size is *a priori* unknown, due to an infinite **integral range** as shown in [Jeulin, 1989]. Scaling laws for variances of properties are computed. Auxetics are architected materials exhibiting a **negative Poisson's ratio**. Mechanical behavior of such materials is investigated for both elastic and plastic domains. 2D and 3D lattices are proposed for industrial applications.

Keywords: Homogenization, architected materials, auxetics, Poisson's fibres, RVE, finite elements, mathematical morphology, selective laser melting.

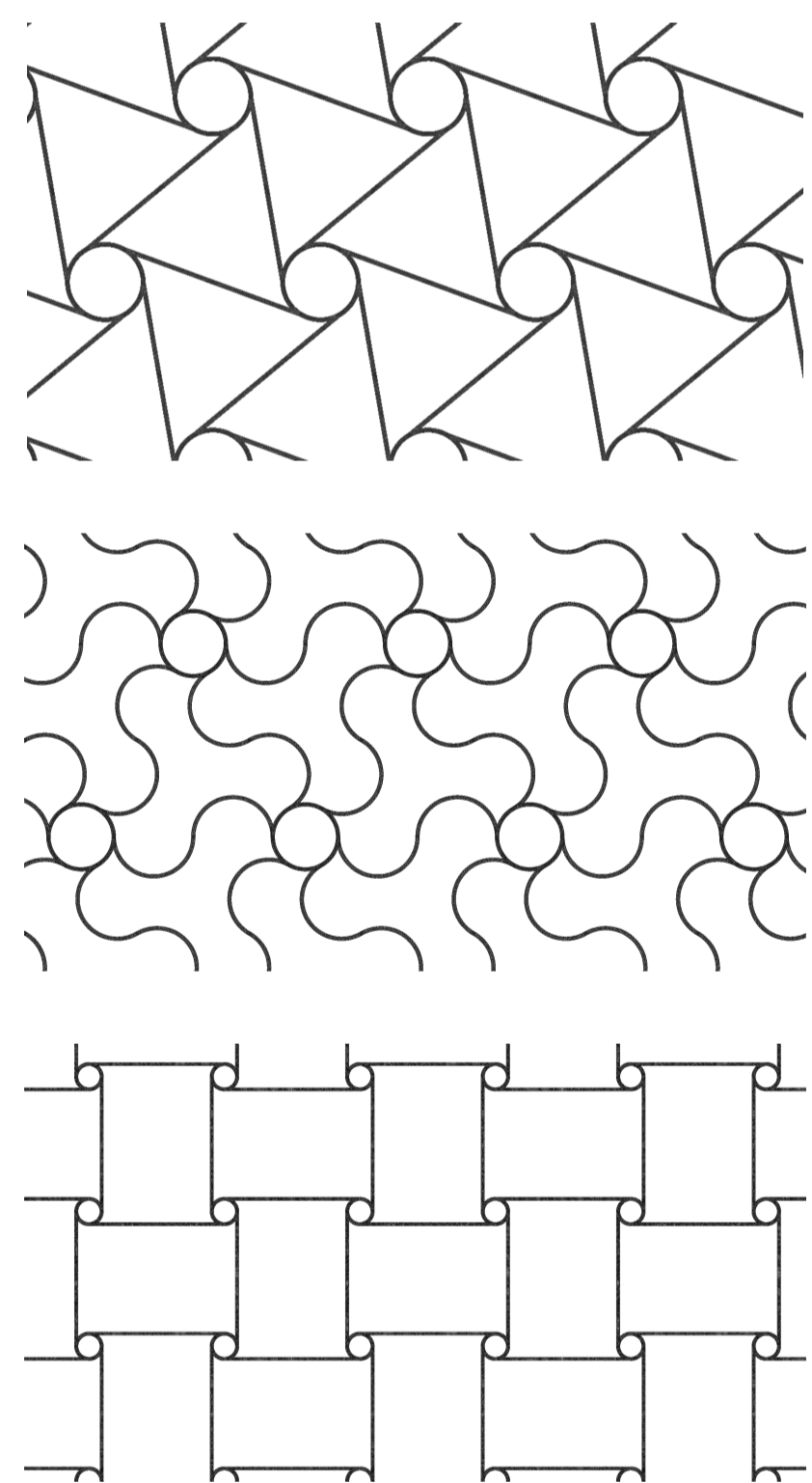
Determination of statistical RVE and effective properties for Poisson's fibres

