Microstructures, homogenization analysis and design

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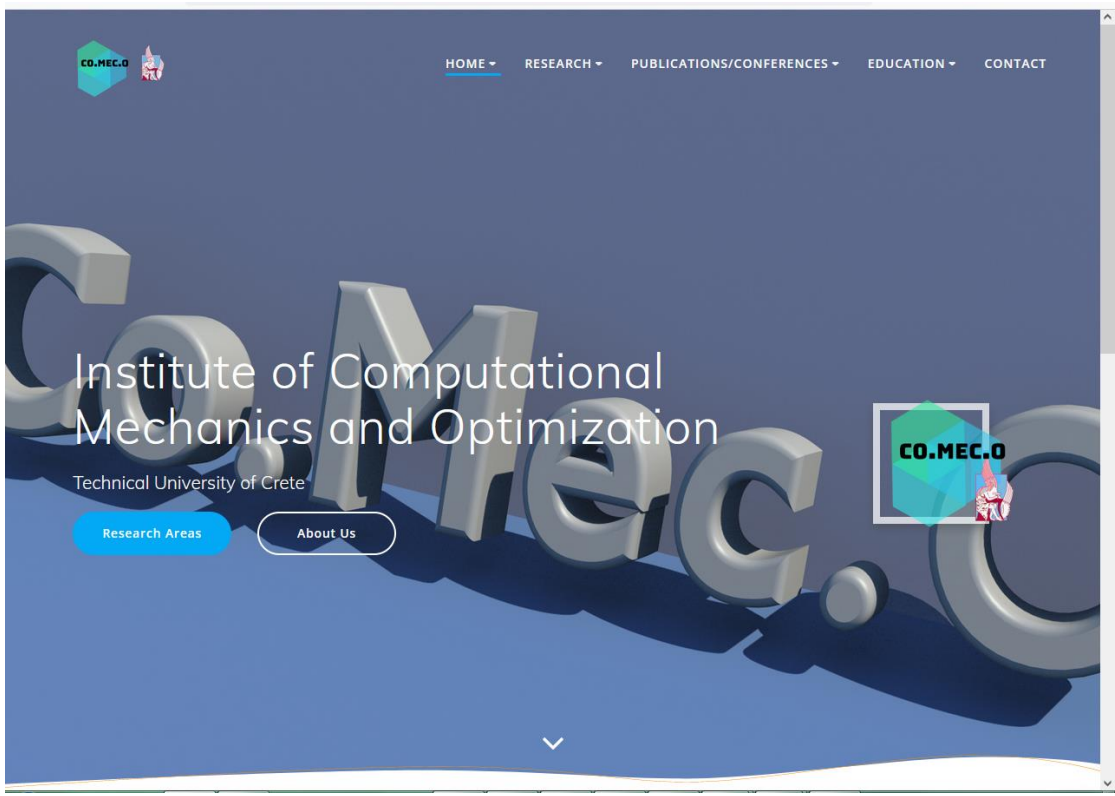

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Microstructures

Lead to homogenized mechanical properties (orthotropic etc)
Can be tailored (graded materials, better than classical composites, suitable for AM)
In dynamics: band gap properties

Lead to mechanical metamaterials

Open questions: defects during construction, a lot of investigation related to 'missing ribs' etc
Technology limitations

Microstructures

In statics: homogenization

In dynamics: band gap properties (homogenization much more difficult, future work)

Homogenization

- Step 1

- Study of a Representative sample in the microscopic scale (RVE)
- Averaging (effective) material properties

- Step 2

- Importing results in the macroscopic scale
- Solution of the equivalent homogeneous structure

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Mathematical framework of homogenization

- Starting with Hill-Mandel energy principle:

$$\boldsymbol{\sigma}^M : \boldsymbol{\epsilon}^M = \frac{1}{V_m} \int_{V_m} \boldsymbol{\sigma}^m : \boldsymbol{\epsilon}^m dV_m$$

- 3 loading states in the RVE boundaries satisfy this principle:
- Linear displacements
- Prescribed tractions
- Periodic boundary conditions

- Linear displacements are chosen:

$$\mathbf{u}|_{\partial V_m} = \boldsymbol{\epsilon}^M \mathbf{x}$$

Mathematical framework of homogenization

- Calculation of the effective quantities:

$$< \boldsymbol{\epsilon} >_{V_m} = \frac{1}{V_m} \int_{V_m} \boldsymbol{\epsilon}^m dV_m, < \boldsymbol{\sigma} >_{V_m} = \frac{1}{V_m} \int_{V_m} \boldsymbol{\sigma}^m dV_m$$

- Further simplification of the procedure

- For a perfectly bonded material:

$$< \boldsymbol{\epsilon} >_{V_m} = \boldsymbol{\epsilon}^M$$

- Formulation for the average stresses:

$$< \boldsymbol{\sigma} >_{V_m} = \frac{1}{V_m} \mathbf{fx} = \boldsymbol{\sigma}^M$$

Mathematical framework of homogenization

- Estimation of the effective elasticity tensor:

$$< \boldsymbol{\sigma} >_{V_m} = \mathbf{E}^* < \boldsymbol{\epsilon} >_{V_m}$$

- Effective elasticity tensor: 9 unknowns

- Thus, 3 loadings of the RVE=>9 equations

Zohdi T.I., Wriggers P. (2008), *An Introduction to Computational Micromechanics*, Springer, The Netherlands.

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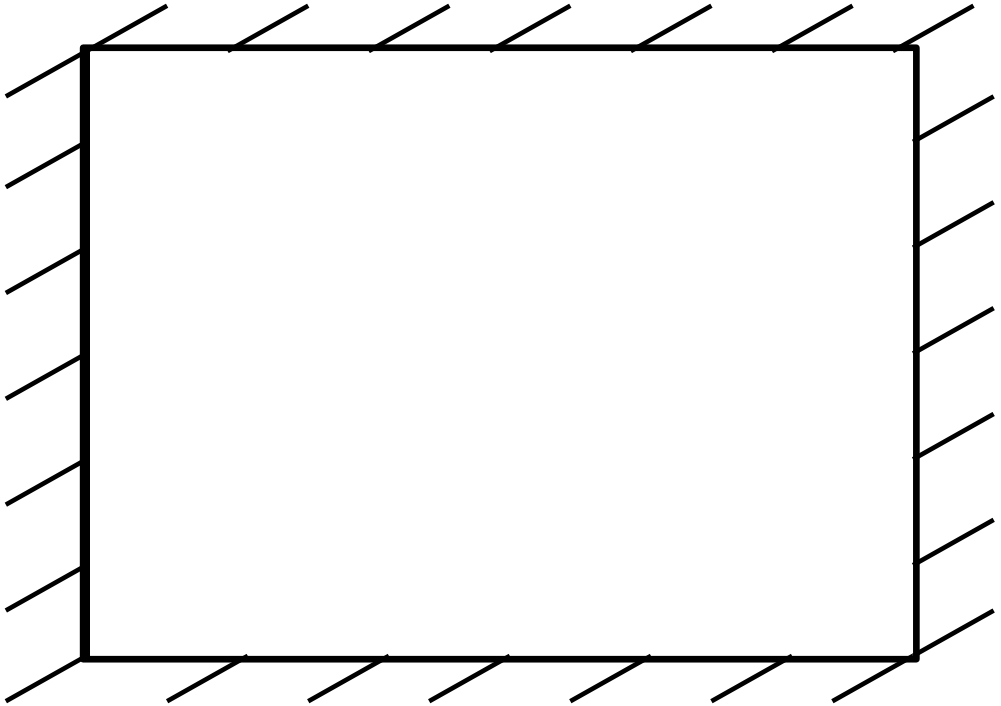
Example 2

Classical homogenization scheme

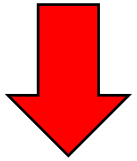


Loading: Linear displacement boundary conditions

Example 2: Results

For material characteristics:

A. Strong material (existing): E=1, ν=0.3
B. Soft material (non-existing): E=0.007, ν=0.007



Effective properties:

E_{xx}	E_{yy}	ν_{xy}	ν_{yx}	G_{xy}
0.066	0.067	-0.2433	-0.2484	0.0117

- Good comparison with topology optimization: Effective Poisson ratio = -0.192

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Simpler analytical homogenization: star-shaped and derivatives

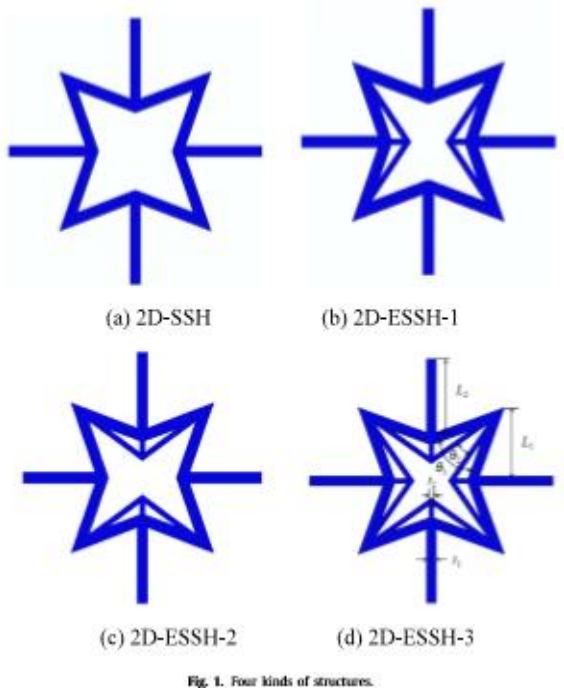

Fig. 1. Four kinds of structures.

Na Xu, Hai-Tao Liu, Ming-Ran An, Liang Wang,
Novel 2D star-shaped honeycombs with enhanced effective Young's modulus and negative Poisson's ratio,
Extreme Mechanics Letters, Volume 43, 2021, 101164, ISSN 2352-4316, https://doi.org/10.1016/j.eml.2020.101164.

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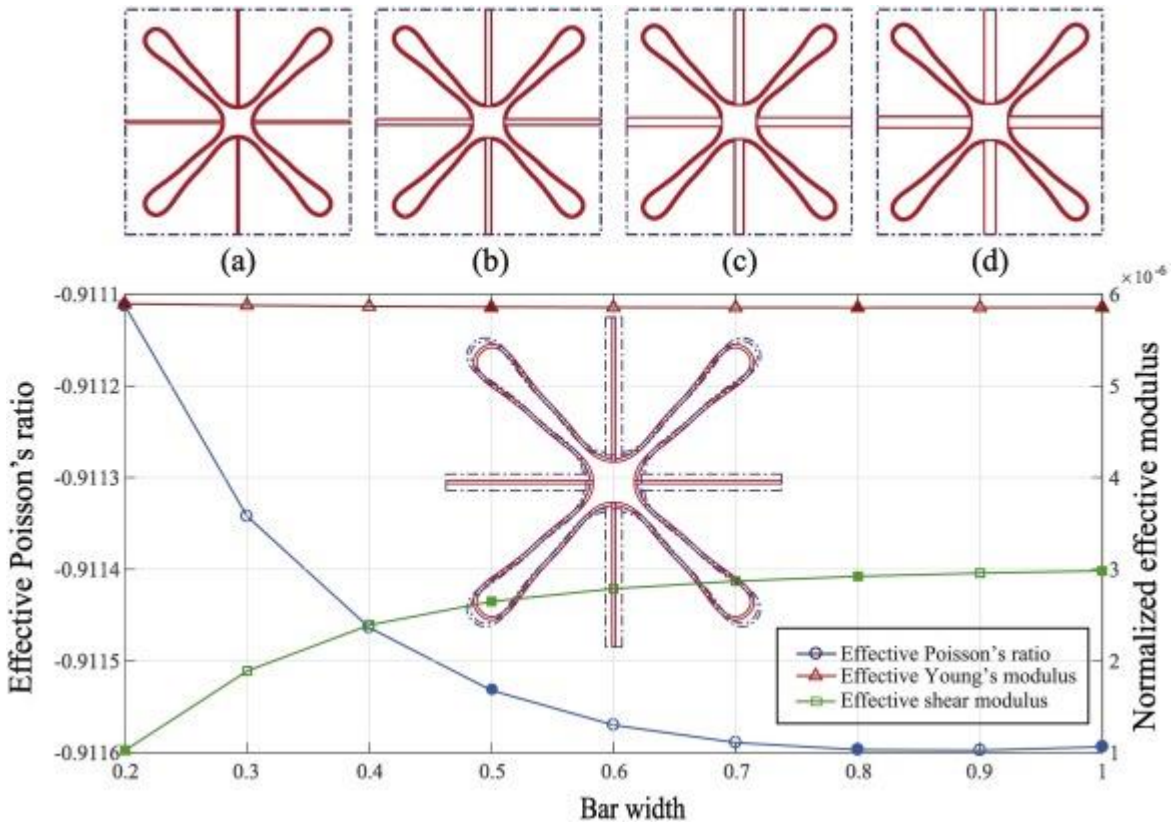
Simpler analytical homogenization: petal auxetics



Deepak Kumar Pokkalla, Zhen-Pei Wang, Leong Hien Poh, Ser Tong Quek, Isogeometric shape optimization of smoothed petal auxetics with prescribed nonlinear deformation, Computer Methods in Applied Mechanics and Engineering, Volume 356, 2019, Pages 16-43, ISSN 0045-7825, https://doi.org/10.1016/j.cma.2019.07.014.

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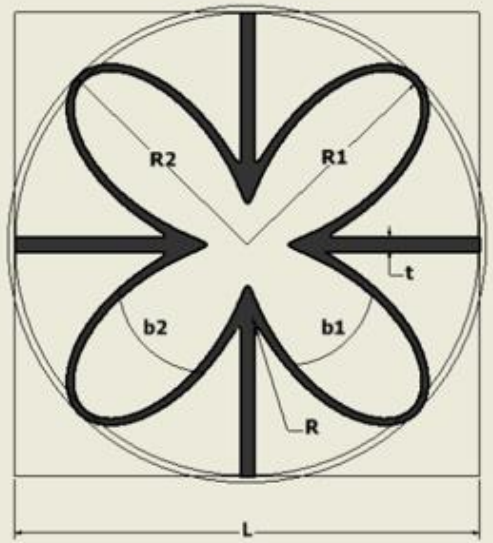
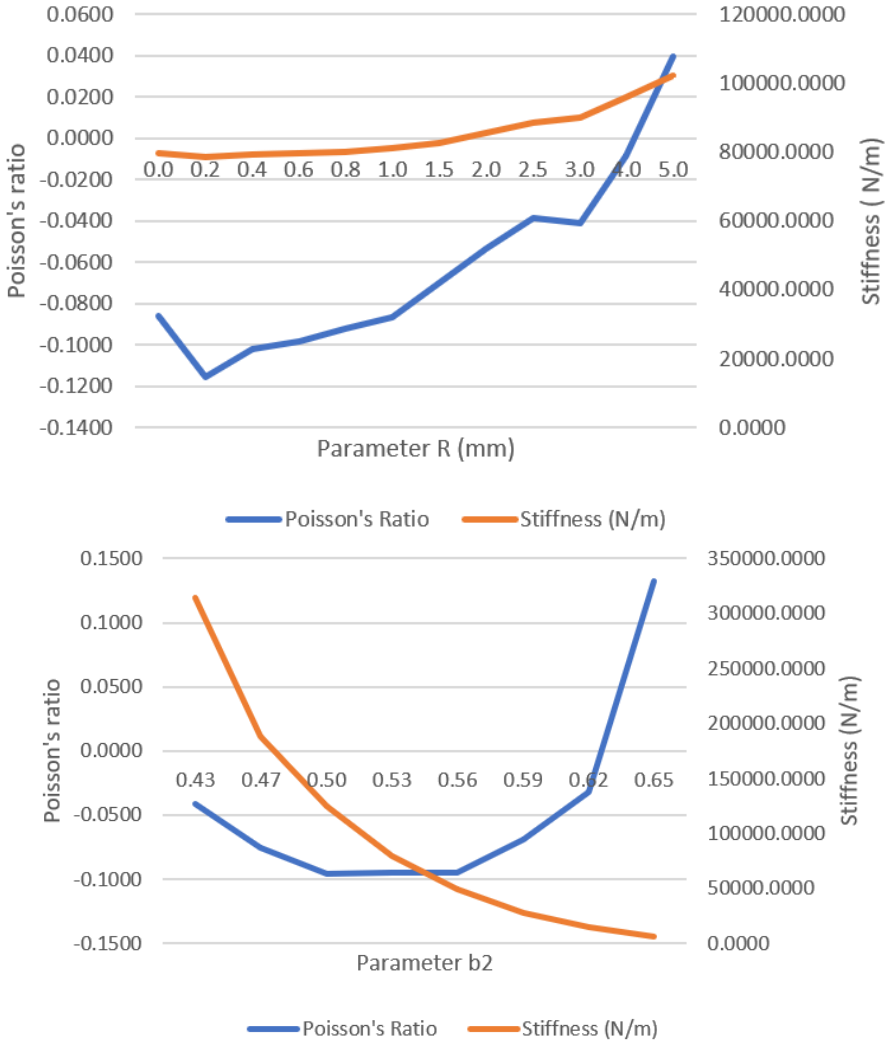
Cookie-shaped auxetics





Koustoumpardis, C.-G. and Stavroulakis, G. (2023) "Mechanical properties of cookie-shaped auxetics using finite elements and soft robotics appllication", *Technische Mechanik - European Journal of Engineering Mechanics*, 43(2), pp. 230–237. doi: 10.24352/UB.OVGU-2023-059.

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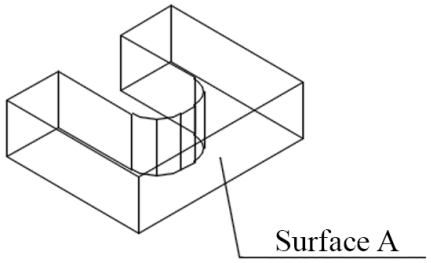
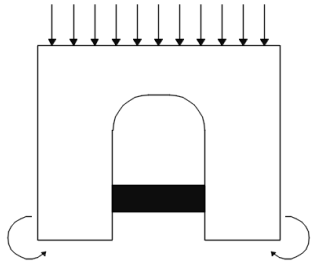
Cookie-shaped auxetics

a)



b)



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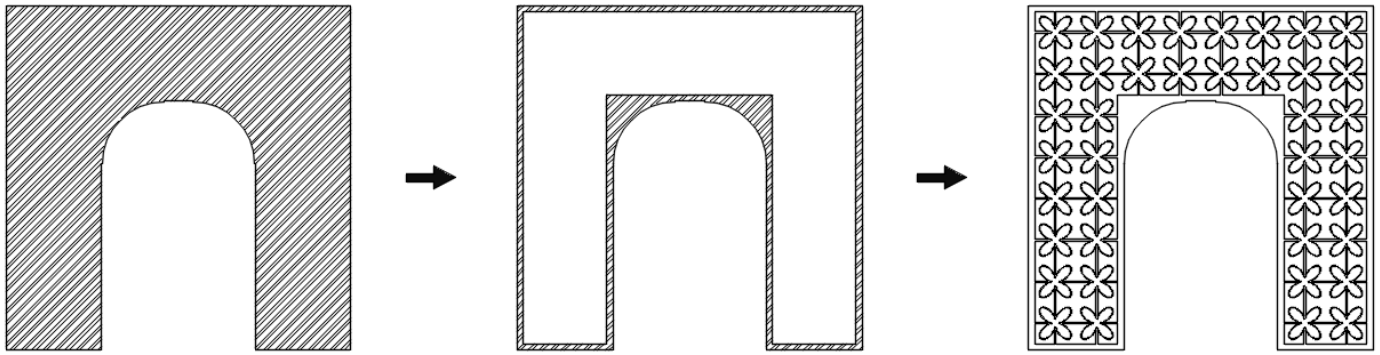

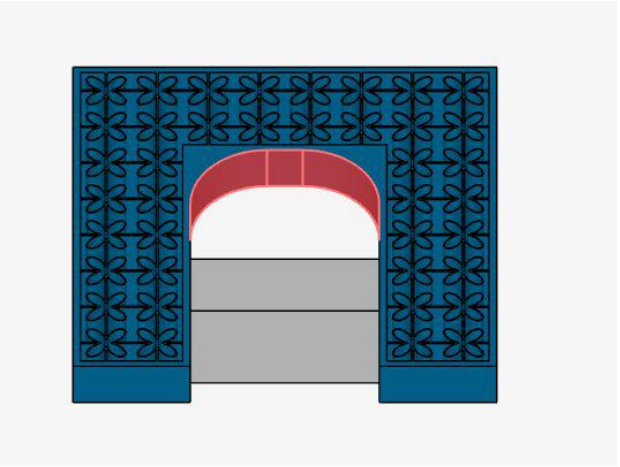

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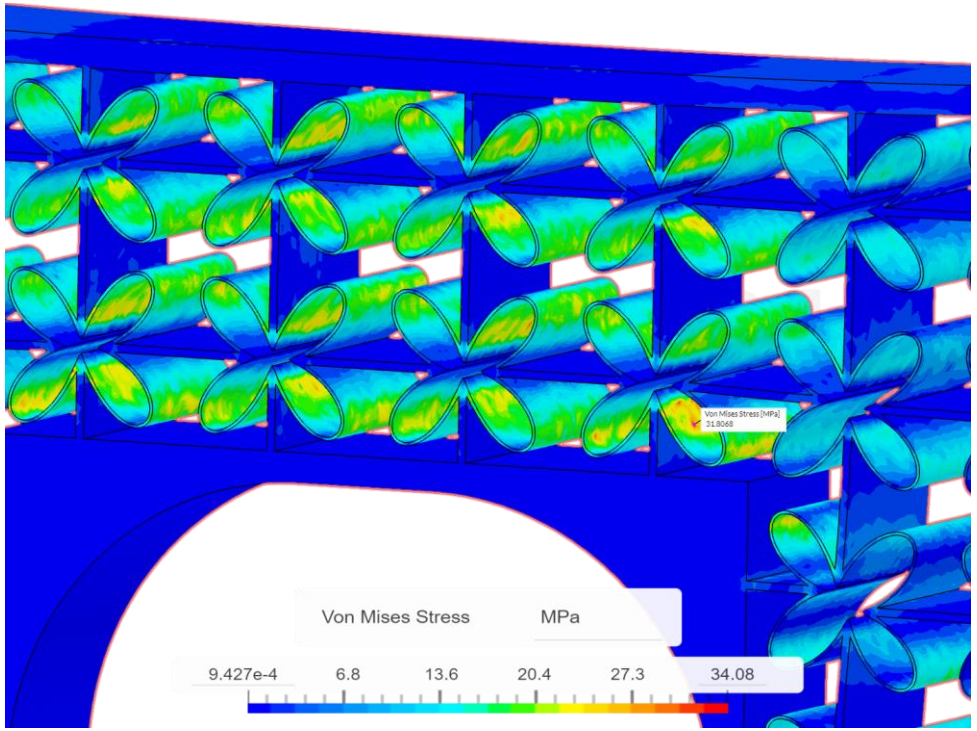

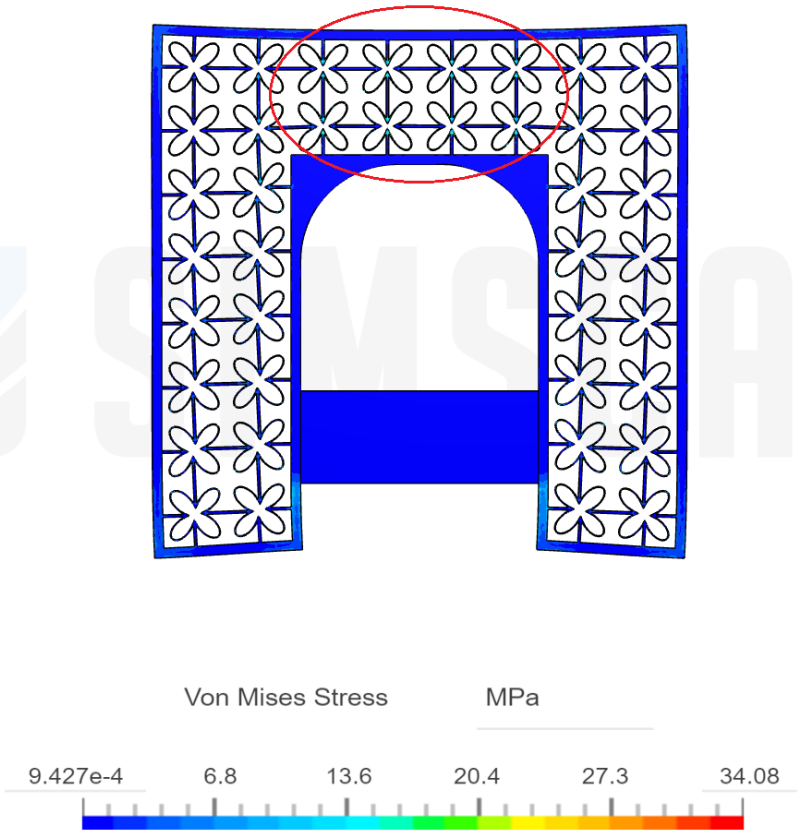

Koustoumpardis, C.-G. and Stavroulakis, G. (2023) "Mechanical properties of cookie-shaped auxetics using finite elements and soft robotics appllication", *Technische Mechanik - European Journal of Engineering Mechanics*, 43(2), pp. 230–237. doi: 10.24352/UB.OVGU-2023-059.

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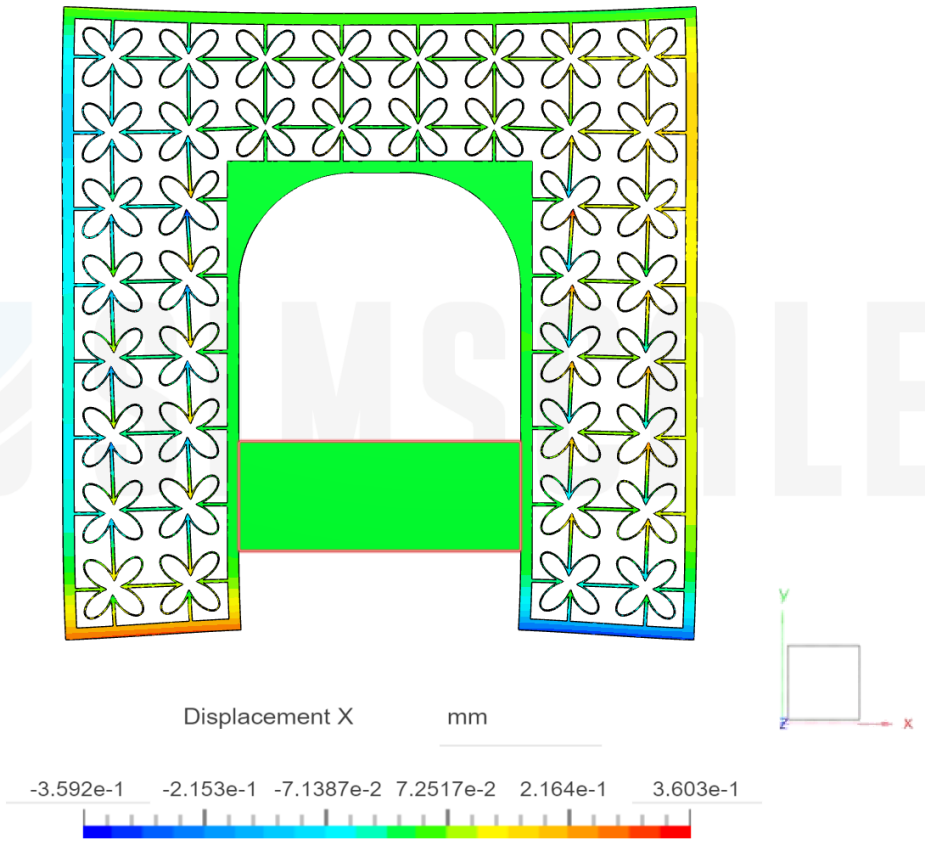
Cookie-shaped auxetics



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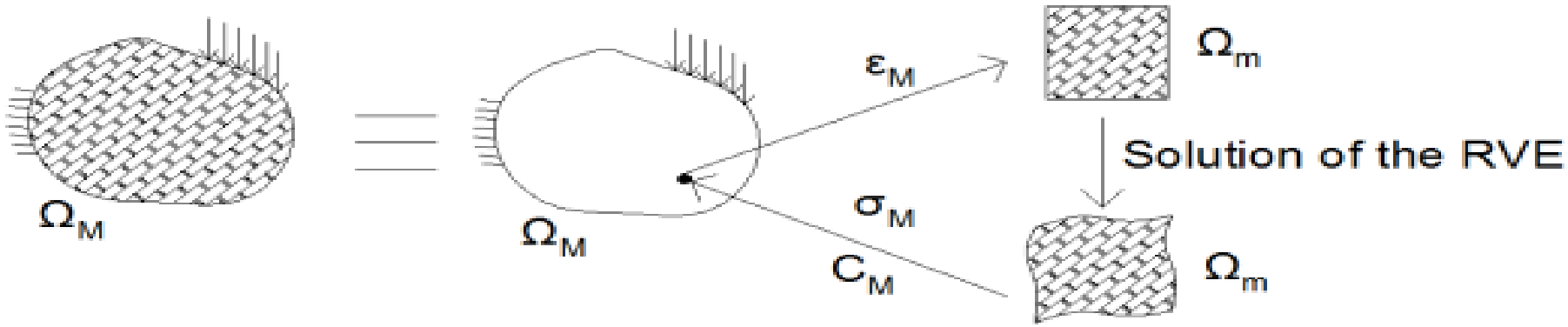
Data-driven homogenization + usage



Classical fe^2 multi-scale homogenization

Each RVE represents the non-linear behaviour of the heterogeneous structure

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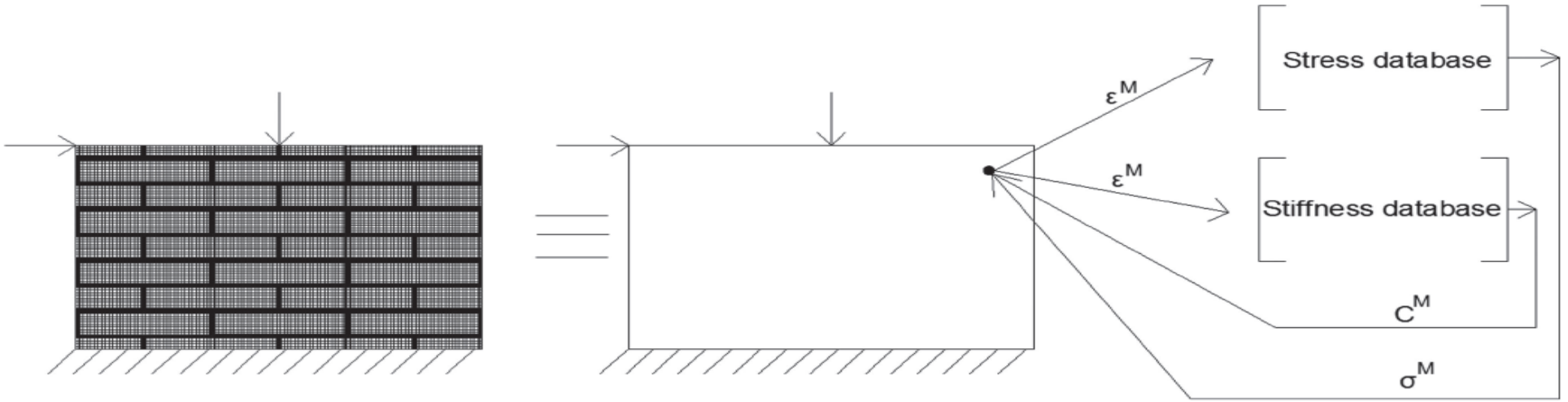
Data-driven schemes

- A. Database interpolation providing the constitutive stress-strain response
- B. Usage of machine learning tools Most often: Artificial Neural Networks (ANN) Training, using data sets



G. Drosopoulos, K. Giannis, M. Stavroulaki, G. Stavroulakis, Metamodeling-Assisted Numerical Homogenization for Masonry and Cracked Structures, CE, J. Eng. Mech, 2018

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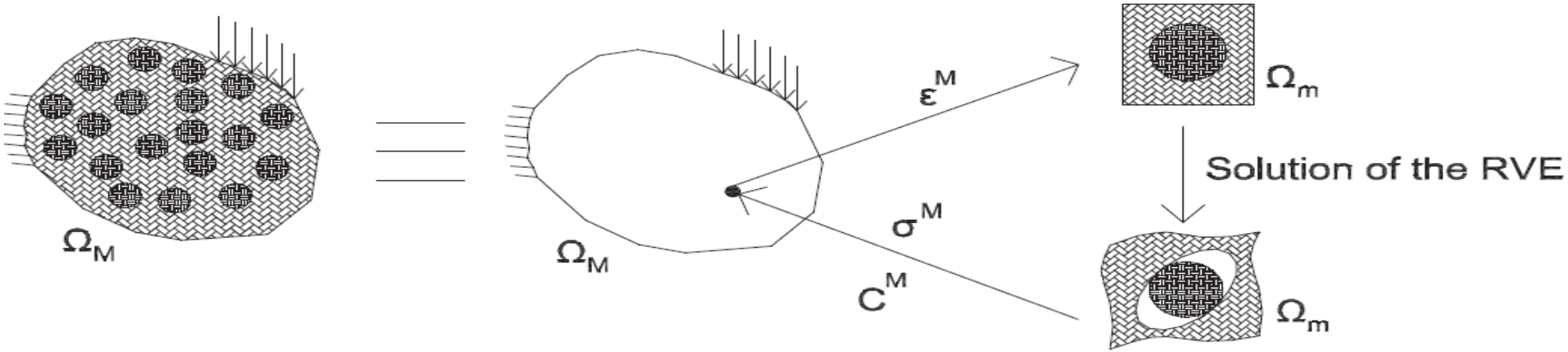
Computational homogenization

- Conventional FE^2
- Solve a Representative Volume Element (RVE)
- For every Gauss point of the macro structure
- Within increments-iterations of Newton-Raphson



G. Drosopoulos, P. Wriggers, G. Stavroulakis, A multi-scale computational method including contact for the analysis of damage in composite materials, Comput. Mater. Sci., 2014

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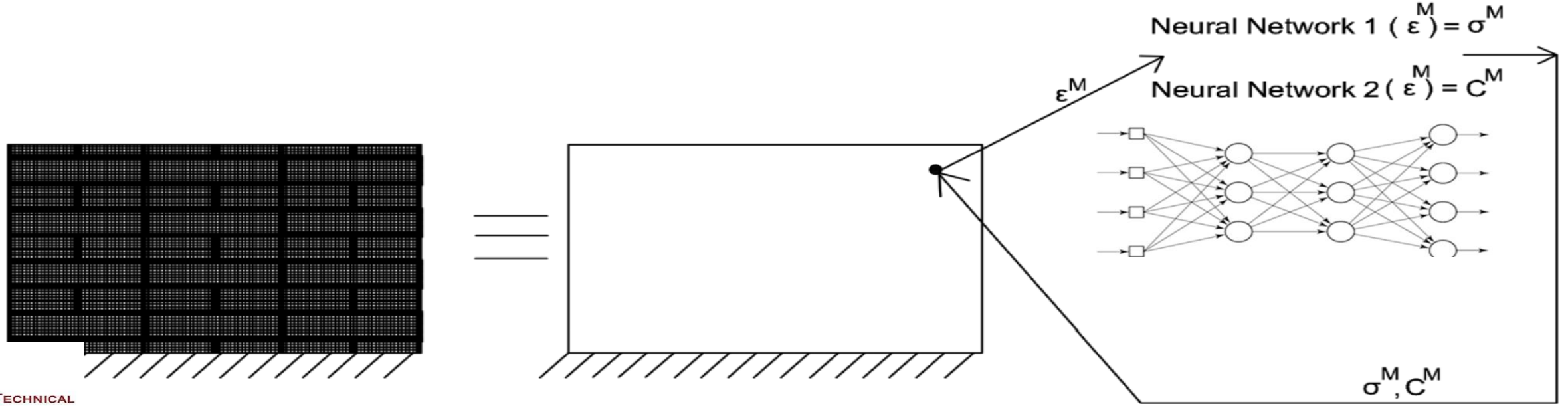
Data-driven computational homogenization

- Substitutes microscopic simulations by a trained ANN
- Providing the effective stress-strain response
- Training takes place “offline” -> increased efficiency



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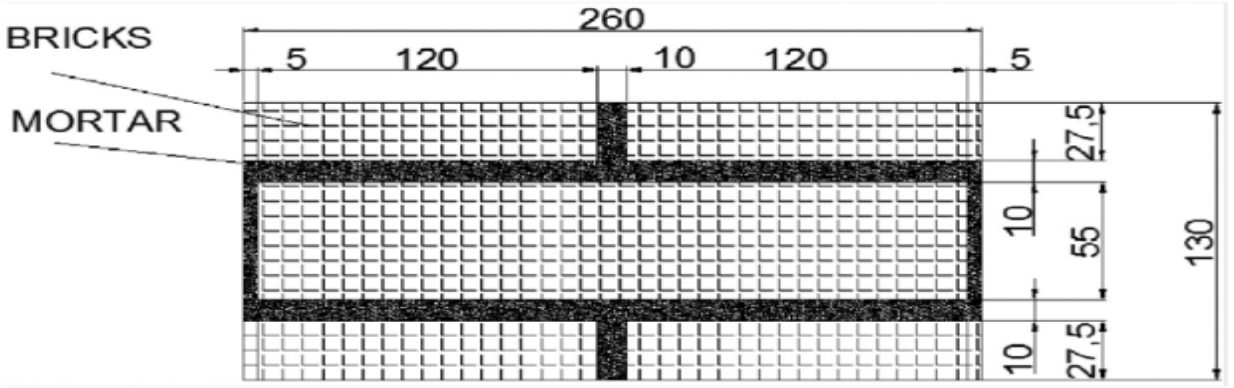
Applications to masonry structures

- Drucker-Prager material law is used for the mortar joints
- To depict damage of the RVE



	Young's modulus (GPa)	Poisson's ratio	Tensile strength (MPa)	Compressive strength (MPa)
Bricks	4,865	0,09	-	-
Mortar joints	1,180	0,06	0,9	3,2

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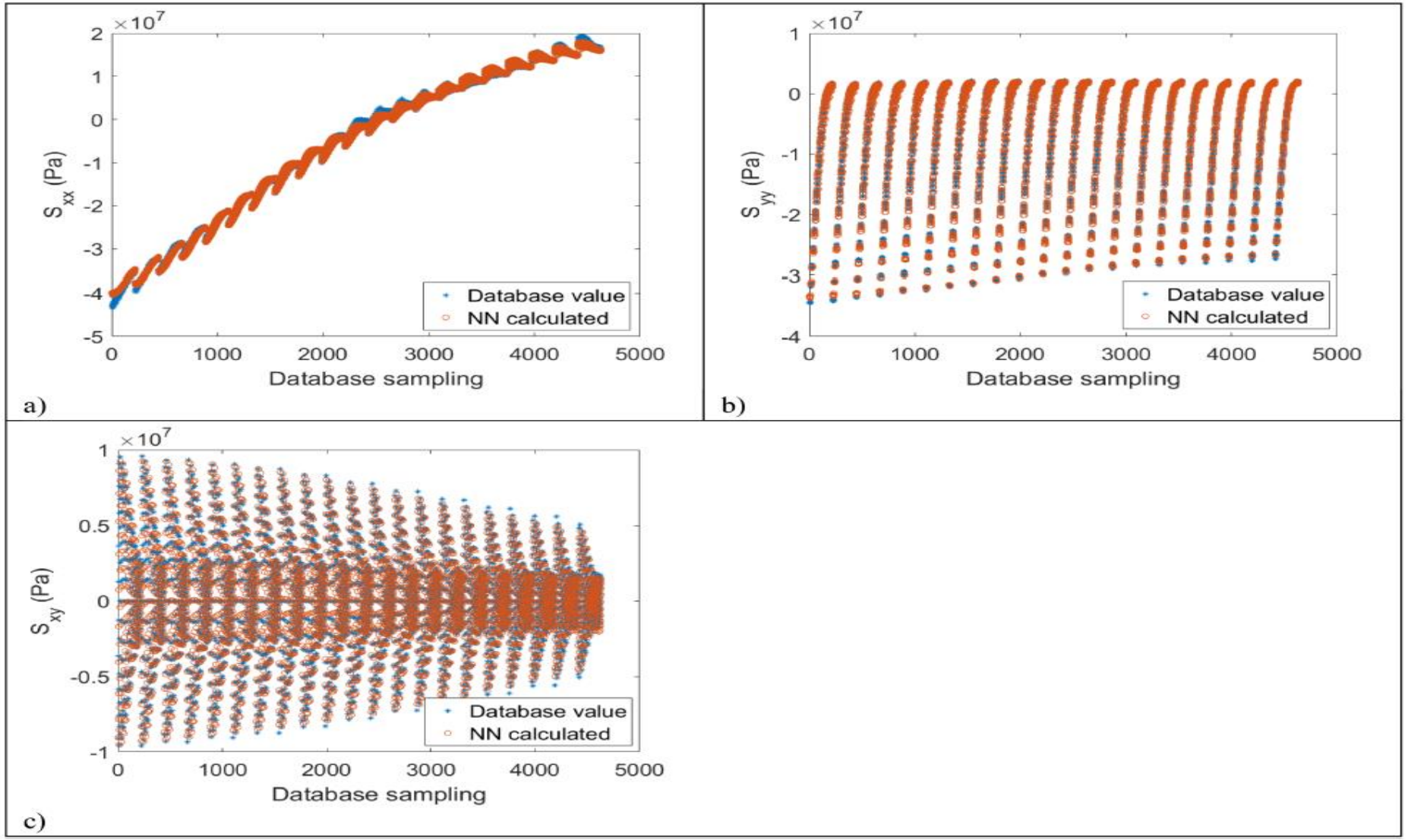
Verification of stress-strain training



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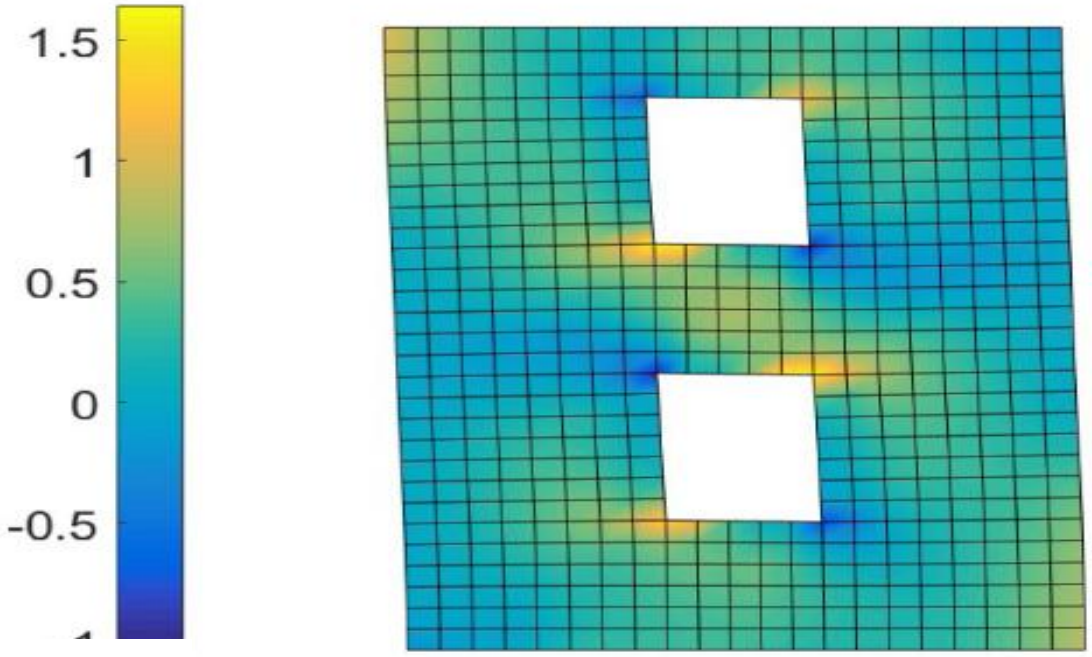
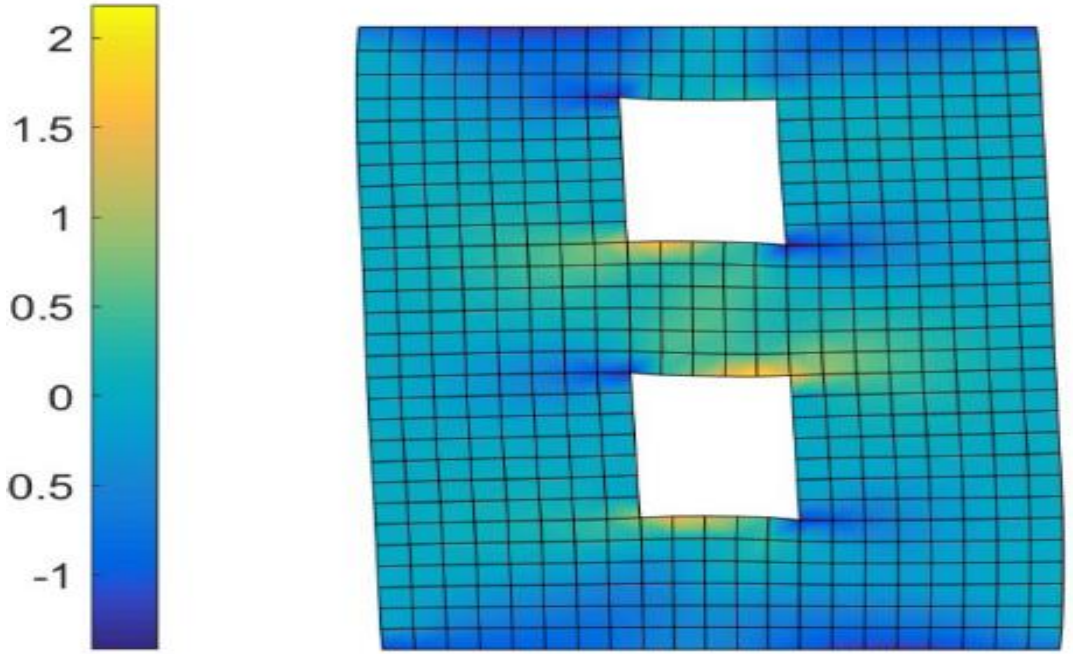
Masonry wall with openings