- Modeling straight infinite randomly entangled interpenetrating Poisson's fibres with intensity λ such as, $\lambda = \frac{\ln(1-V_V)}{\pi^2 R^2}$ with R fibres radius and V_V volume fraction of fibres.
- Optimization of surface (vtkSim, Yams) and volume meshes (GHS3D) for finite element computation.
- Estimation of RVE size based on method established in [Kanit et al., 2003].
- Simulation of samples with an increasing quantity of fibres; scaling laws are computed.
- Homogenization using mixed, kinetic (KUBC) and static uniform boundary conditions (SUBC).



Homogenization and mechanical investigation of auxetic lattice structures

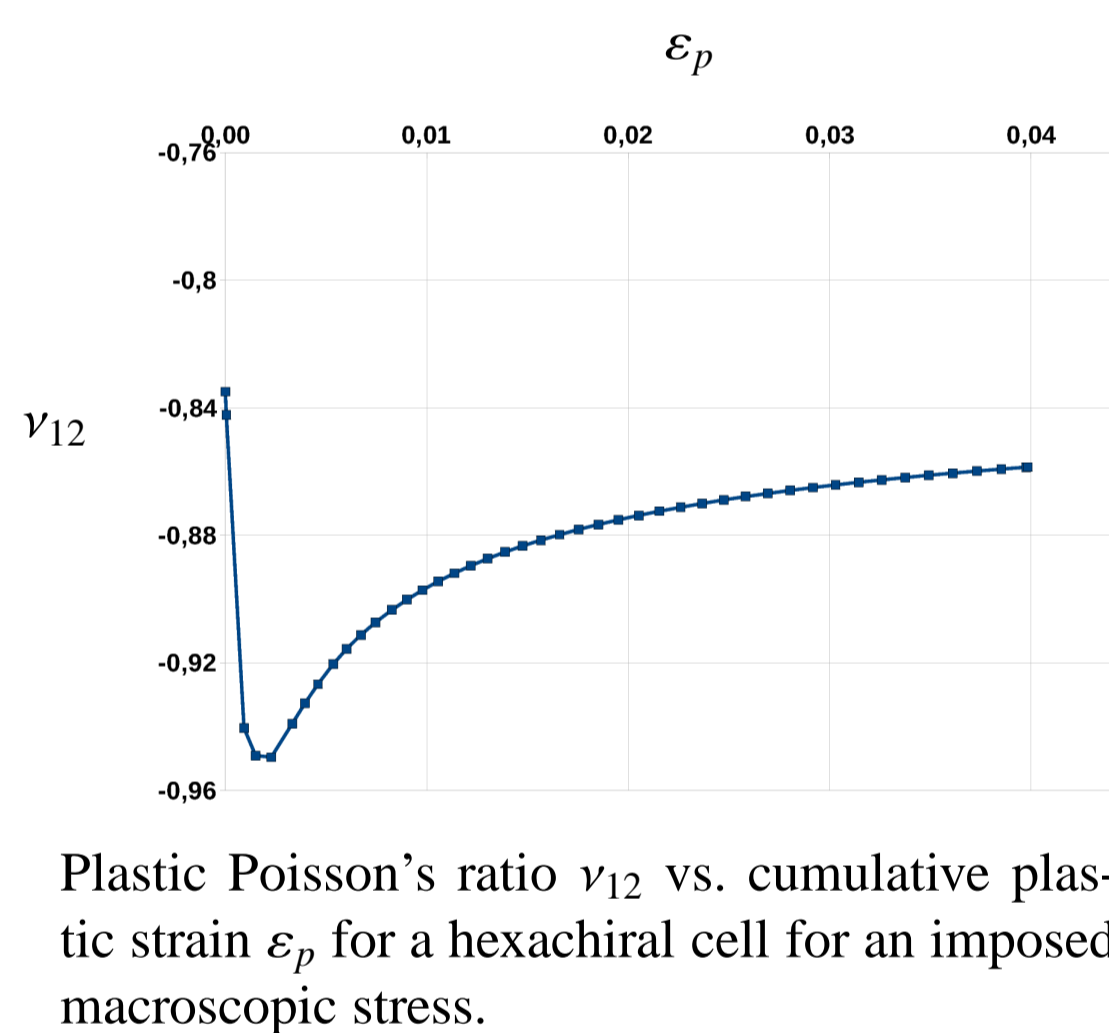
- Modeling of original auxetic periodic cells and examples from the literature.
- Numerical homogenization (FE) using periodic boundary conditions with imposed macroscopic stress or strain.
- Analytical representation of elastic moduli and Poisson's ratio in 3D.
- Design and manufacture of 3D quasi-isotropic auxetic lattice structures.