- Max principal stresses

Interpolation FE^2



Proposed ANN- FE^2



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Microstructures

In statics: homogenization

In dynamics: band gap properties (homogenization much more difficult, future work)

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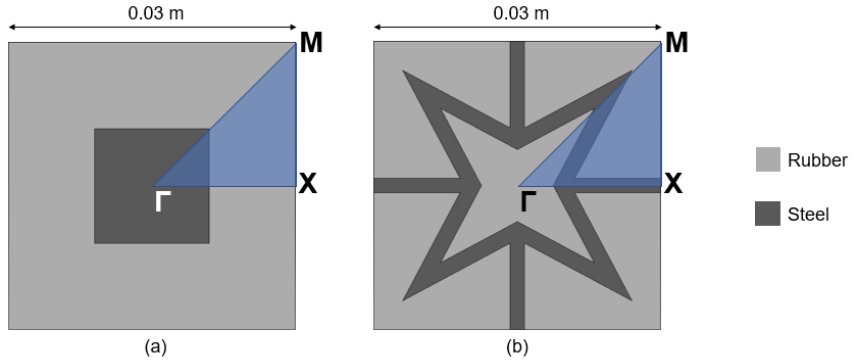
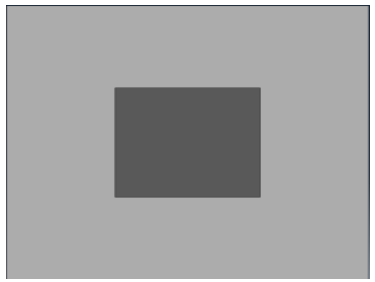
Resonant Unit Cell



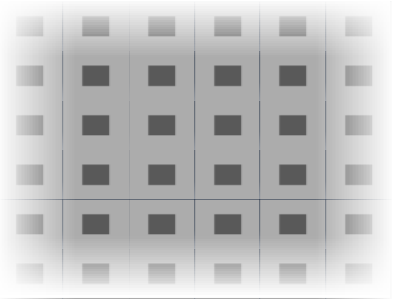
Unit Cell

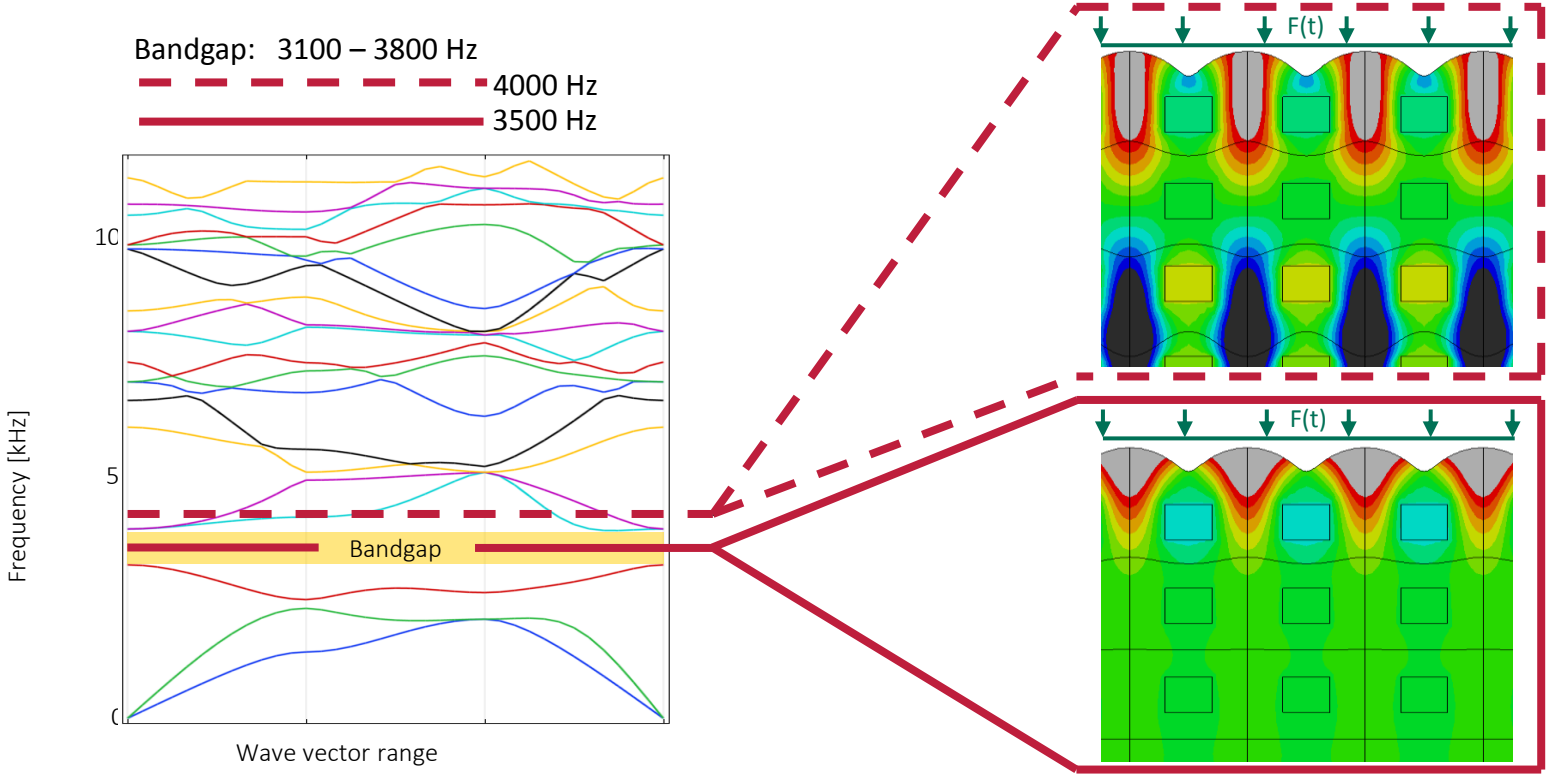


Rubber

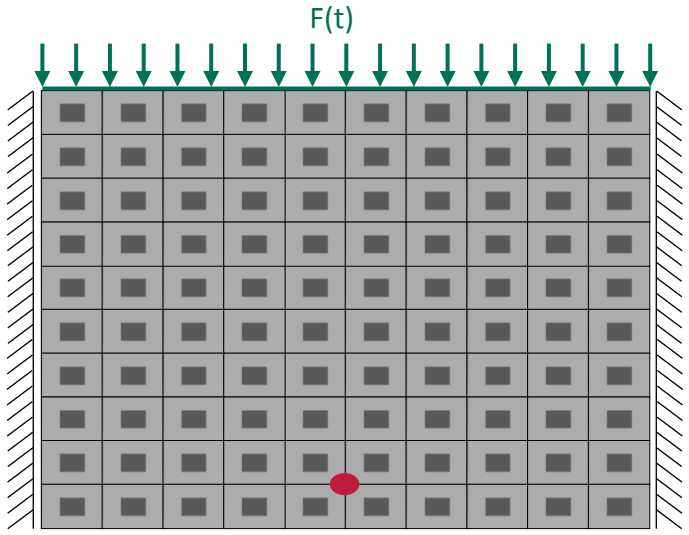
Steel

Periodic Lattice

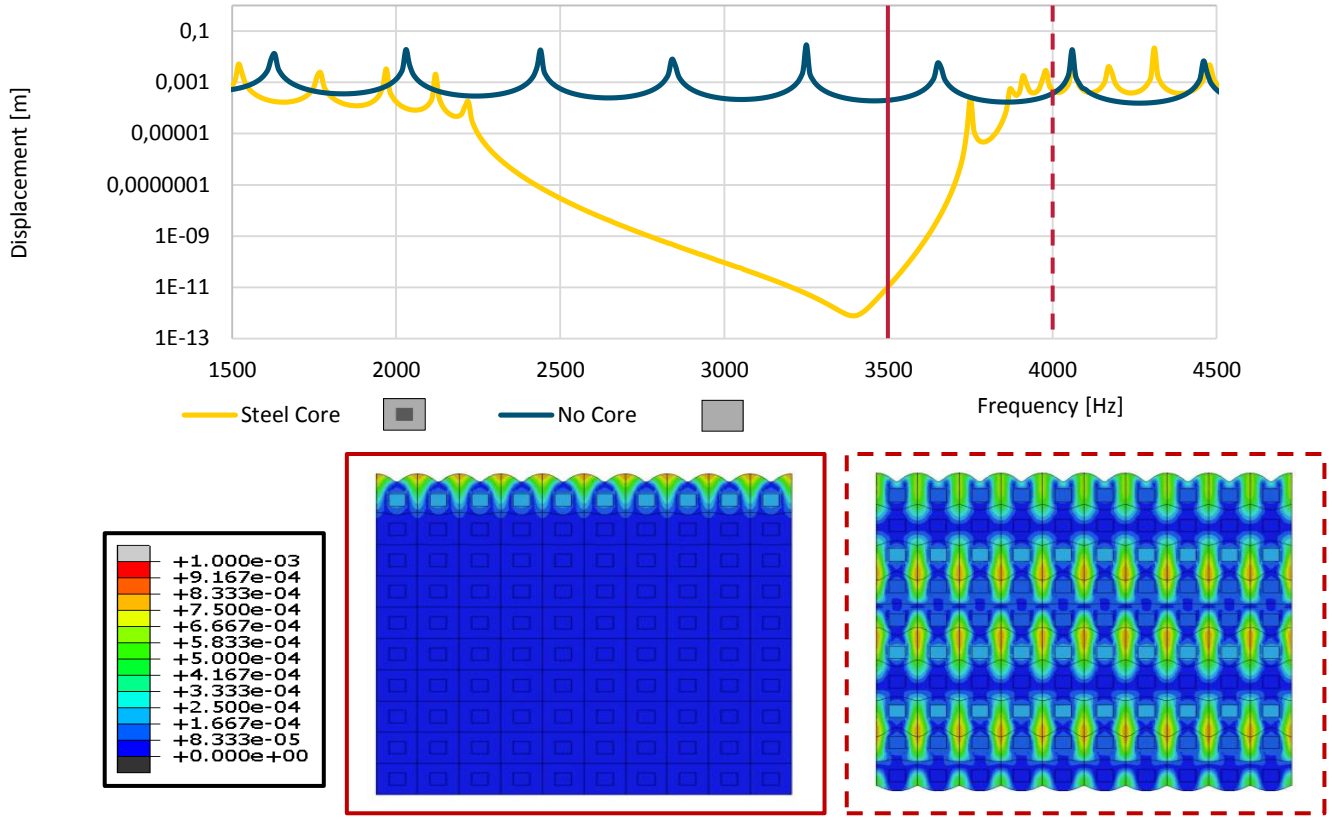




Resonant Lattice: Composite with band gaps



- 10 by 10 resonant unit cells
- Harmonic pressure load on top surface
- Oscillations measured at the bottom ( )



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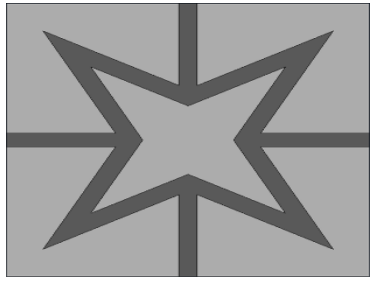
Auxetic Unit Cell: metamaterial with band gaps

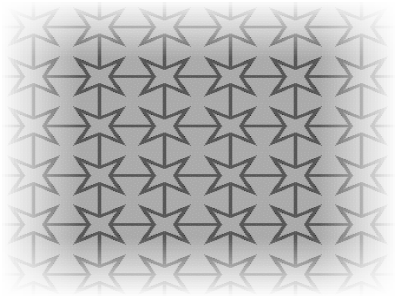
Unit Cell

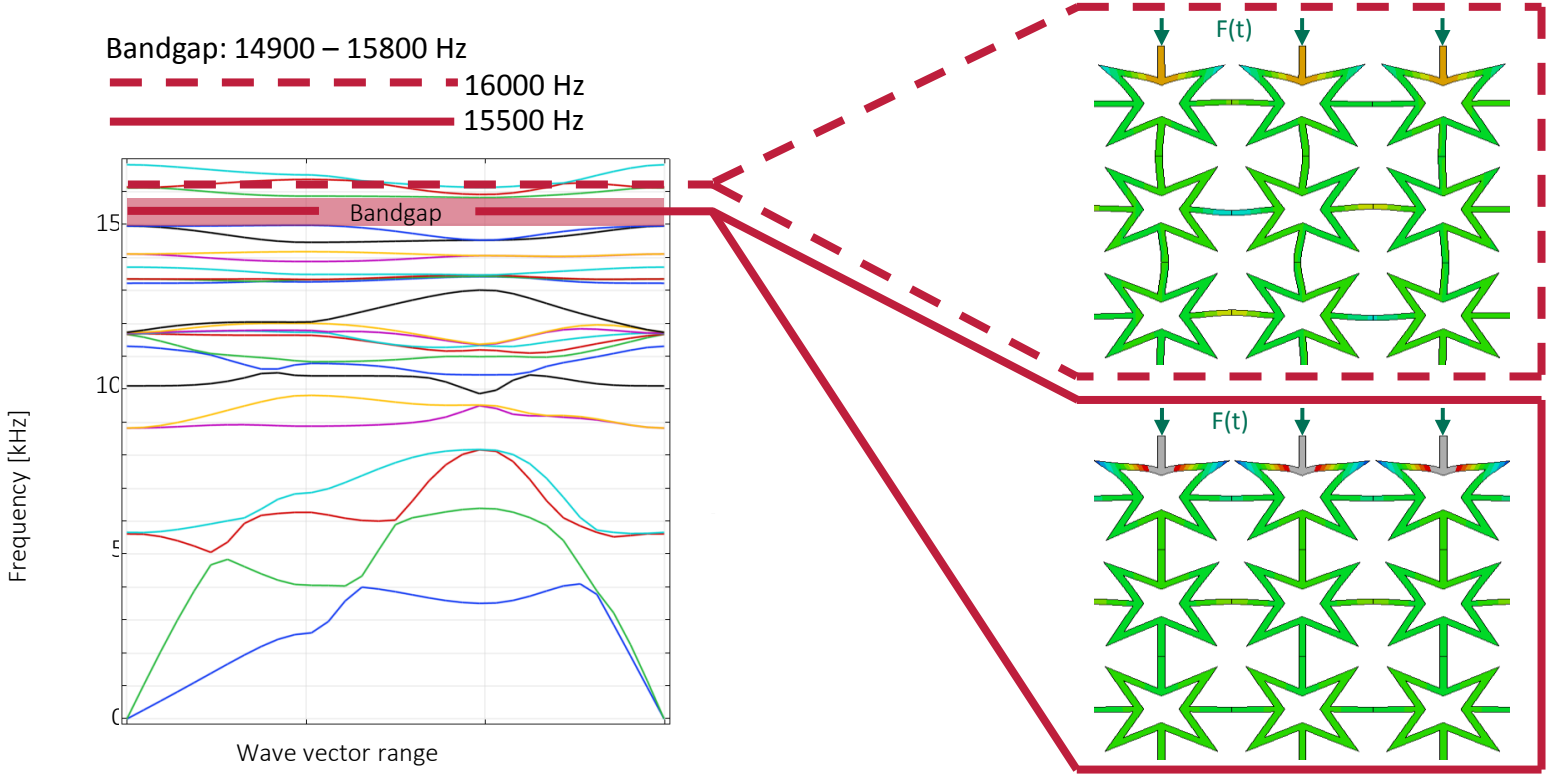


Rubber

Steel

Periodic Lattice





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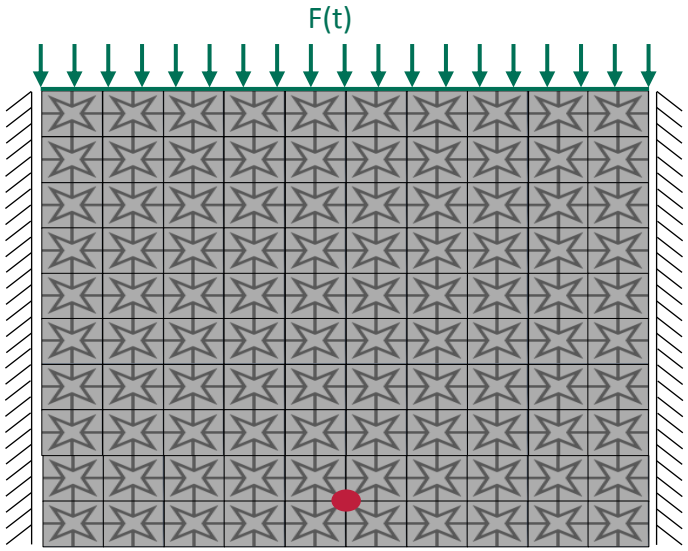
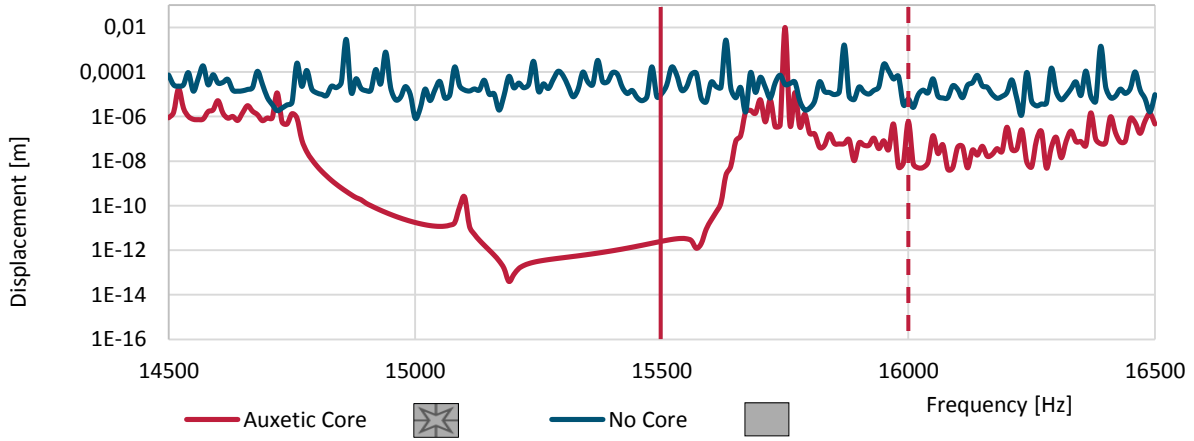
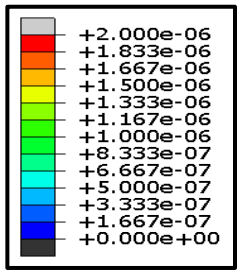
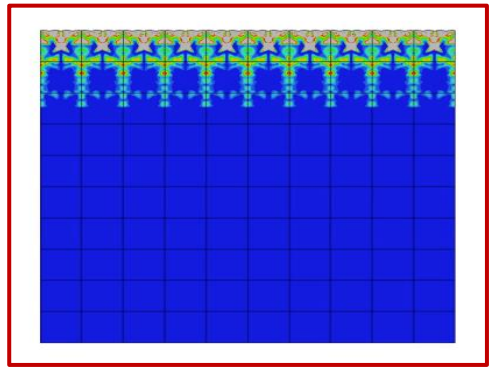
Auxetic Lattice and band-gap formation

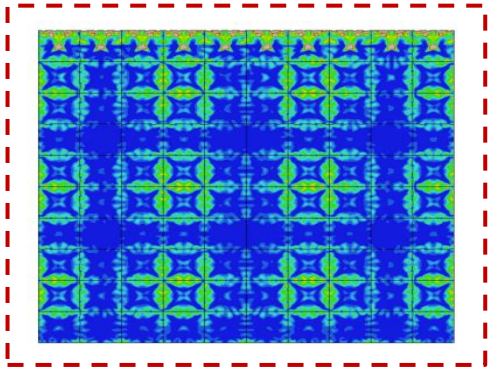




- 10 by 10 auxetic unit cells
- Harmonic pressure load on top core surface
- Oscillations measured at the bottom ( )







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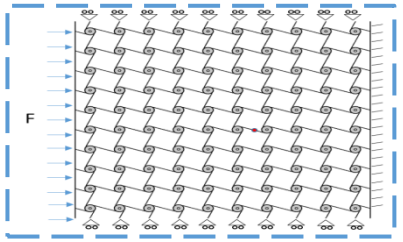
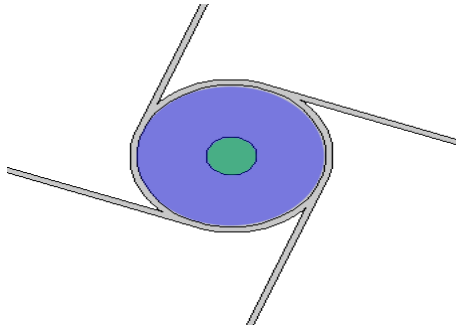
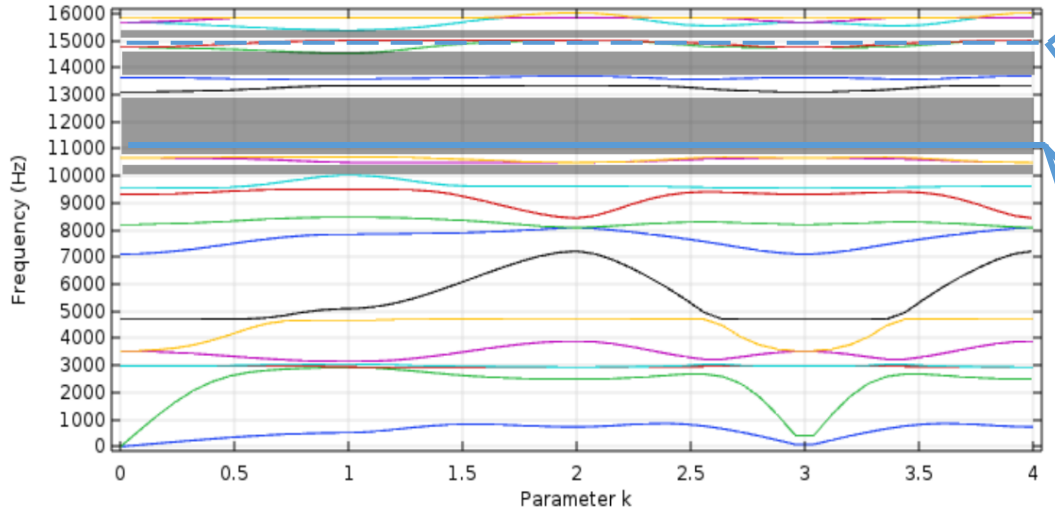
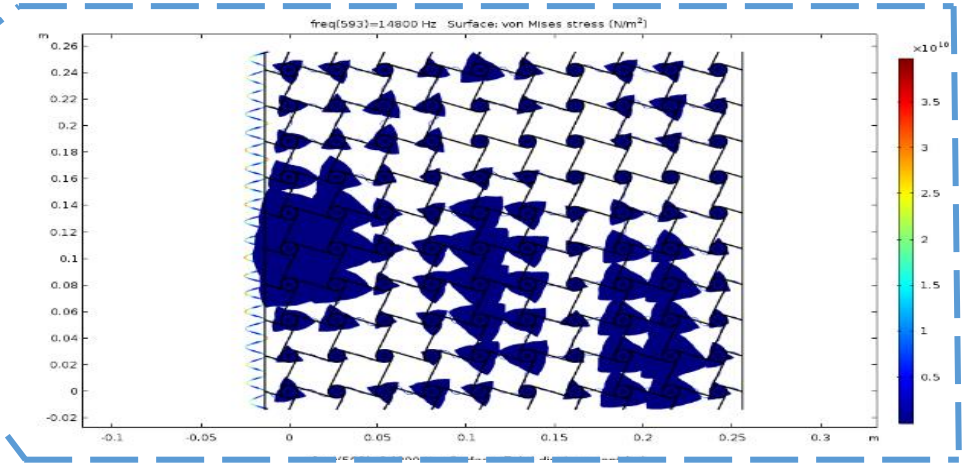
P.I. Koutsianitis, G.K. Tairidis, G.A. Drosopoulos, G.E. Stavroulakis. Conventional and star-shaped auxetic materials for the creation of band gaps. Archive of Applied 89 (12), 2545-2562, 2019.

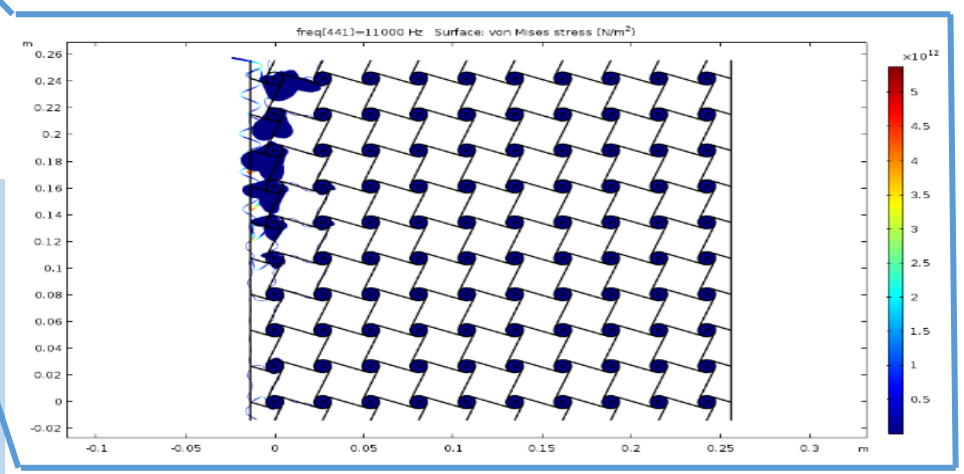
Chiral microstructures
With band gaps











Chinis, D.; Stavroulakis, G.E. Band Gap Analysis for Materials with Cookie-Shaped Auxetic Microstructures, Using Finite Elements. *Appl. Sci.* **2023**, *13*, 2774. https://doi.org/10.3390/app13052774

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Bloch theory

The whole lattice can be obtained from the correlation of the unit cell

The displacement $q(r_j)$ of the lattice points of the unit cell for the case of plane waves

$$q(r_j) = q_j e^{(i\omega t - k r_j)}$$

where
q_j is the amplitude
ω is frequency
k is the wave vector

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Bloch theory

According to the Bloch's theorem, the displacement at the j[th] point in any cell can be identified

$$q = q(r_j)e^{k(r-r_j)} = q(r_j)e^{(k_1 n_1 + k_2 n_2)}$$

where:

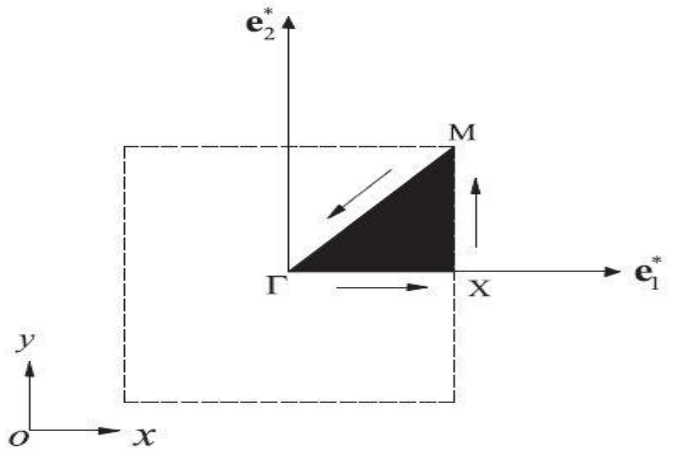
$$k_1 = k\ e_1 = \delta_1 + i\varepsilon_1$$
$$k_2 = k\ e_2 = \ \delta_2 + i\varepsilon_2$$

k_1 and k_2 denote the components of wave vector k which dissipates along the vectors e_1 and e_2

δ denotes the attenuation constant

Bloch theory

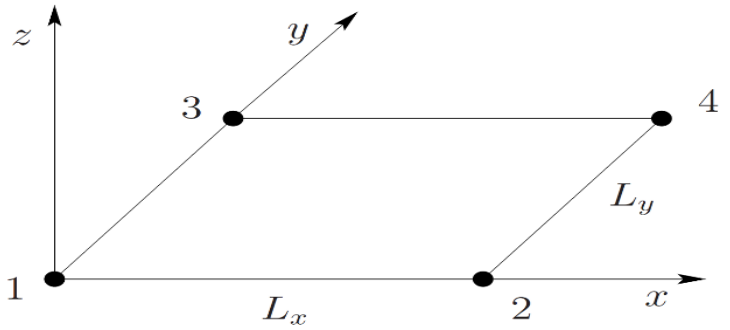
The possible extraction of band gaps is based on the assumption of wave vectors which are following the first Brillouin zone and the irreducible Brillouin zone (Γ-X-M)



In general, periodic structures are systems with identical segments, coupled to their neighboring. More specifically, uniform 2-D structures can be considered as a special case of periodic structures which are homogeneous in x and y

Bloch theory

Finite element model of a rectangular segment with a 4–noded rectangular element



$$q = [q_1^T \; q_2^T \; q_3^T \; q_4^T]$$

where

q_j are the nodal degrees of freedom of the nodes of the jth corn

The equation of motion of the element of reference is given as

$$(-\omega^2 M + i\omega C + K)q = f$$

where

M, C and K are the mass, damping and stiffness matrices respectively, ω is the natural frequency, f is the loading vector and i the imaginary number

Bloch theory

The propagation of the wave can then be obtained from the so-called propagation constants

$$\mu_\chi = \kappa_x L_x \qquad \mu_y = \kappa_y L_y$$

which in turn, provide the relation among the periodic displacements q on the sides of the periodic element as:

$$q_2 = \lambda_x q_1 \qquad q_3 = \lambda_y q_1 \qquad q_4 = \lambda_x \lambda_y q_1$$

where: $\lambda_x = e^{-i\mu_x}$ $\lambda_y = e^{-i\mu_y}$

As a result, the nodal degrees of freedom can be rewritten as:

$$q = \Lambda_R q_1$$

where

$$\Lambda_R = \left[I \ \lambda_x I \ \lambda_y I \ \ \lambda_x \lambda_y I\right]$$

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Bloch theory

In the free response case, a possible equilibrium at node 1 gives that nodal forces of every element which is connected to node 1 is zero. Thus, we have:

$$\Lambda_L f = 0$$

where:

$$\Lambda_L = \left[I \ \lambda_x^{-1} I \ \ \lambda_y^{-1} I \ \ \left(\lambda_x \lambda_y\right)^{-1} I \right]$$

The modal equations can be reformed as:

$$\left(-\omega^2 \bar{M}\left(\mu_x, \mu_y\right) + i\omega \bar{C}\left(\mu_x, \mu_y\right) + \bar{K}\left(\mu_x, \mu_y\right)\right) q = f$$

where $\bar{M} = \Lambda_L M \Lambda_R$, $\bar{K} = \Lambda_L K \Lambda_R$ and $\bar{C} = \Lambda_L C \Lambda_R$ are the reduced matrices.

The eigenvalue problem can be written as:

$$\bar{D}\left(\omega, \lambda_x, \lambda_y\right) = 0$$

where $\bar{D}$ is the reduced dynamic stiffness matrix.

Optimization problem

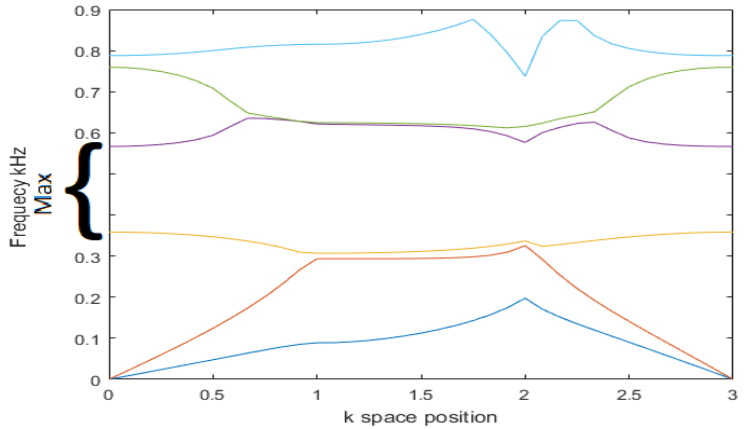
Objective Function

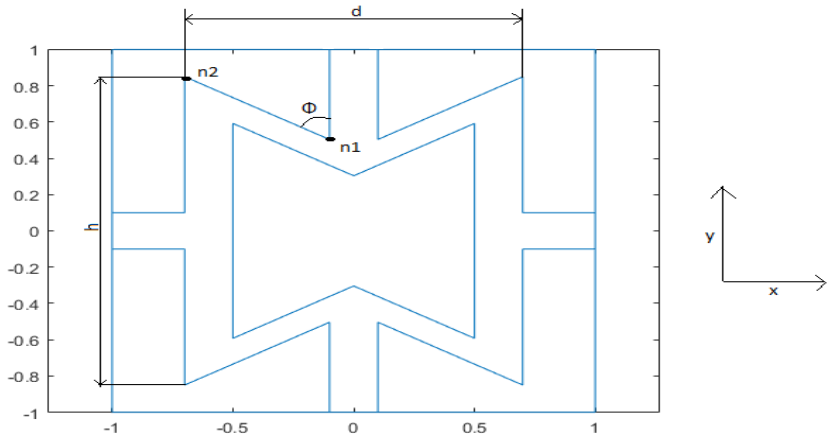
Maximize the Band Gap Area

Constraints

Symmetry design constraints
e.g. at y axis: n2<1
at x axis: n1<0, etc.

Design Variables:
Heigth: h ϵ [0.2, 1.9]
Width: d ϵ [0.2, 1.9]
Angle: Φ ϵ [50º, 120º]





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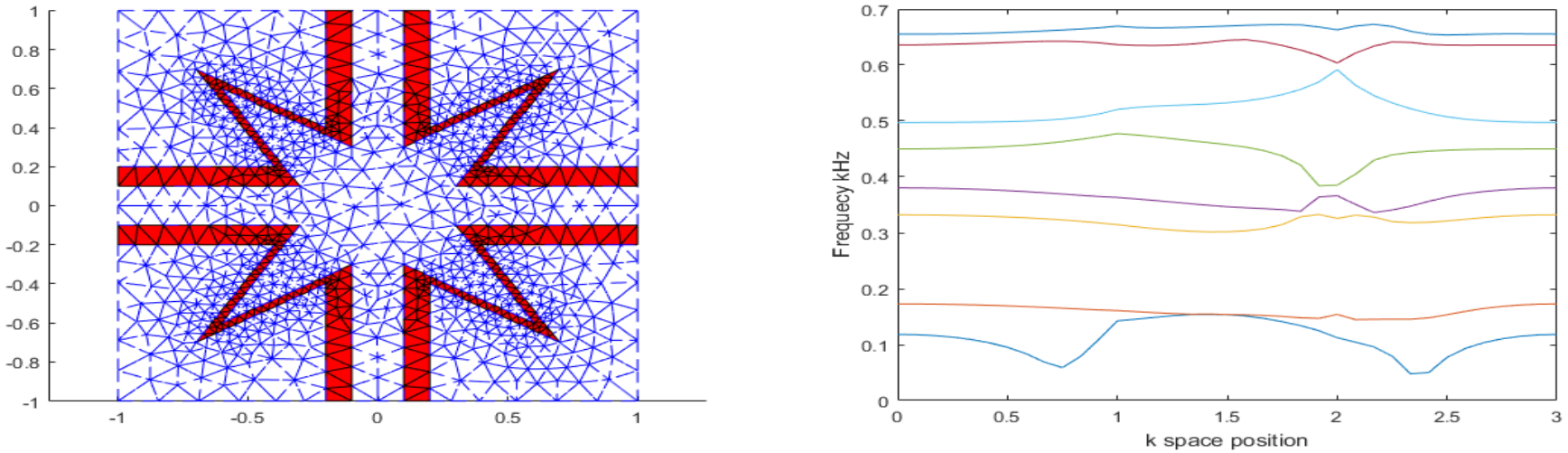
Numerical results

Star-shaped unit cell

Star shape unit cell with 0.1m thickness



Square unit cell with auxetic core with thickness=0.1m and its dispersion curve

The band gaps appear in a lot of regions, like between second and third eigenvalues

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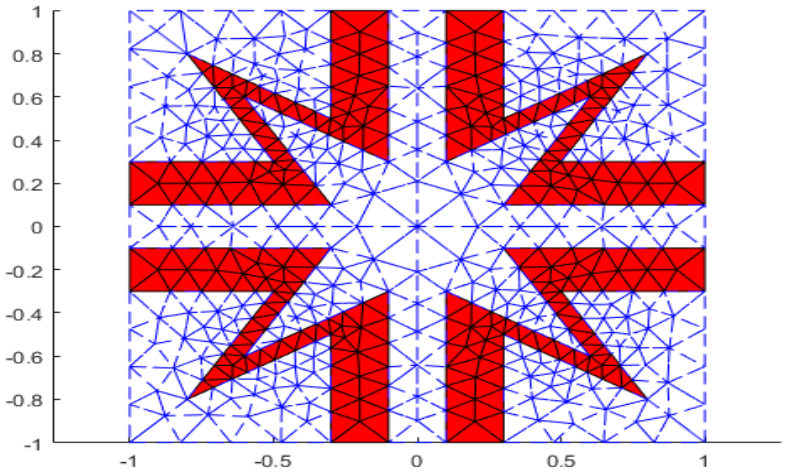
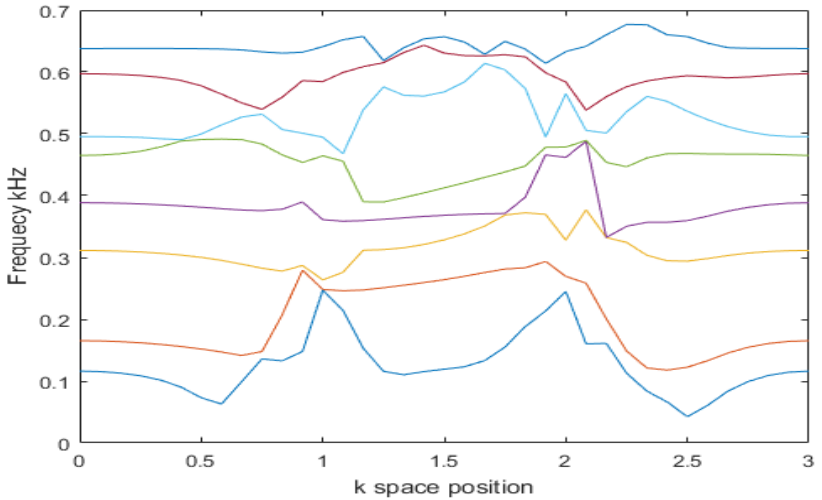
Numerical results

Star-shaped unit cell

Star shape unit cell with 0.2m thickness





Square unit cell with auxetic core with thickness=0.2m and its dispersion curve

The band gaps do not appear in this case

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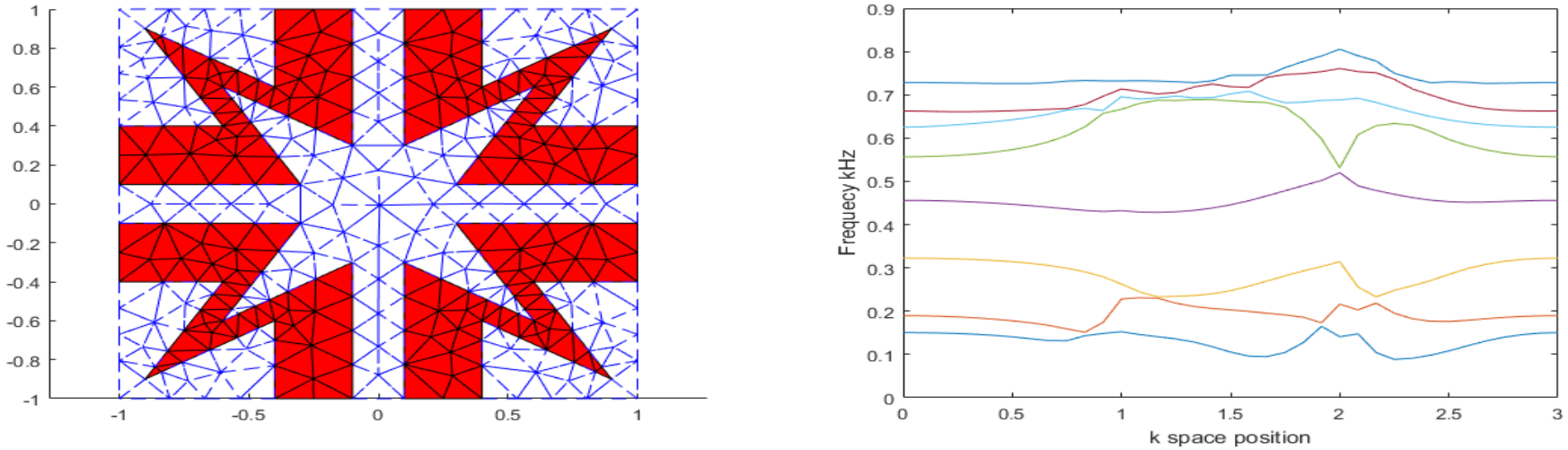
Numerical results

Star-shaped unit cell

Star shape unit cell with 0.3m thickness



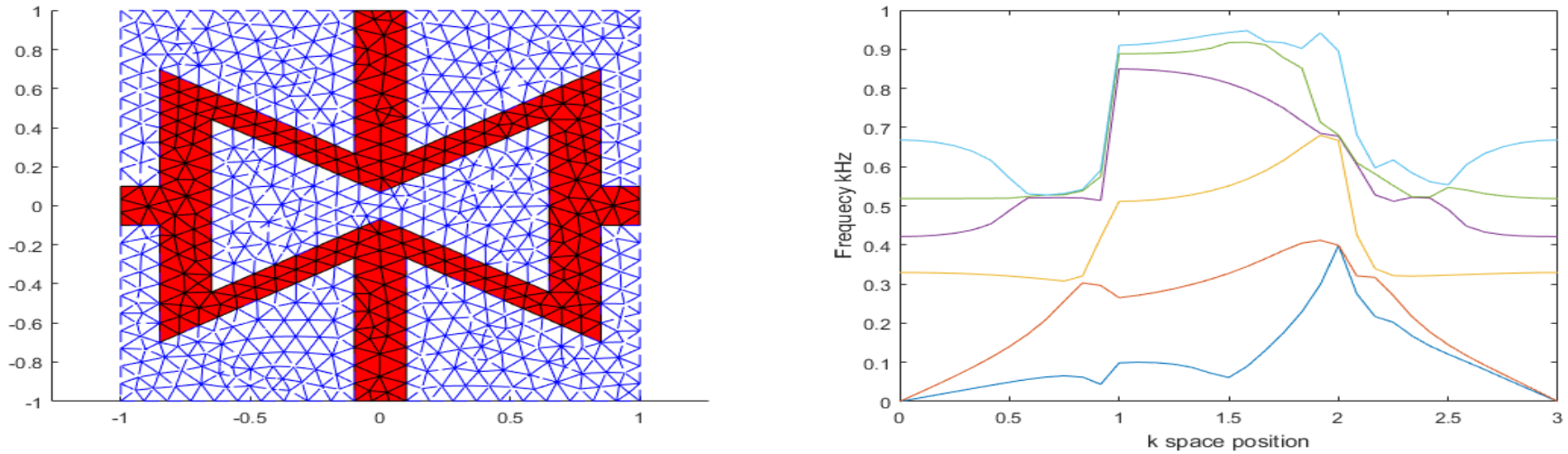
Square unit cell with auxetic core with thickness=0.3m and its dispersion curve

The band gaps appear in a lot of regions, however they are narrower compared to the case of thickness which equals to 0.1m.