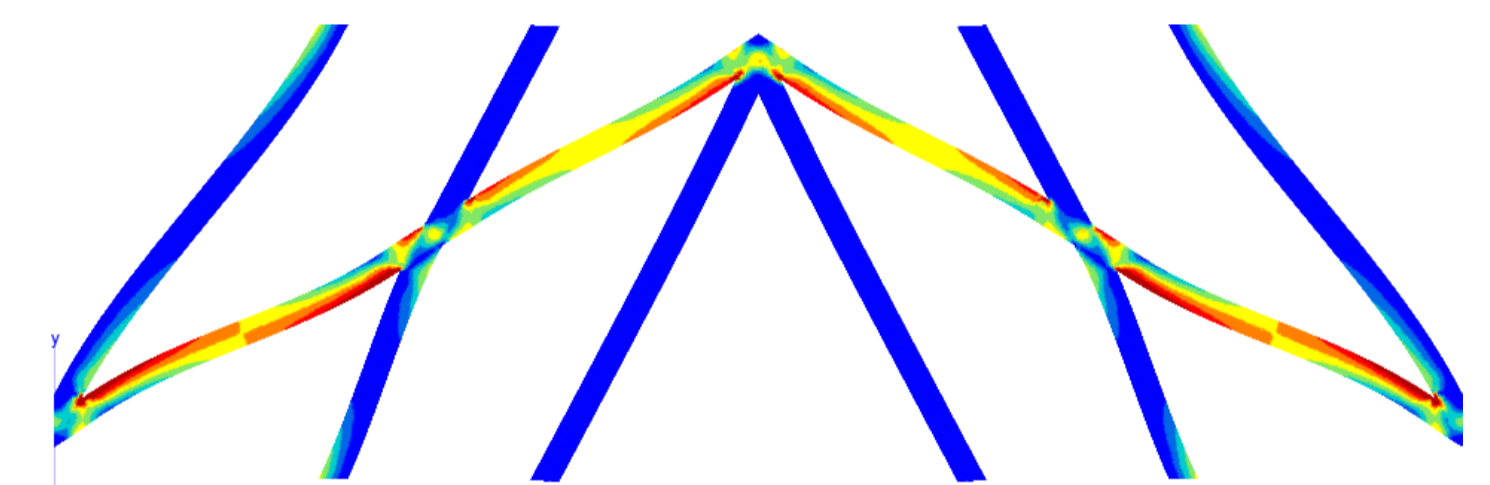
Auxetic lattice from the literature (hexachiral)
 $\nu = -0.83$, $V_V = 7\%$
 [Prall and Lakes, 1997]

Original transverse isotropic chiral structure
 $\nu = -0.25$, $V_V = 7\%$
 [Dirrenberger et al., 2011]