Numerical results

Hexagon-shaped unit cell

h=1.4m, d=1.7m b=0.2m, $\Phi=60^{o}$



Square unit cell with hexagon auxetic core its dispersion curve

The band gaps do not appear in this case

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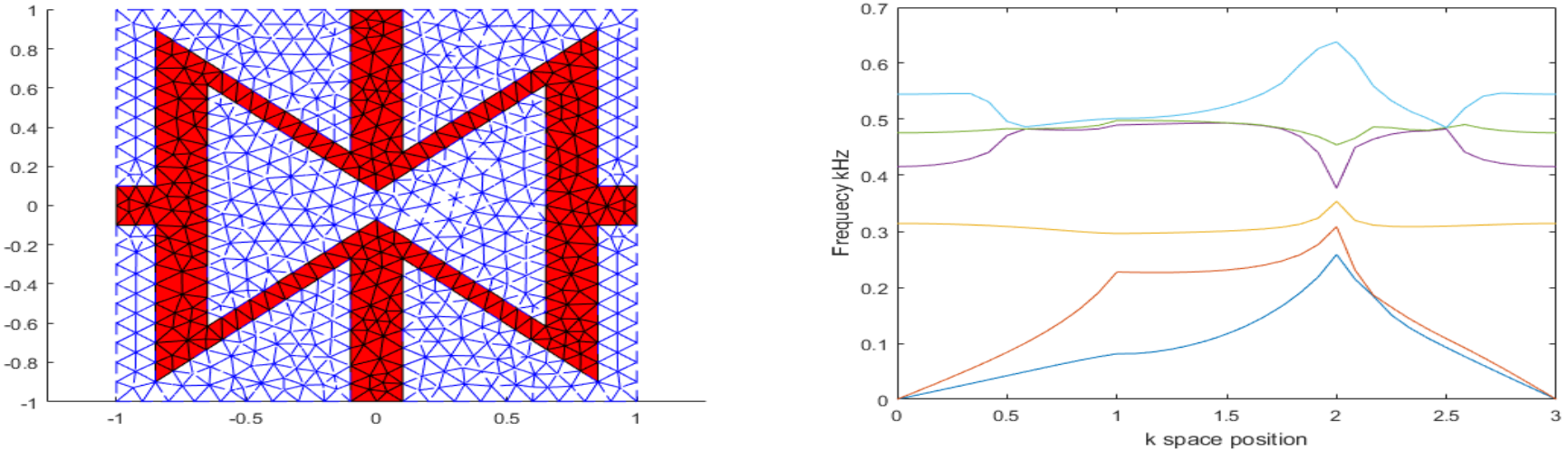
Numerical results

Hexagon-shaped unit cell

h=1.8m, d=1.7m b=0.2m, $\Phi=60^{o}$



Square unit cell with hexagon auxetic core its dispersion curve

In the case band gaps appear between 3rd and 4th eigenvalues, and the frequency range is equal to 23.3Hz.

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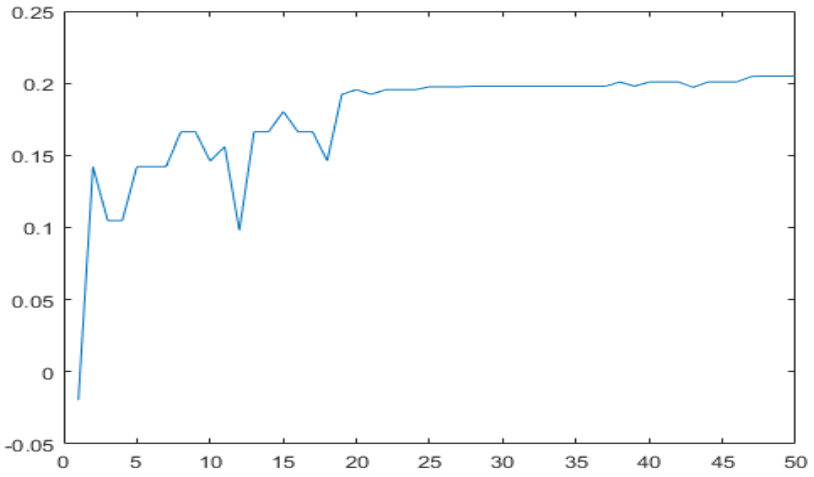
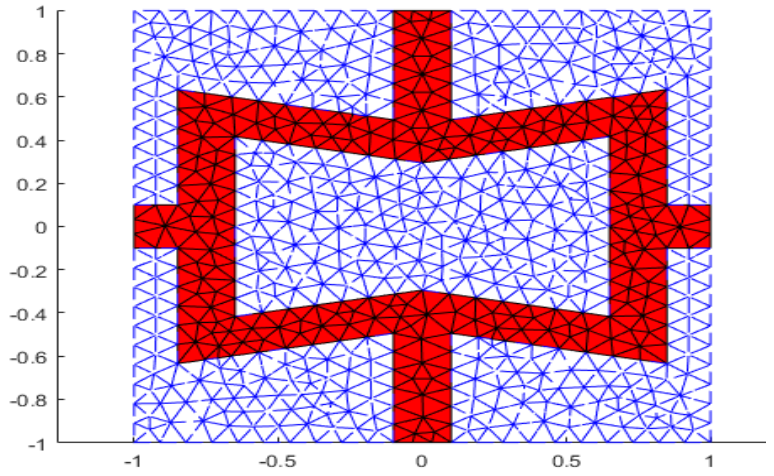
Numerical results

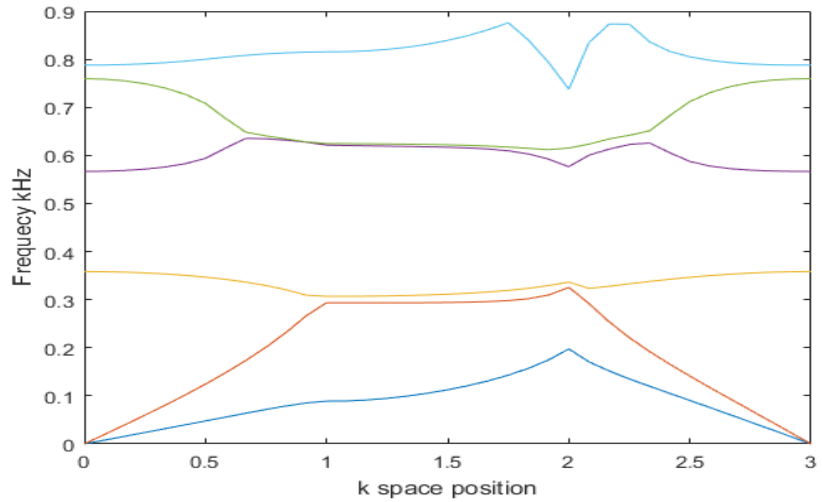
Optimized hexagon-shaped auxetic unit cell

Optimization the band gap between 3rd and 4th in order to achieve auxetic behavior.





Optimized core of the unit cell



The optimized values of the design variables are:
Angle Φ=78.4^o , Height h=1.27m, Width d=1.69m
Maximum Range= 214Hz

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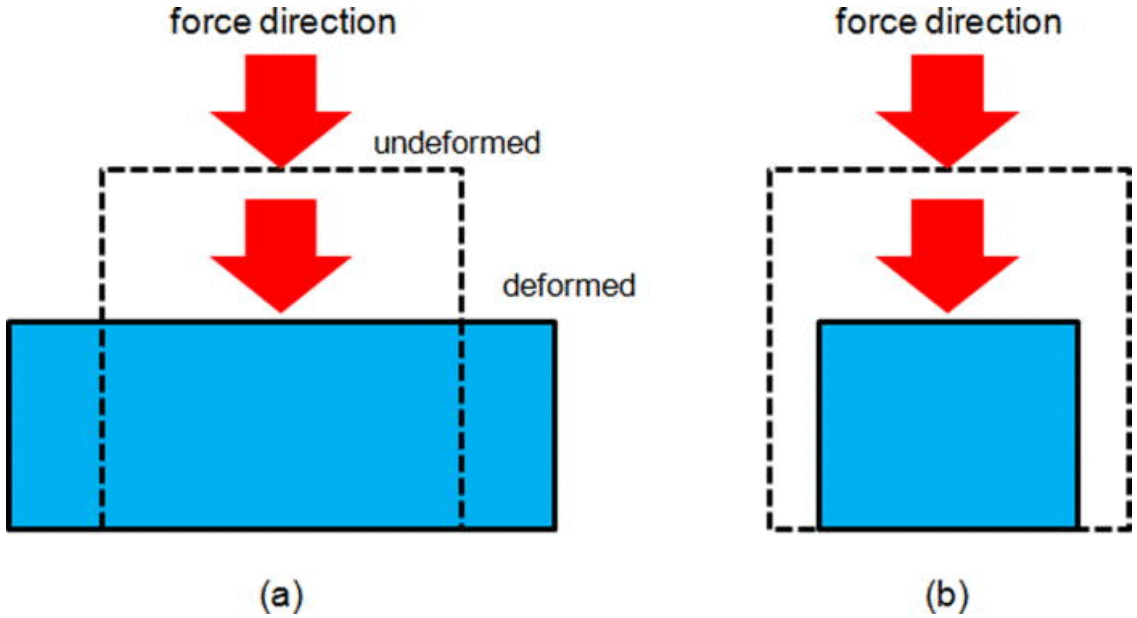
Model example:
Auxetics and technological applications

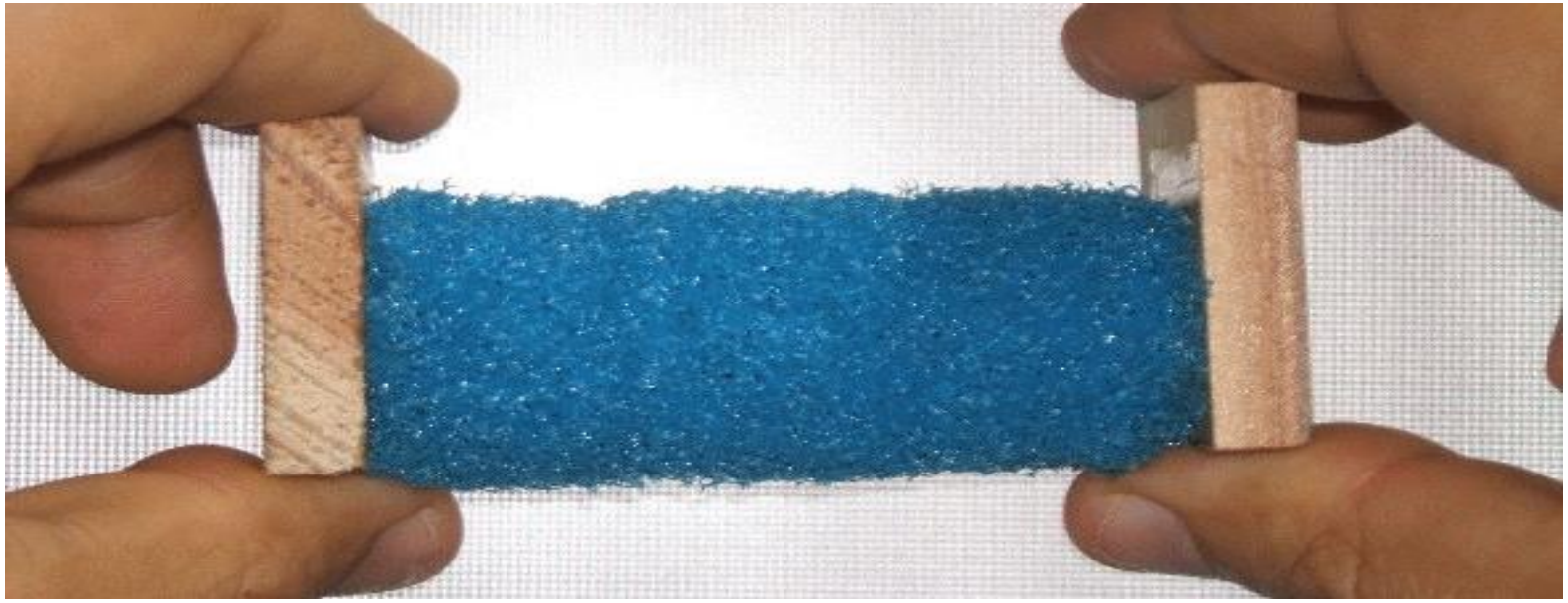
Negative Poisson's ratio

Explained and created by microstructures

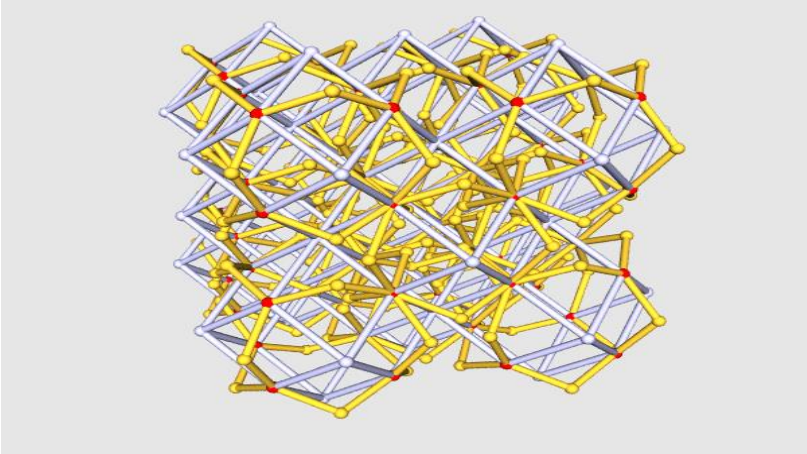
Interesting applications

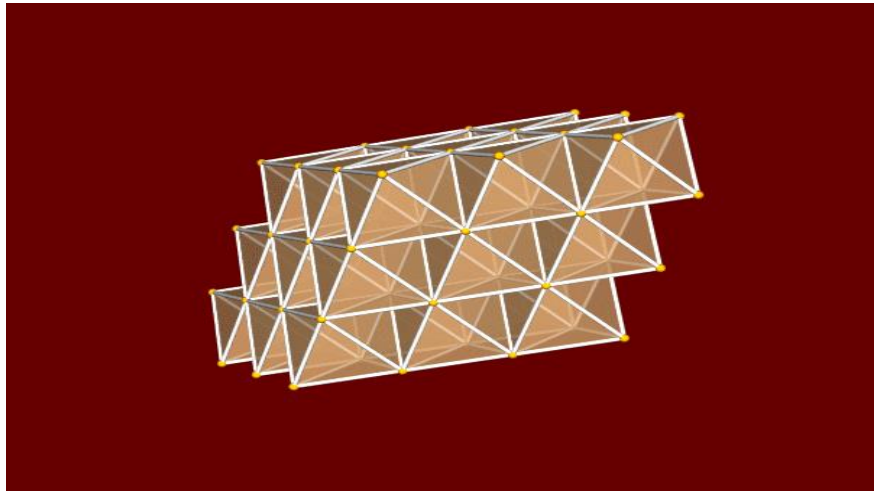
Auxetic material = αυξητικό υλικό

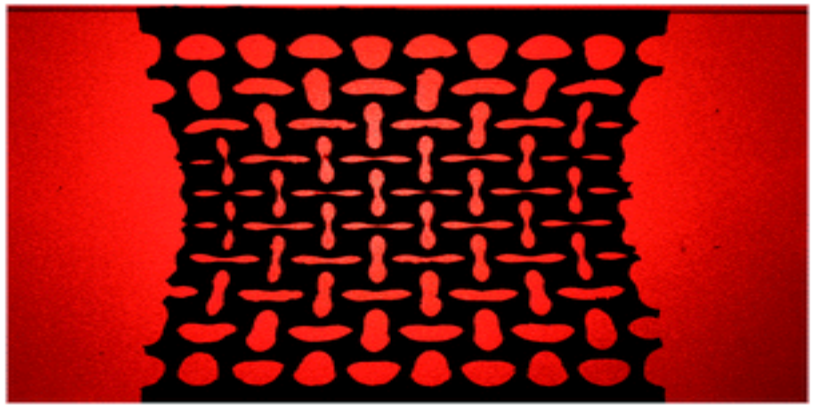


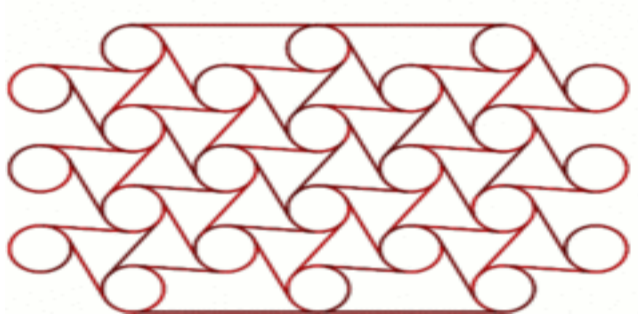


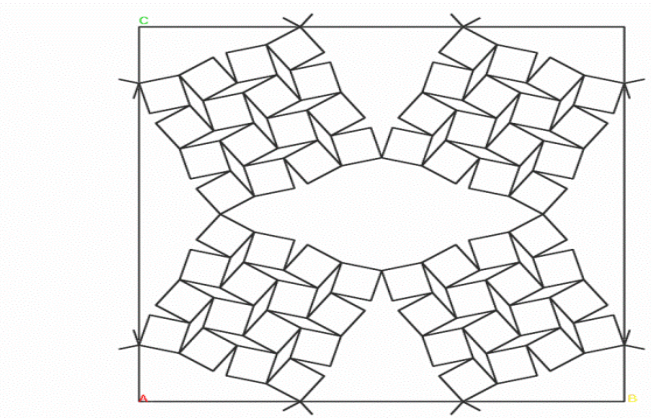
Auxetic mechanisms





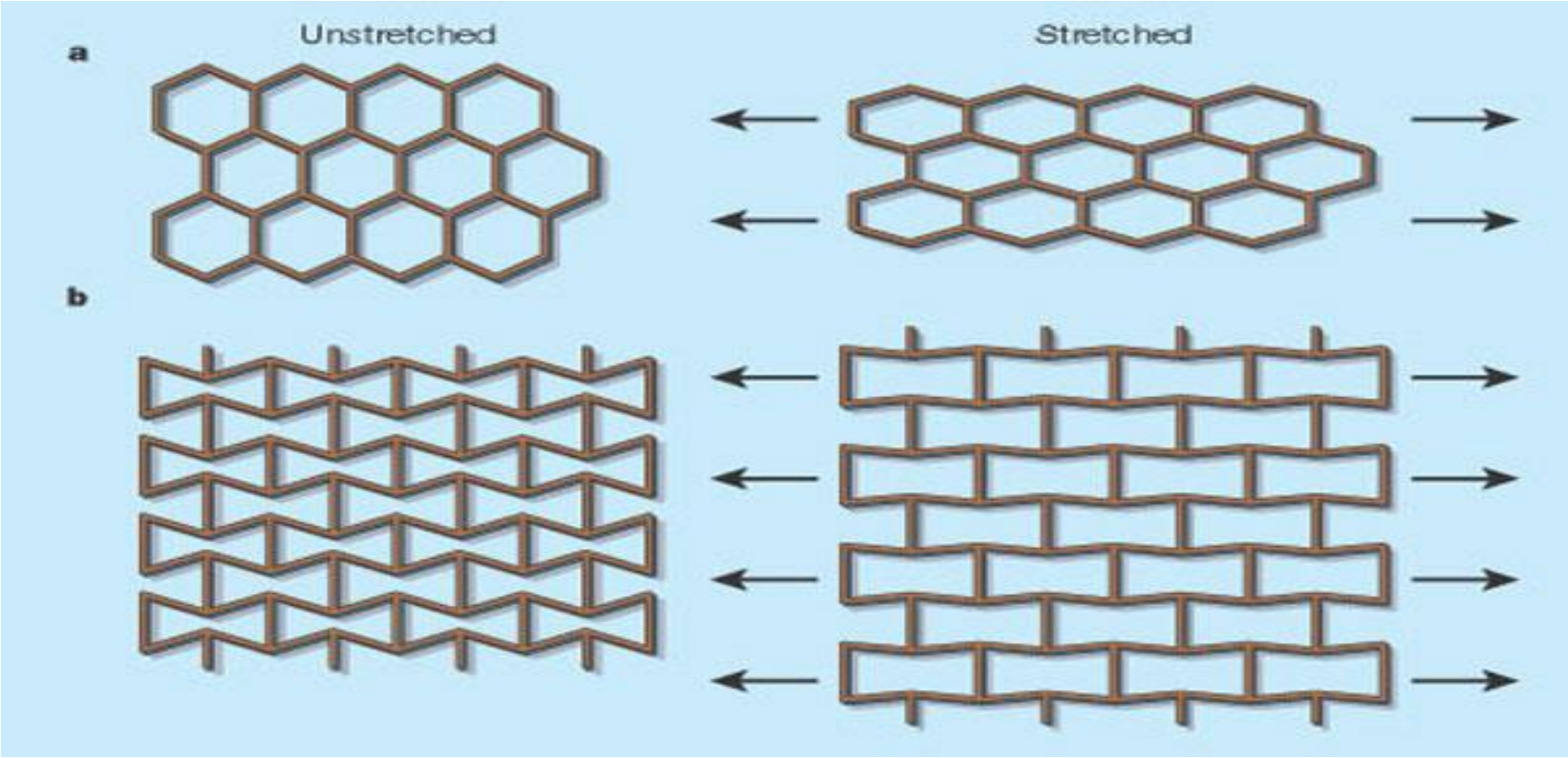






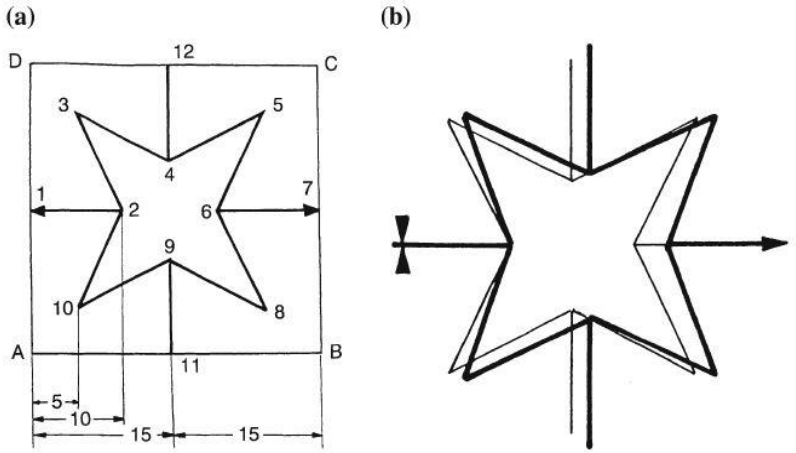
Auxetic Material

- Negative Poisson's ratio

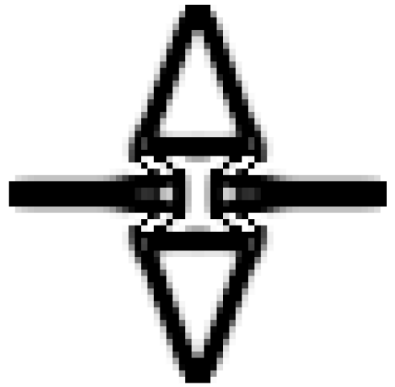


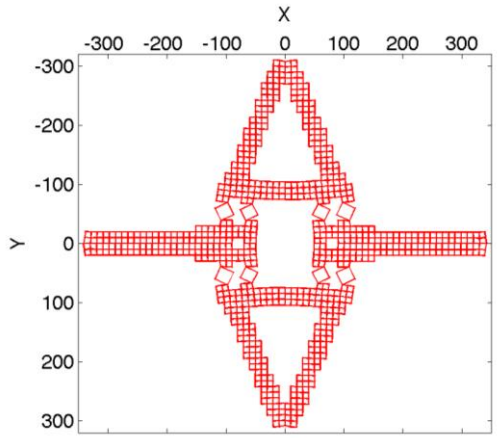
Topology Optimization and Auxetic Microstructure

Auxetic microstructures lead to metamaterials with useful mechanical behaviour, in statics and dynamics. Beyond classical (e.g. star-shaped) microstructures, topology optimization gives much more flexibility.



Source: Negative Poisson's ratios in composites with star-shaped inclusions: a numerical homogenization approach. Theocaris, P.S., Stavroulakis, G.E. & Panagiotopoulos, P.D. *Archive of Applied Mechanics* **67,** 274–286 (1997)





Source: Topology optimization for compliant mechanisms, using evolutionary-hybrid algorithms and application to the design of auxetic materials, N. Kaminakis, G.E. Stavroulakis, 2012
Kaminakis, PhD, TUC 2013

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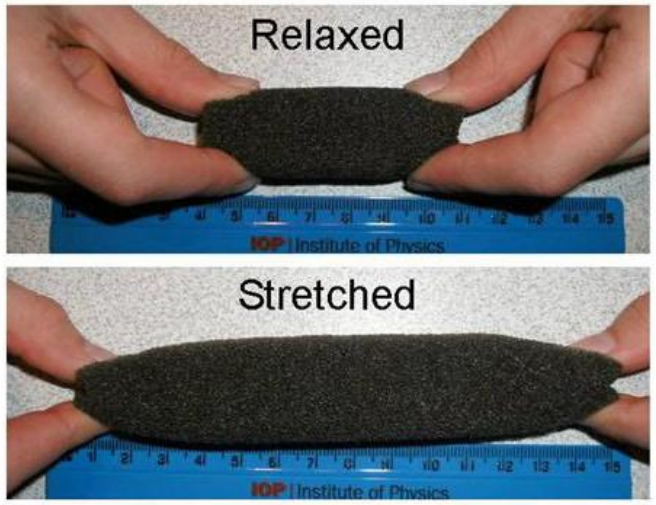
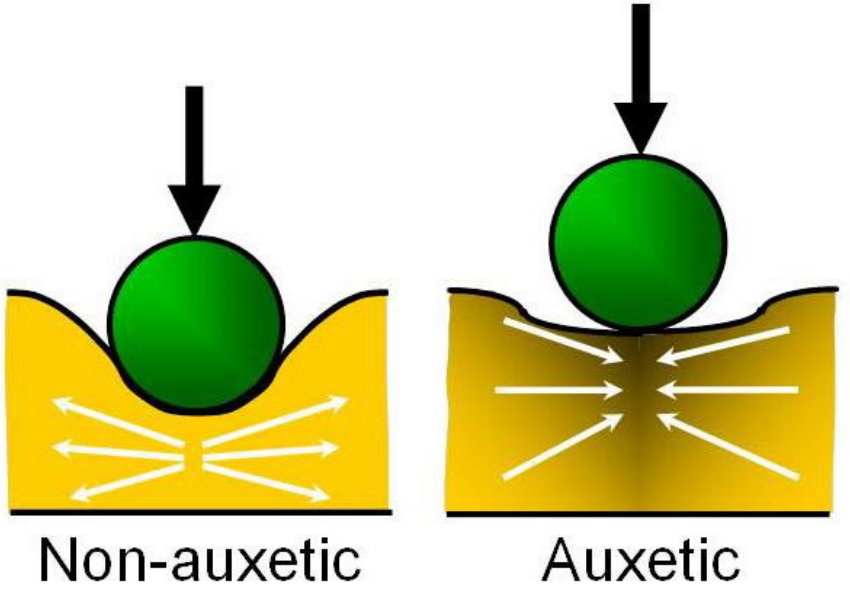
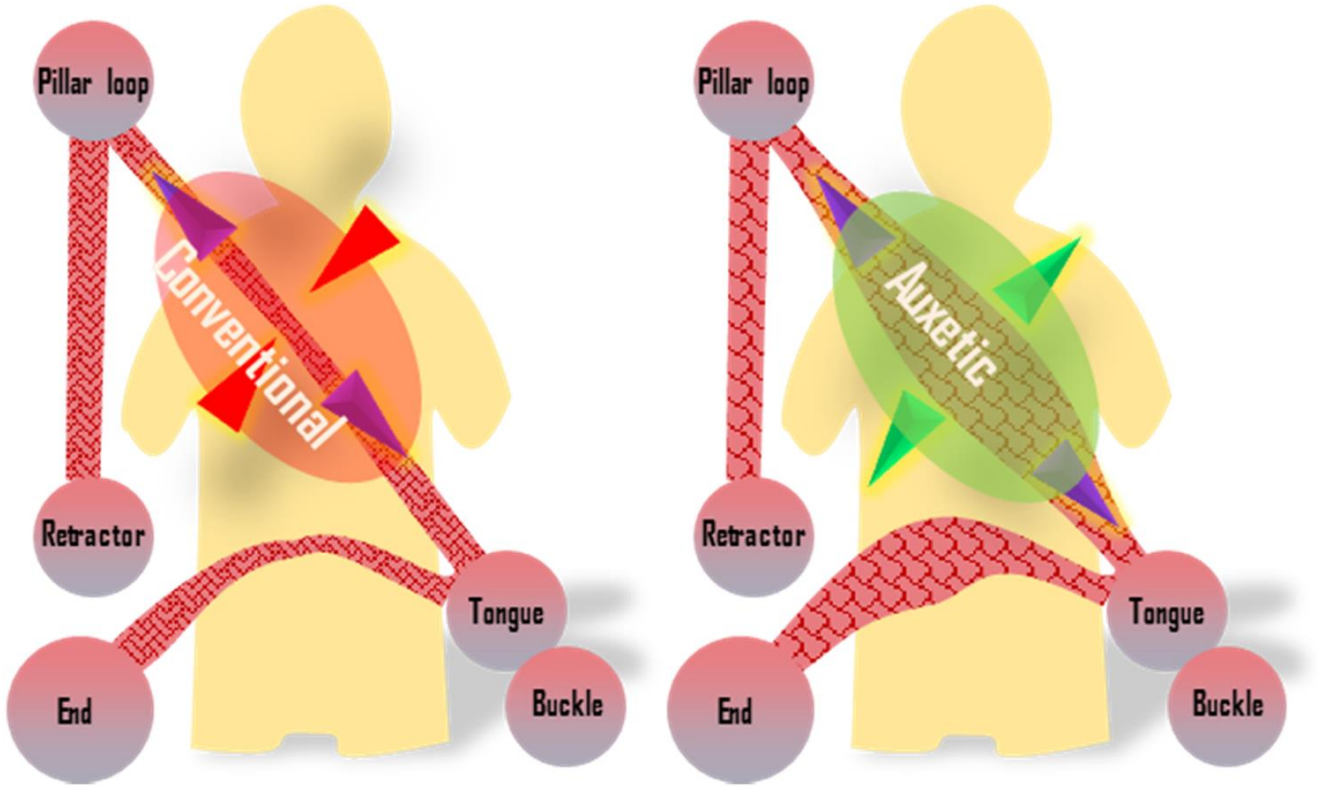
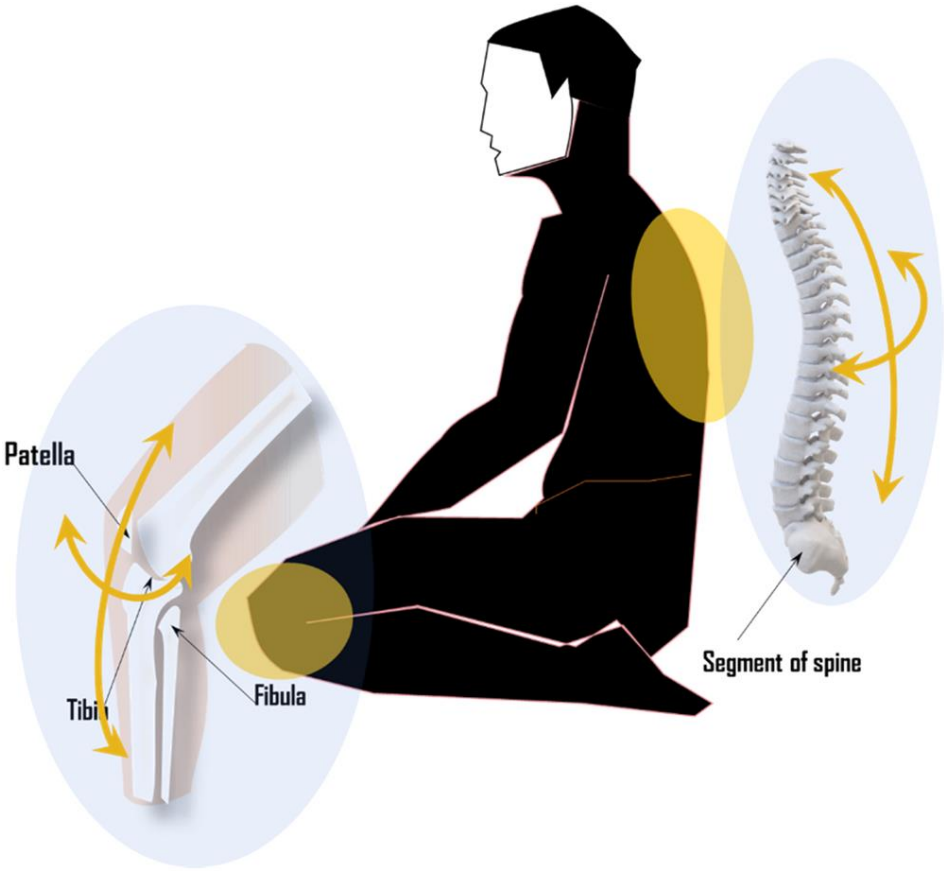
Properties of auxetics





Auxetic applications: protection





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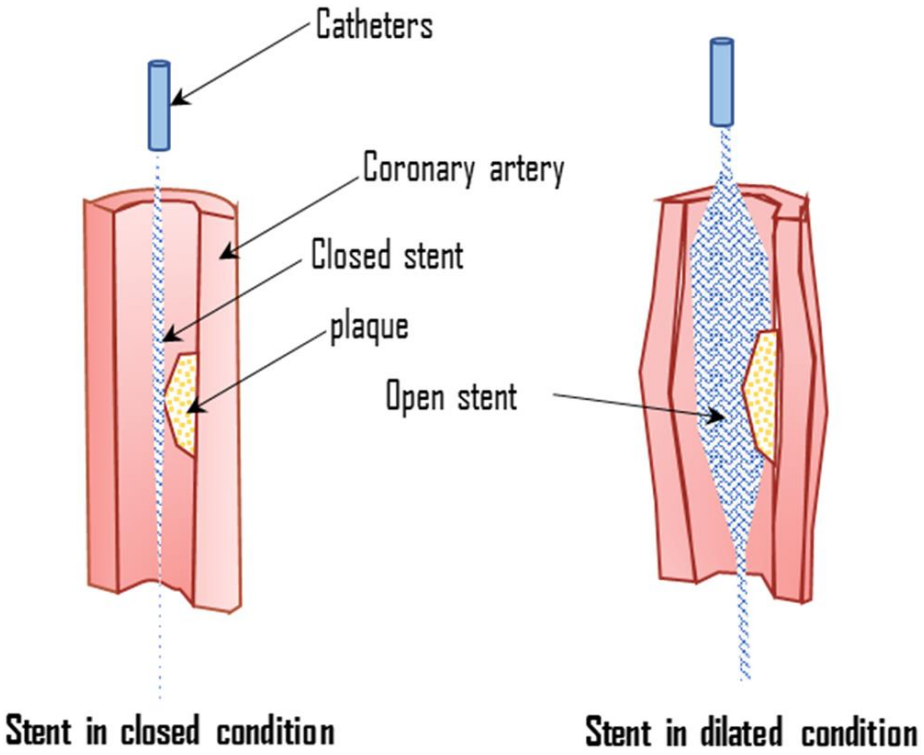
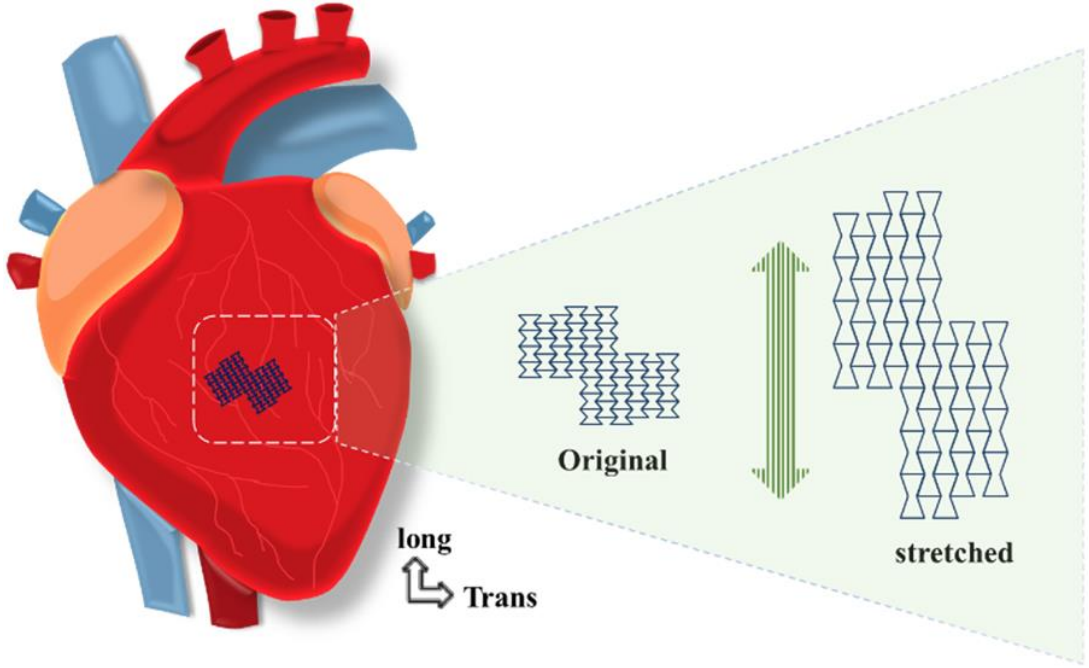
Auxetic applications: biomechanics



Auxetic stents



Auxetic cardiac patches

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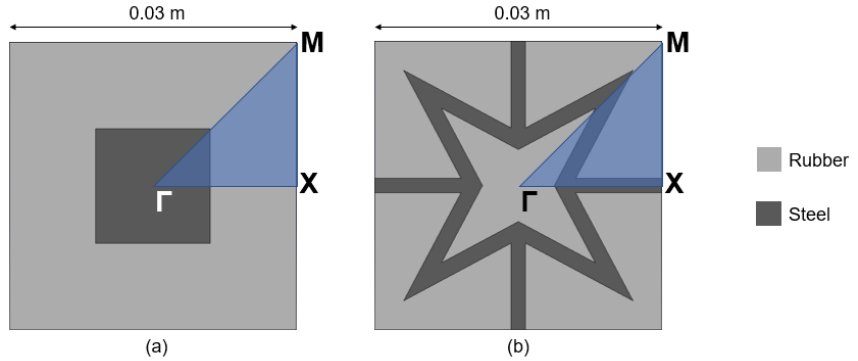
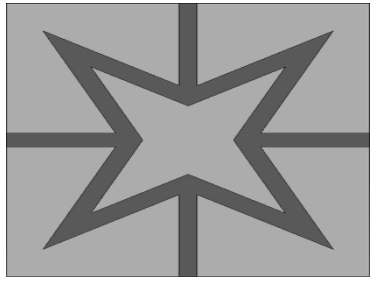
Band gaps with Auxetics



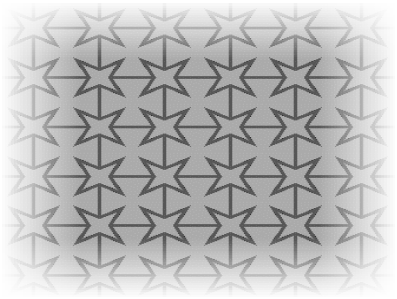
Unit Cell

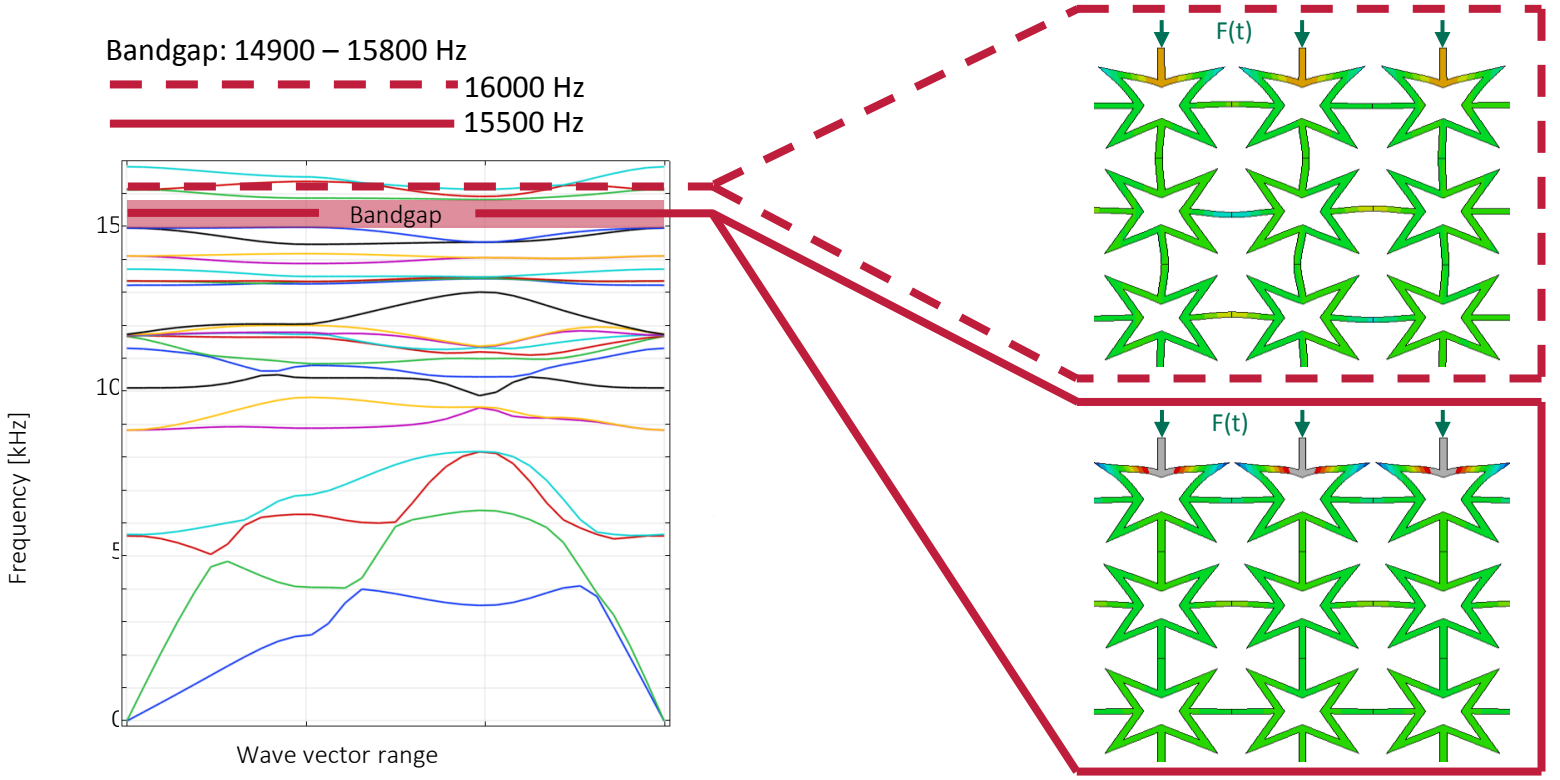


Rubber

Steel

Periodic Lattice

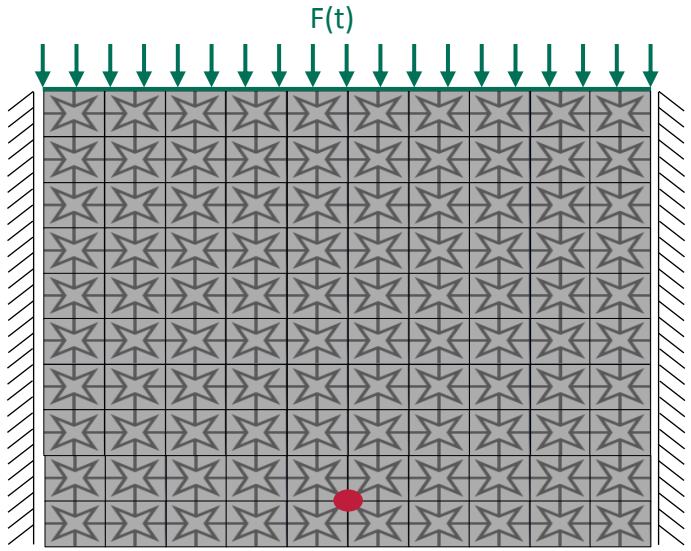




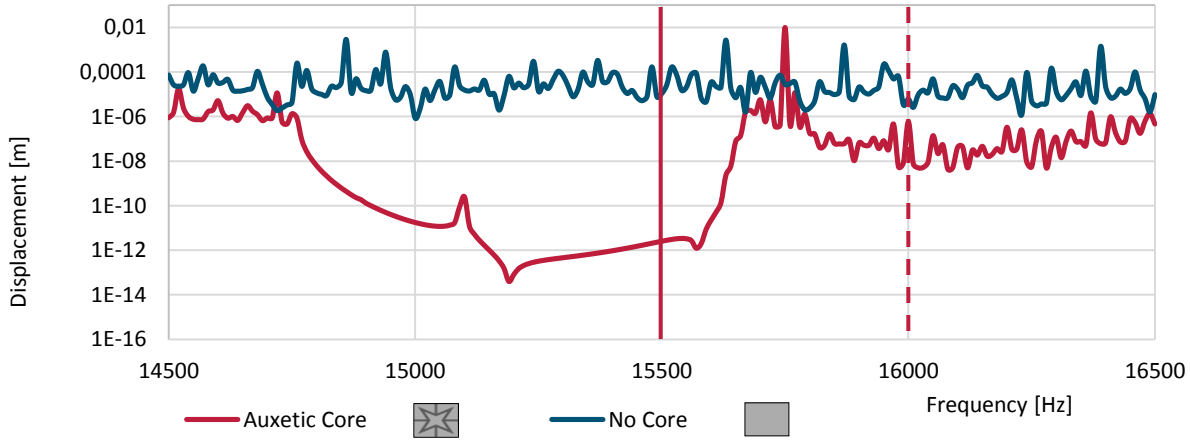
M. Rechenberg, Bachelor Thesis, TU Braunschweig, 2020, P. Koutsianitis PhD, TUC, 2020

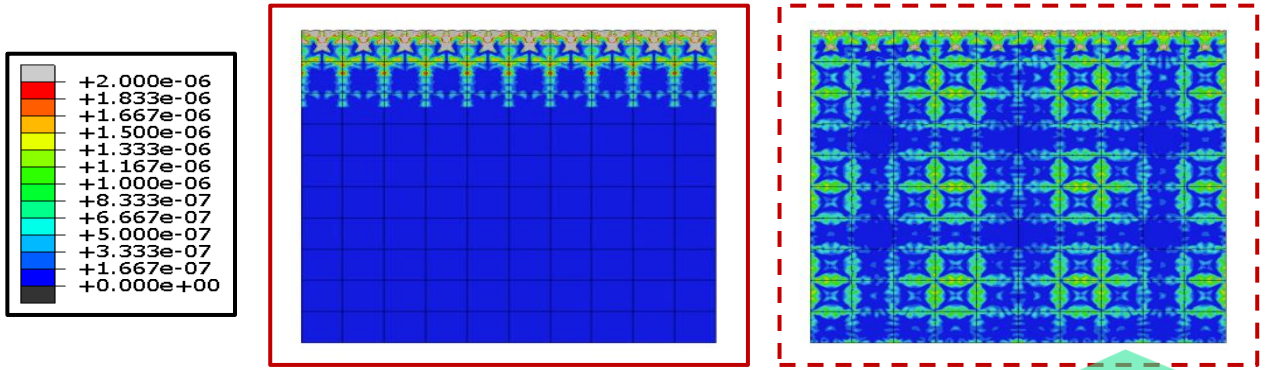
P.I. Koutsianitis, G.K. Tairidis, G.A. Drosopoulos, G.E. Stavroulakis. Conventional and star-shaped auxetic materials for the creation of band gaps. Archive of Applied 89 (12), 2545-2562, 2019.