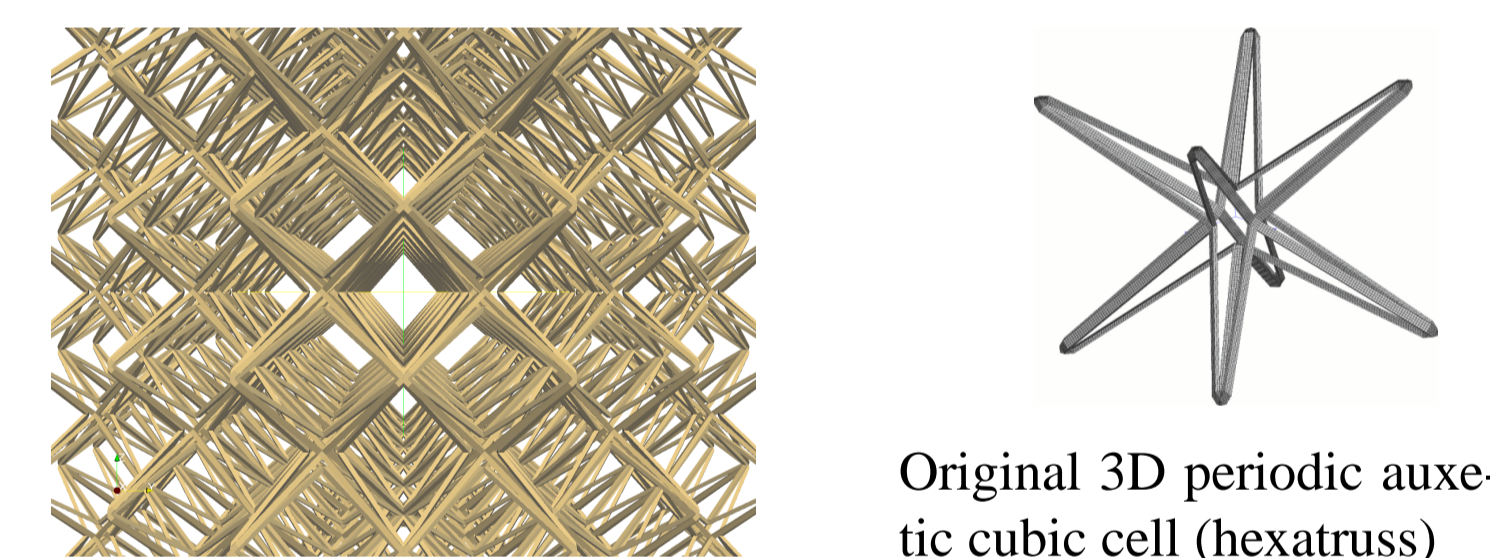
Cubic anti-chiral structure from the literature
 $\nu = f(\phi)$, $V_V = 7\%$
 [Alderson et al., 2010]



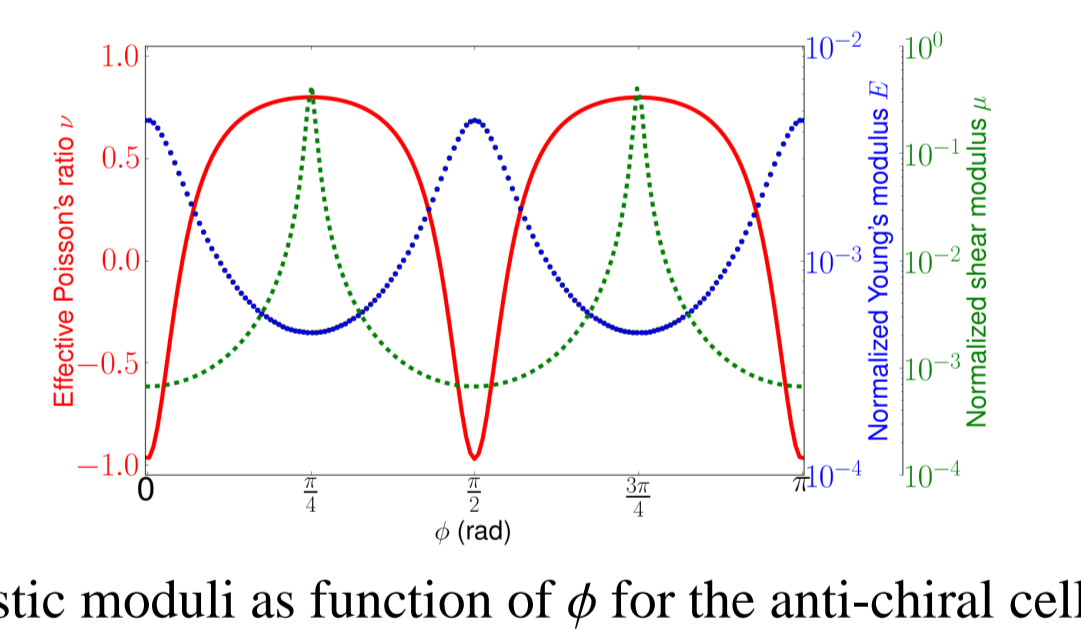
Plastic Poisson's ratio ν_{12} vs. cumulative plastic strain ϵ_p for a hexachiral cell for an imposed macroscopic stress.