Band gaps with Auxetics

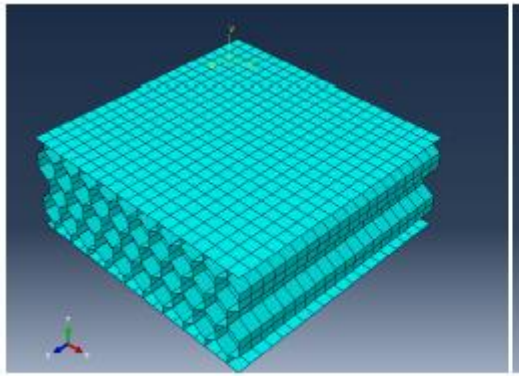


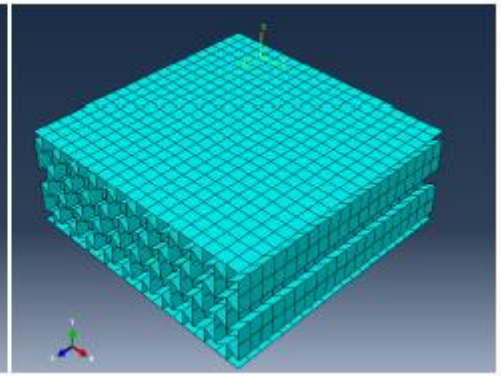
- 10 by 10 auxetic unit cells
- Harmonic pressure load on top core surface
- Oscillations measured at the bottom ( )



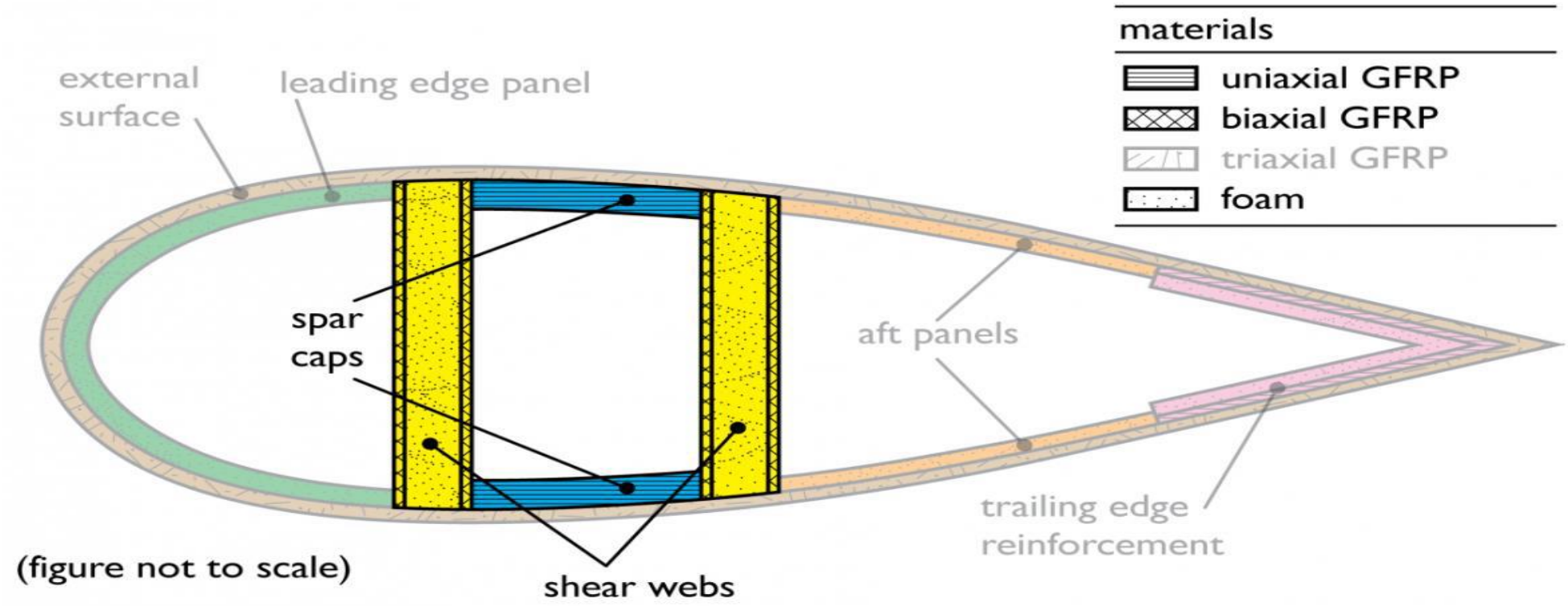


Application on vibration-isolation at high-speed boat



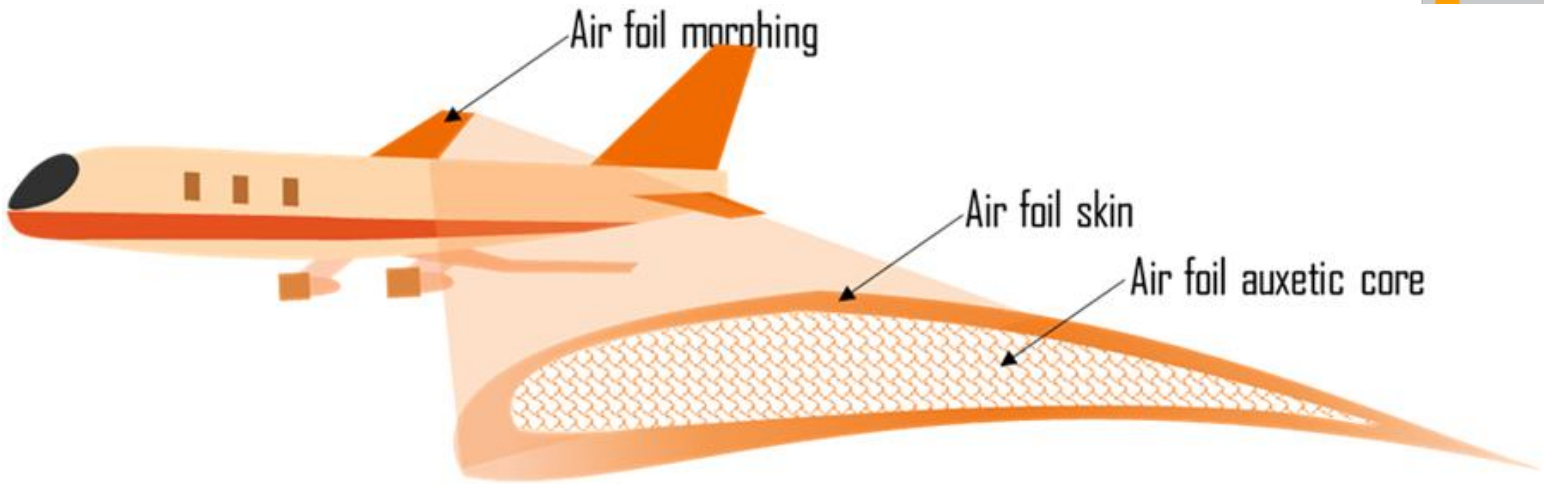


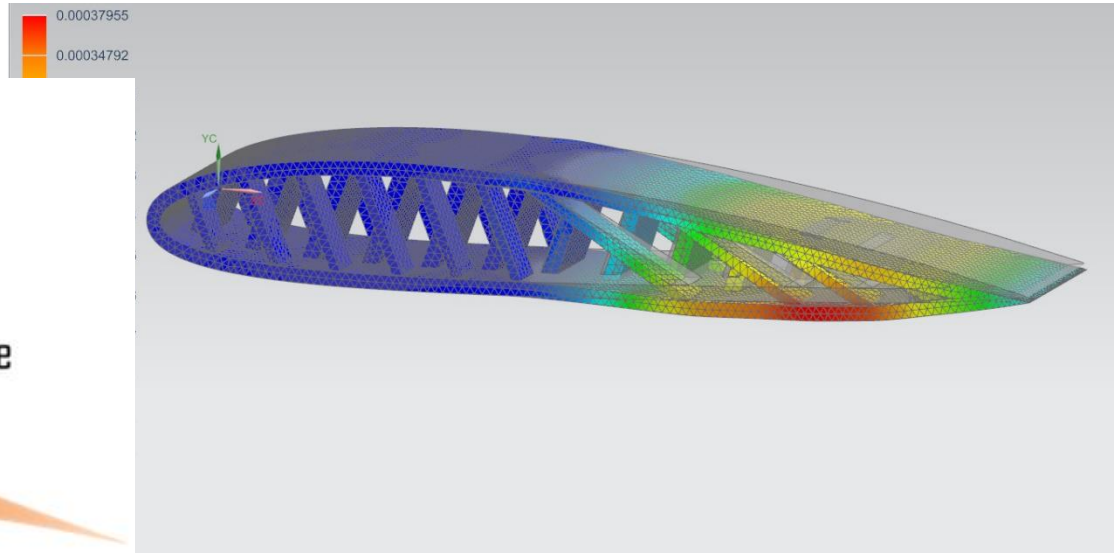
Auxetic isolation for wind turbine blades



K. Koutroumpas, Diploma Thesis TUC 2016

Morphing of blades





D. Vokas, Diploma Thesis TUC 2019

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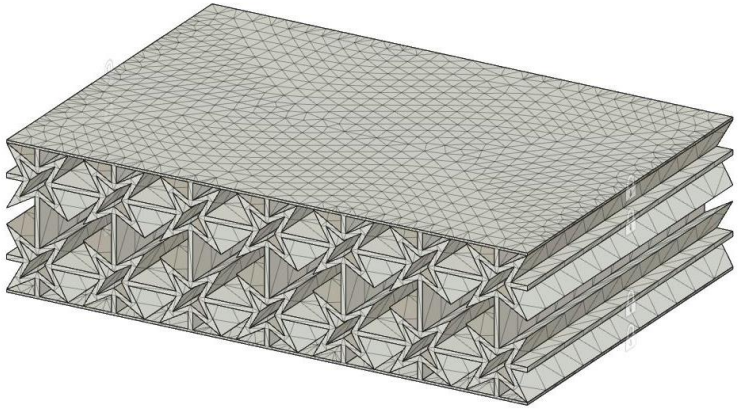
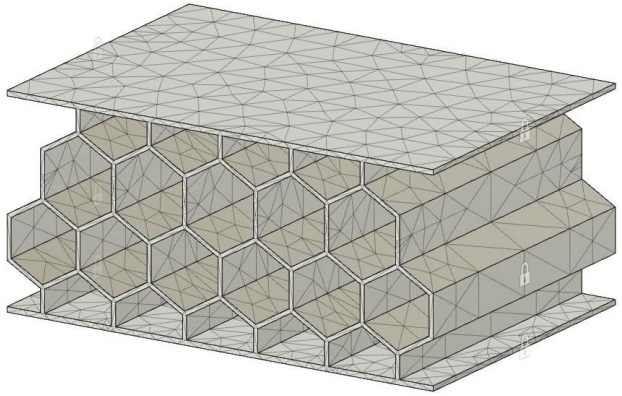
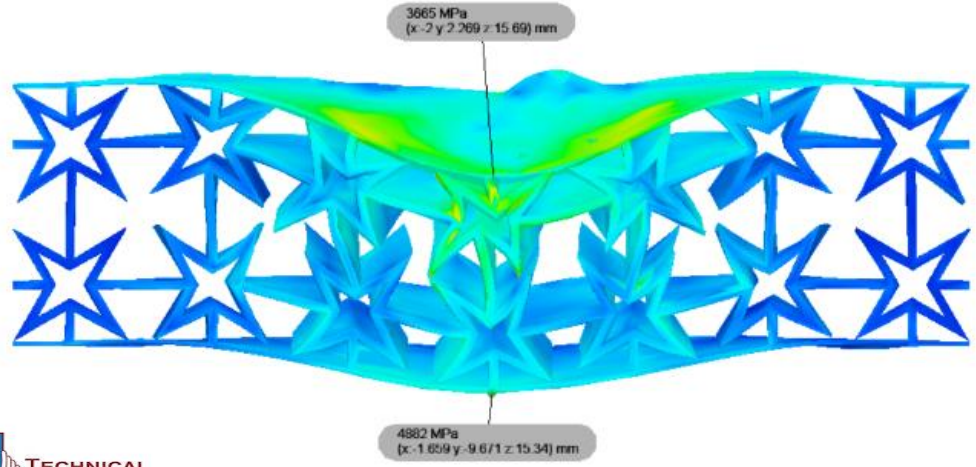
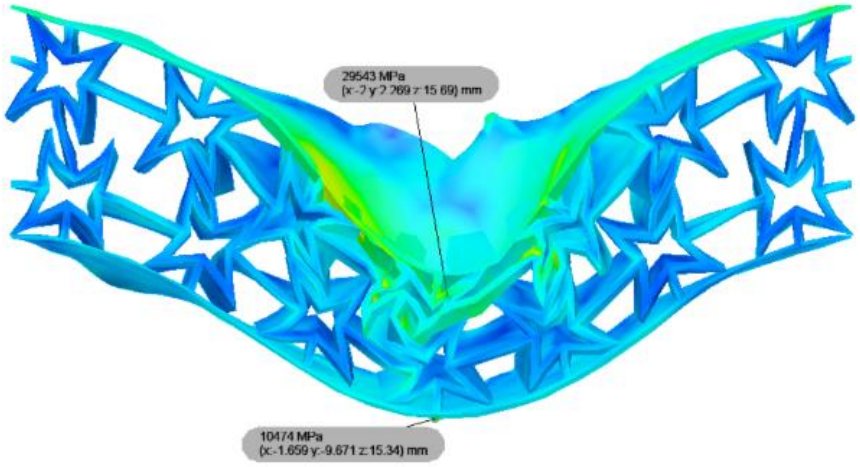
Bullet penetration in an auxetic plate









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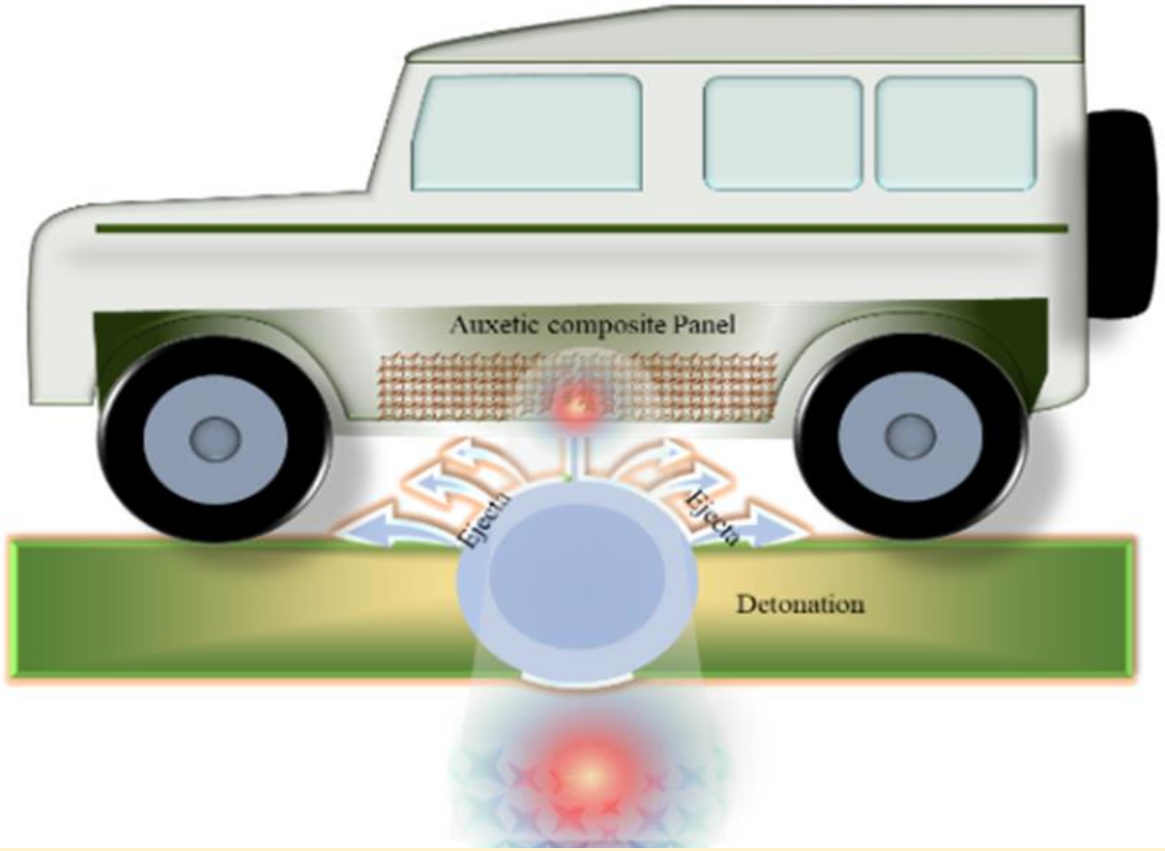
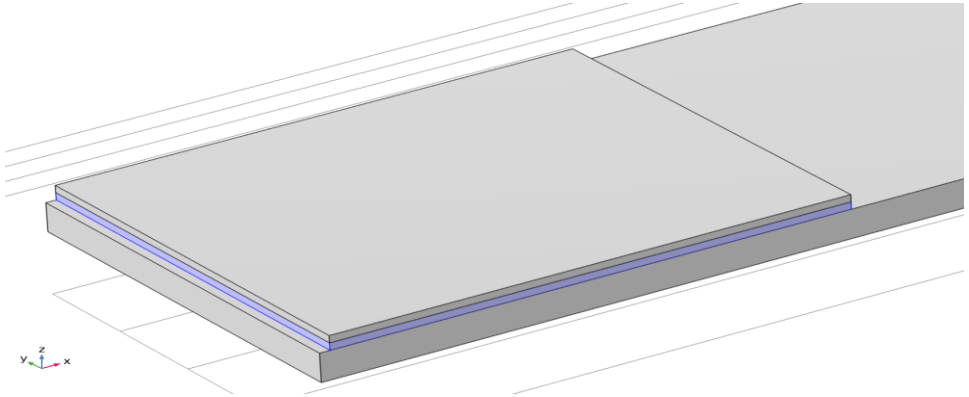
I. Ntintakis, PhD TUC 2023

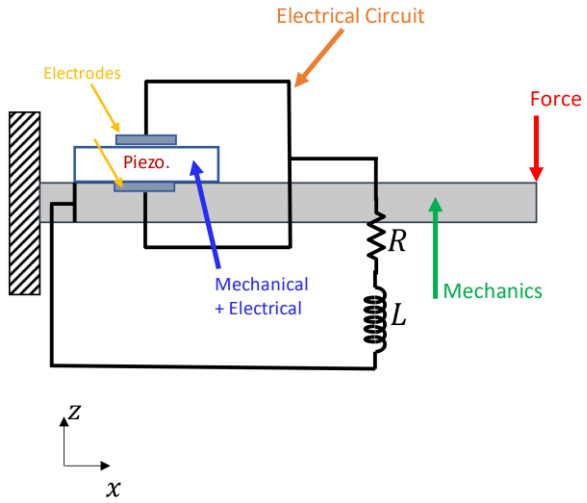
Auxetic armour protection of vehicles

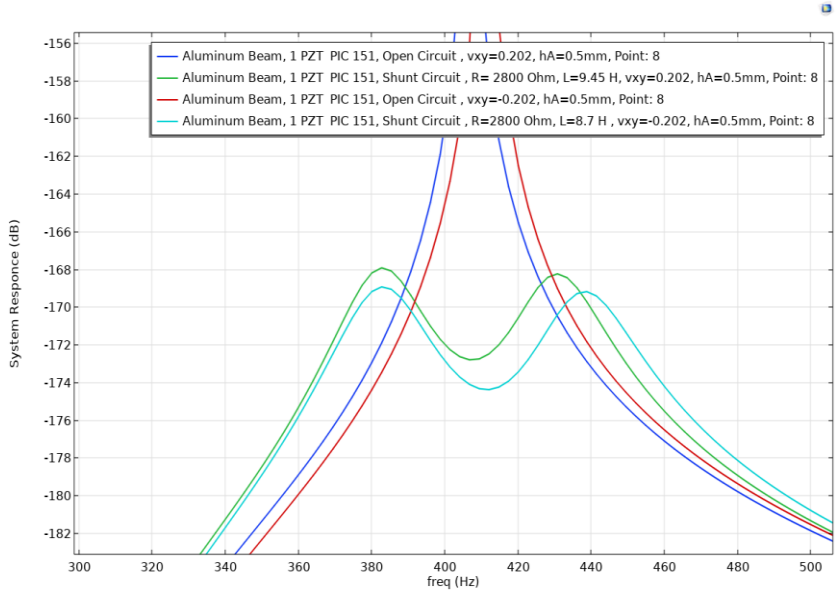


Auxetic mechanical metamaterials and their futuristic developments: A state-of-art review. Madhu Balan P , Johnney Mertens A , M V A Raju Bahubalendruni Materials Today Communications 34 (2023) 105285

Auxetic enhancement of shunted piezoelectrics







Modeling of shunted piezoelectrics and enhancement of vibration suppression through an auxetic interface, Micromachines 2023
Maria-Styliani Daraki, Konstantinos Marakakis and Georgios E. Stavroulakis