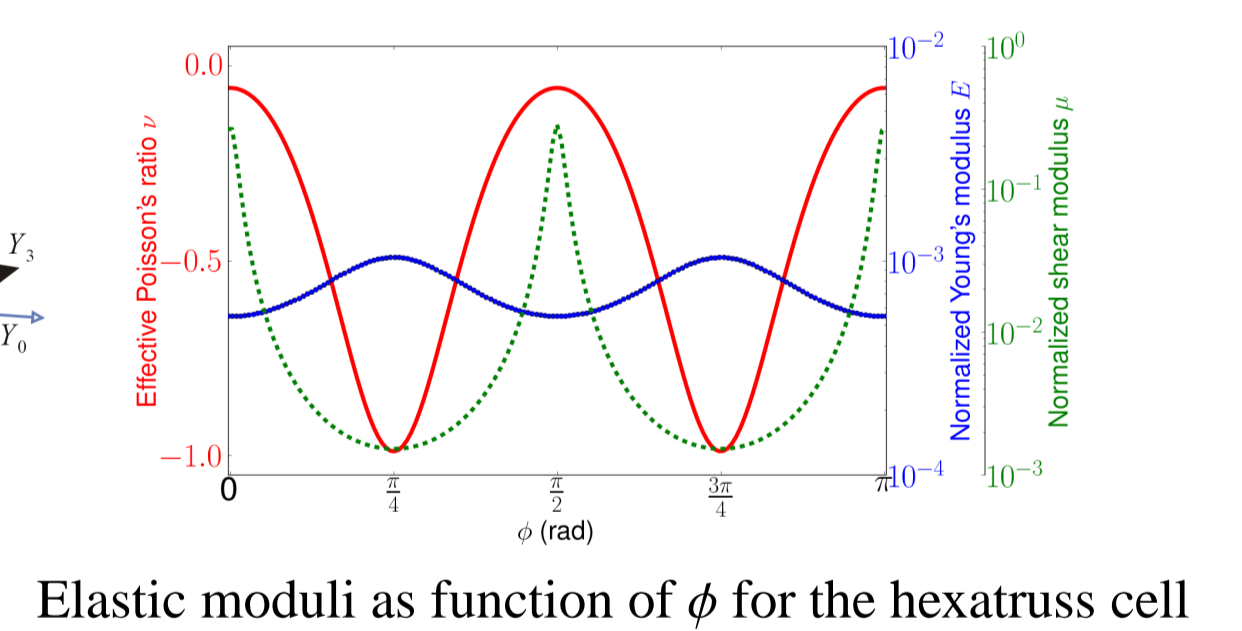
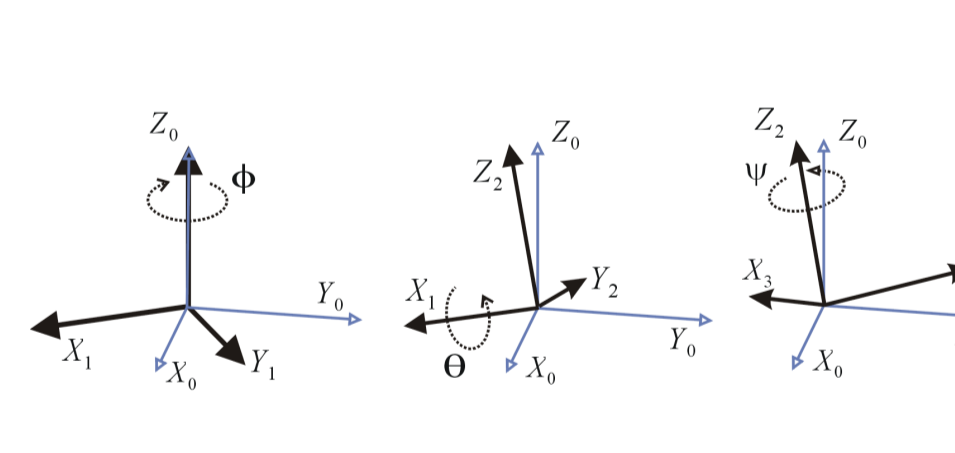
ϵ_p map for an imposed macroscopic strain $E_{11} = 0.1$ of an auxetic microstructure from [Milton, 1991]



Original 3D periodic auxetic cubic cell (hexatruss)



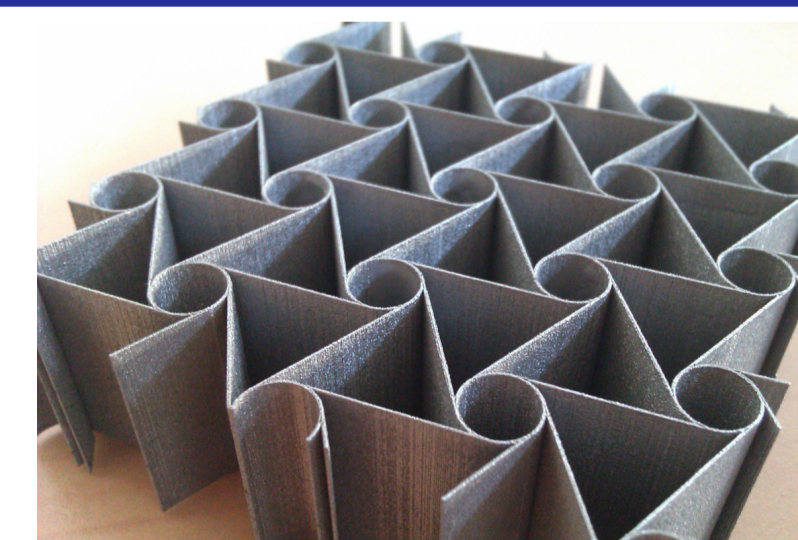
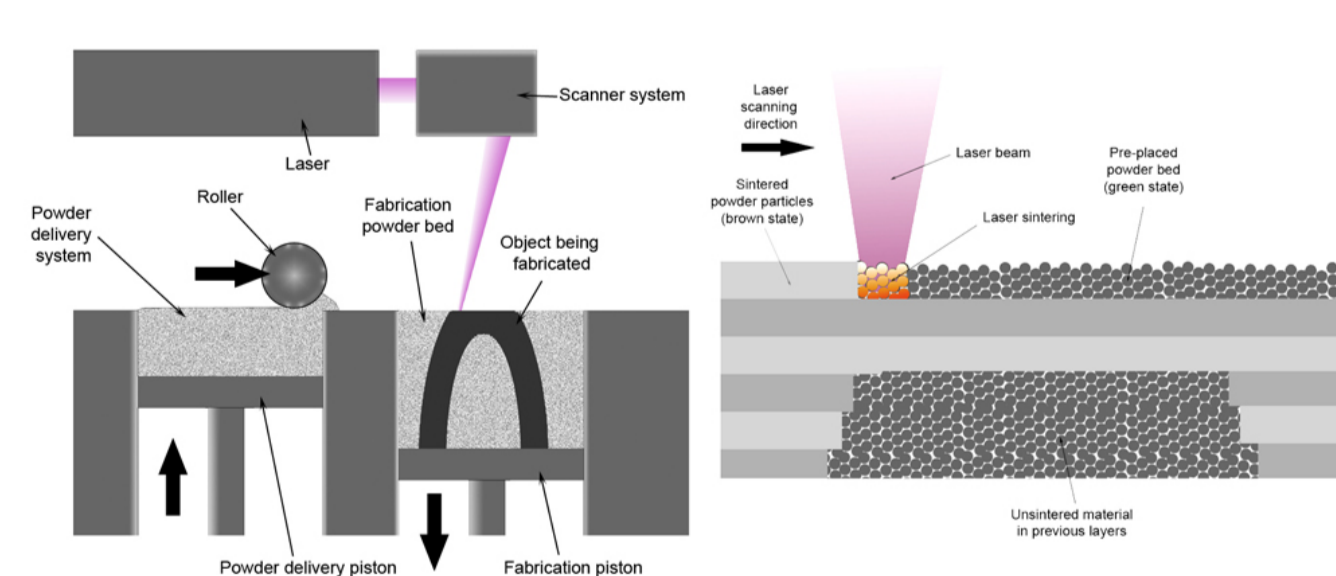
Elastic moduli as function of ϕ for the anti-chiral cell



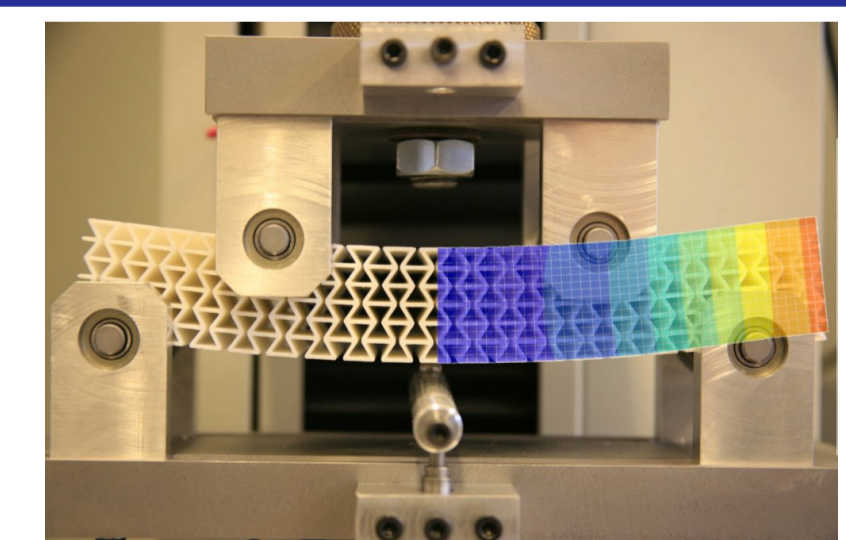
Elastic moduli as function of ϕ for the hexatruss cell

Direct fabrication using selective laser melting and experimental validation

- Direct fabrication from alloy or polymer powders
- Compressive, 3 and 4-points bending tests
- Image correlation measurements
- Comparison between FEM and experiments
- Available process for production of micro-architected materials in the industry (aerospace, automotive, biomedical, etc.)



316L steel hexachiral lattice sample made with SLM



4-points bending test of PA 12 re-entrant honeycombs

Conclusions and prospects

- Modeling and homogenization tools, in association with the set of goals for the MANSART project, resulted in the development of architected materials likely to replace aluminium honeycombs currently serving as core for sandwich composites intensively used in the aerospace industry. The non-linear static and dynamic mechanical behavior of such materials has yet to be characterized using FEM and experiments; indentation and acoustic damping tests will be conducted in order to bring out interesting functional properties for auxetics, due to their high shear modulus. Quasi-isotropic 3D auxetic lattices shall be developed.
- The study of Poisson's fibres highlighted a scaling law for the volume fraction variance proportional to V_V^2 . Efforts are being made to obtain scaling laws concerning elastic moduli, simulations with more fibres are needed. Statistical convergence is slower; for the same precision, Poisson's fibres' RVE is larger than for a classical Boolean variety. Future work on these microstructures will include: static uniform boundary conditions (SUBC) calculations, larger simulation size, mesh rationalization, domain decomposition, thermal homogenization and Fast Fourier Transform computations.

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[Prall and Lakes, 1997] Prall D. and Lakes R. S. (1997). International Journal of Mechanical Sciences, vol. 39 n° 3, pp 305-314.