K. Marakakis, PhD, TUC, 2022

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Nike patented auxetic soles

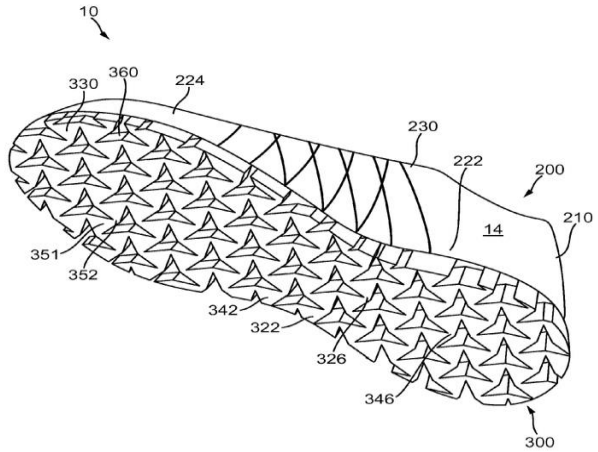
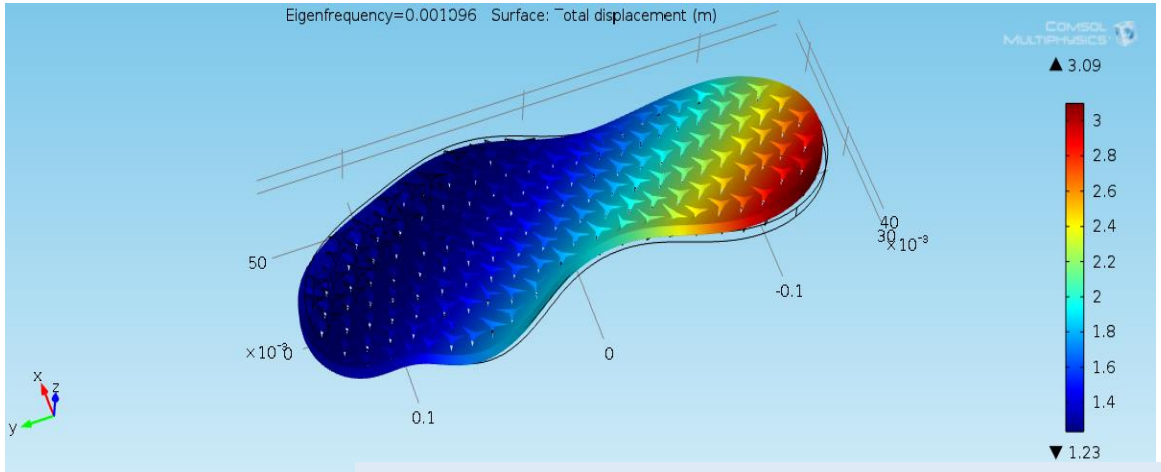


FIG. 3



P. Boura, Master Thesis, TUC 2016

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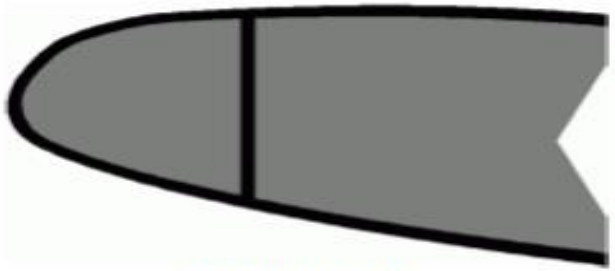
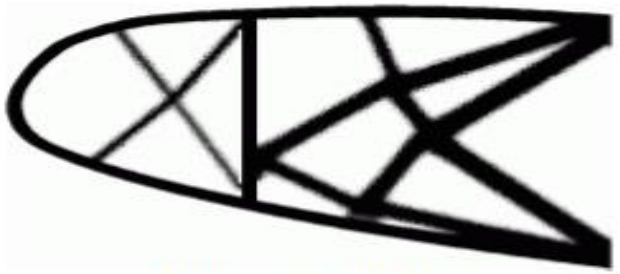
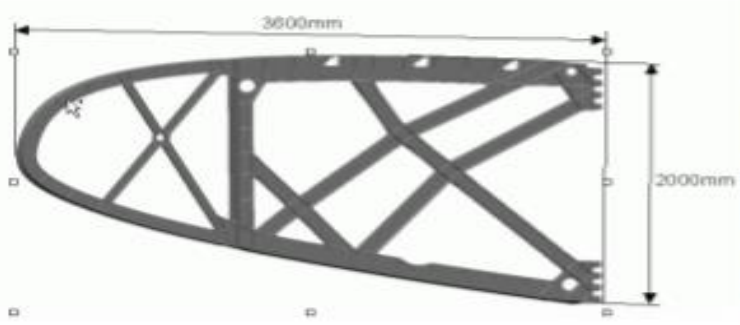
Topology Optimization



Design domain



Optimized topology



Actual structure

Manufactured wing structure

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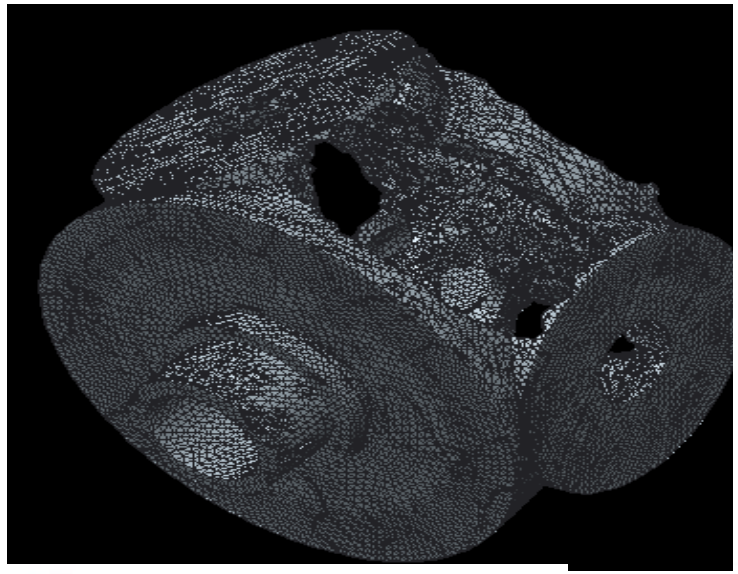
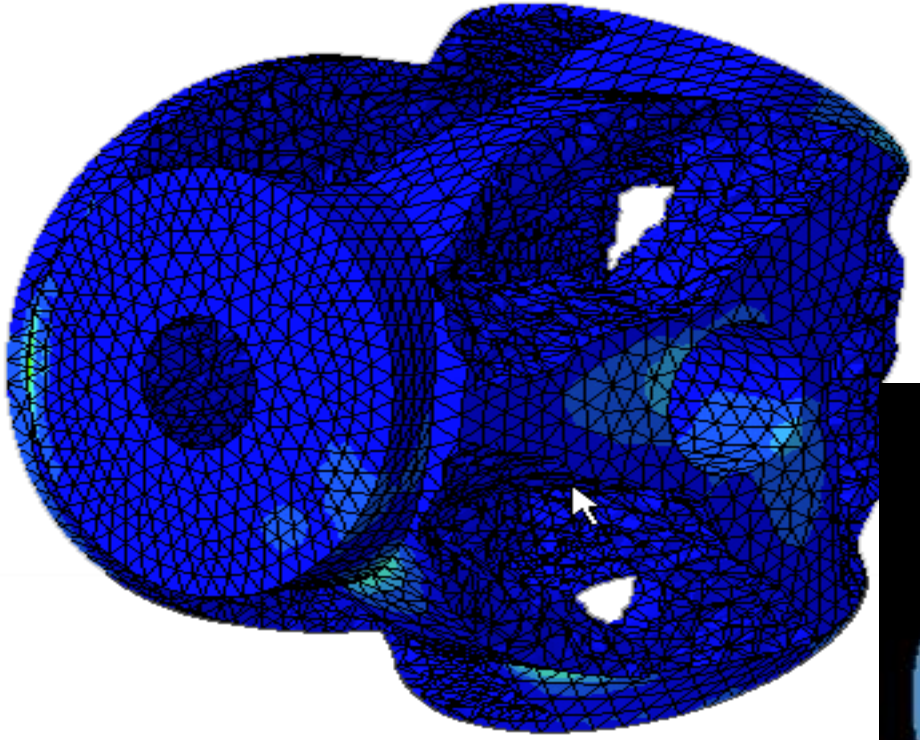
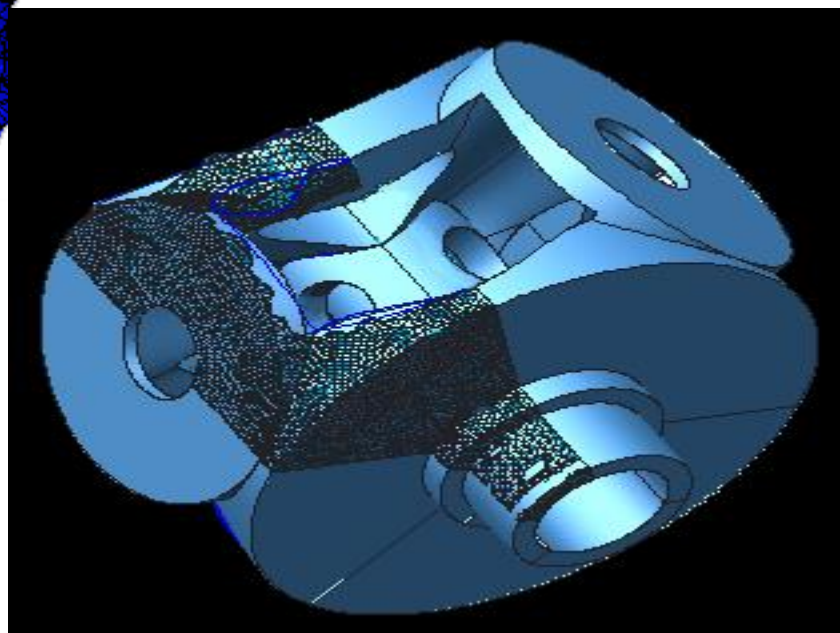
A structural part of the A380 aircraft of Airbus

Topology optimization of a rotor, in a wind turbine







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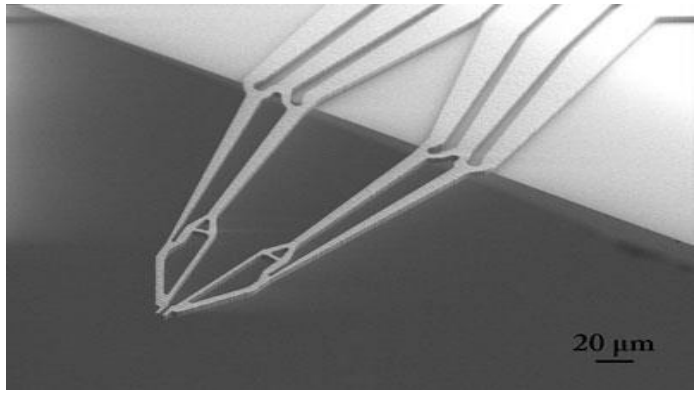
Fetsi, Diploma Thesis, Technical University of Crete, 2015

Topology Optimization Mechanisms



Nanomechanics Gripper (*Image: Özlem Sardan, DTU*, www.nanohand.eu)

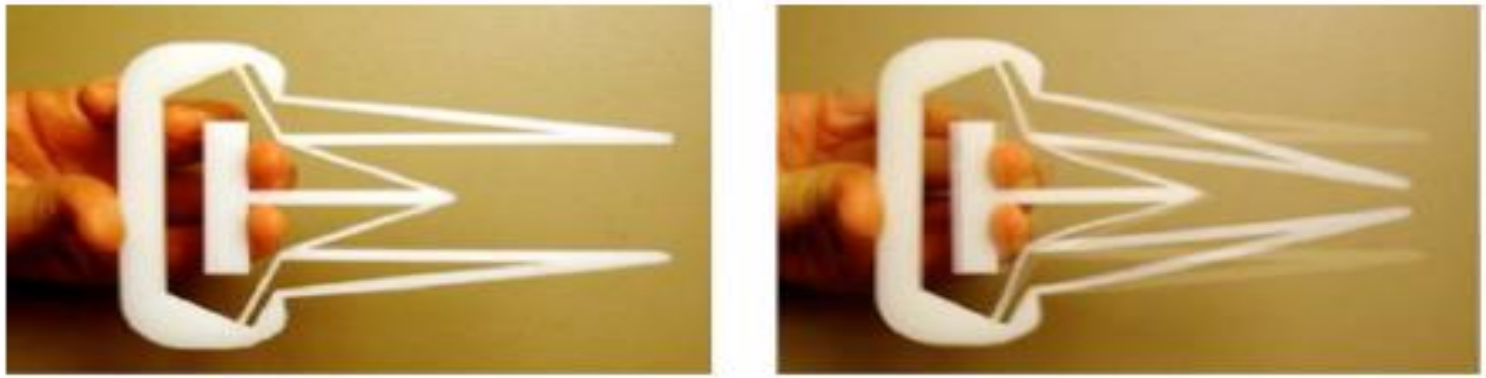


Fig. 7 Prototype of the compliant gripper in its inactive mode (left) and gripping mode (right)

Mechanical Gripper modelled as a Compliant mechanism.

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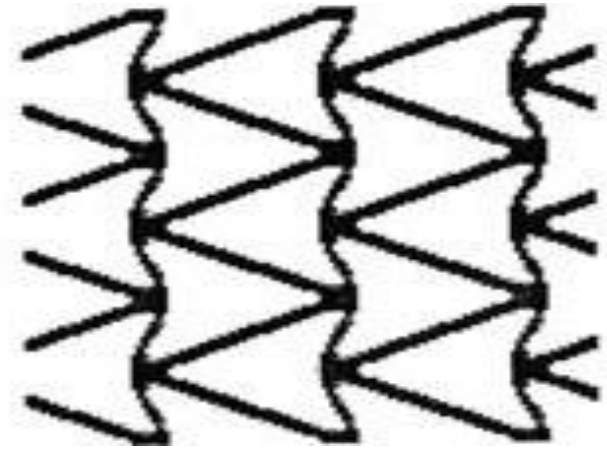
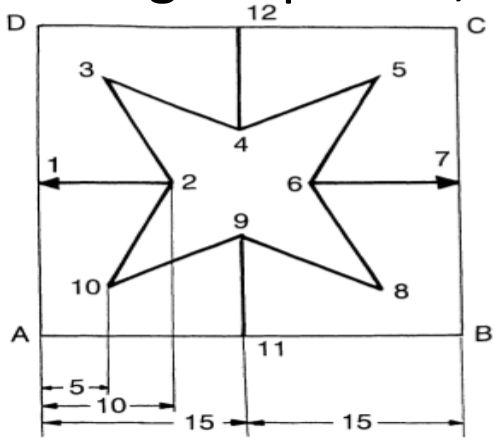
Auxetic Material

Previous works (based on flexible microstructures)

- Larsen et all, 1997



- Theocharis, Stavroulakis, Panagiotopoulos, 1997



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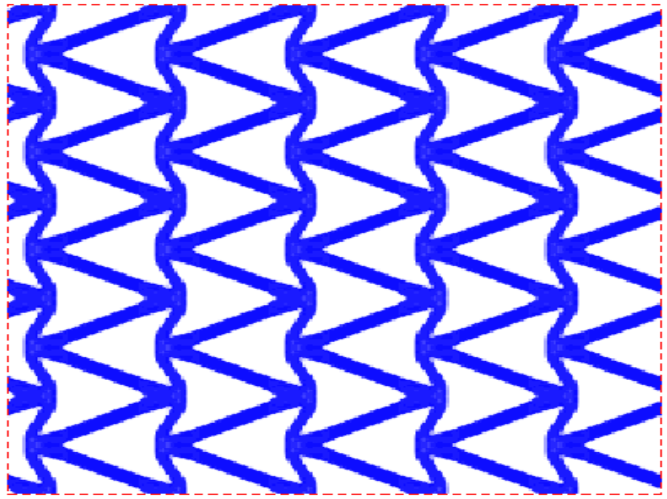
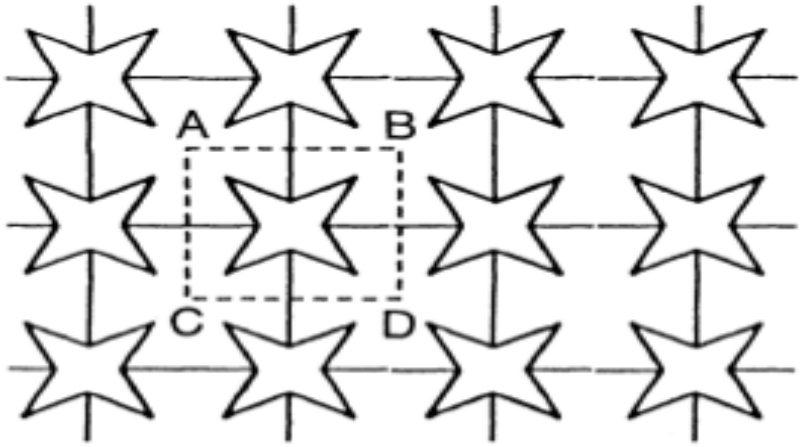
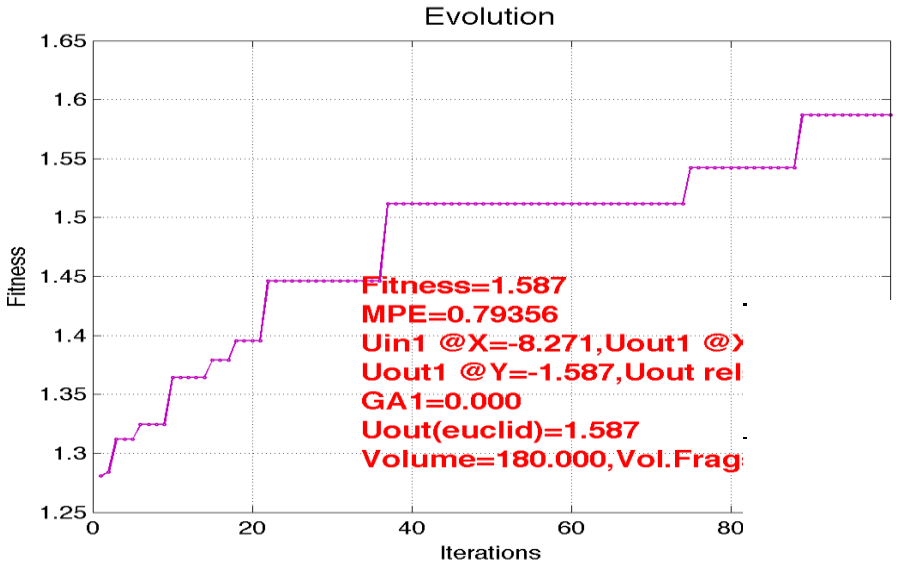


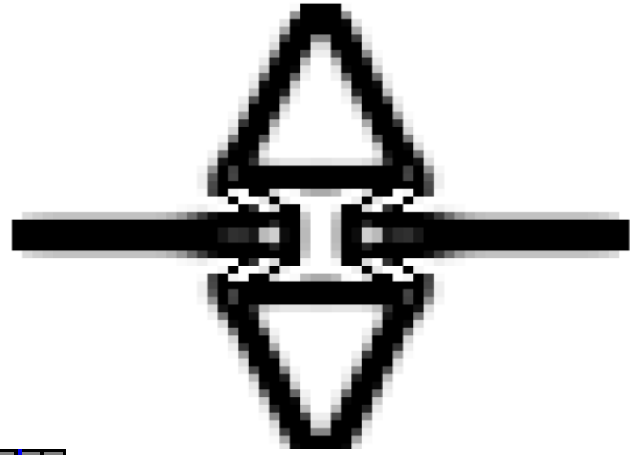


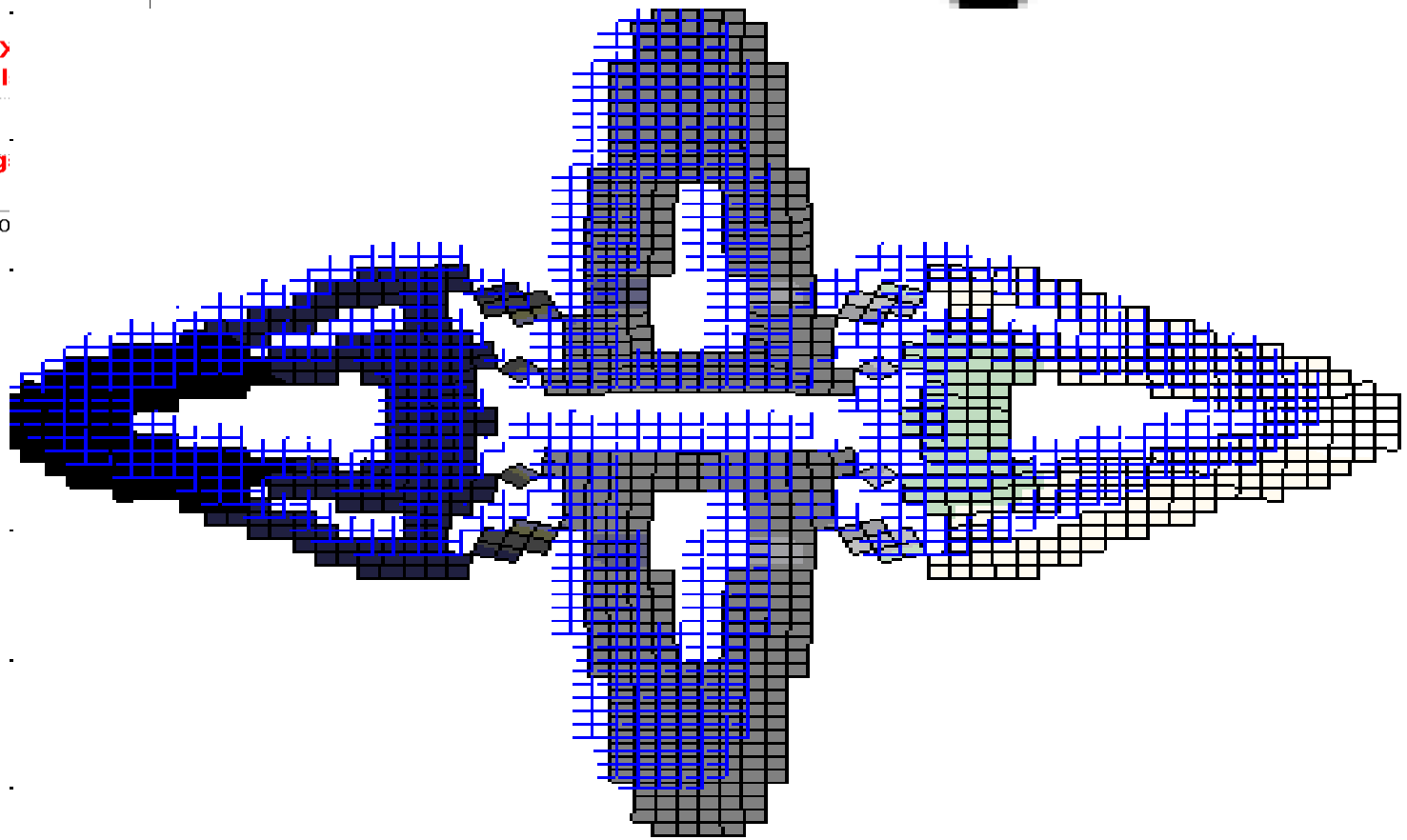
Continuous formulation
30x30 elements, Volume fraction: 4



Poissons Ratio=

$$-\frac{-1.587}{-8.271}=-0,192$$





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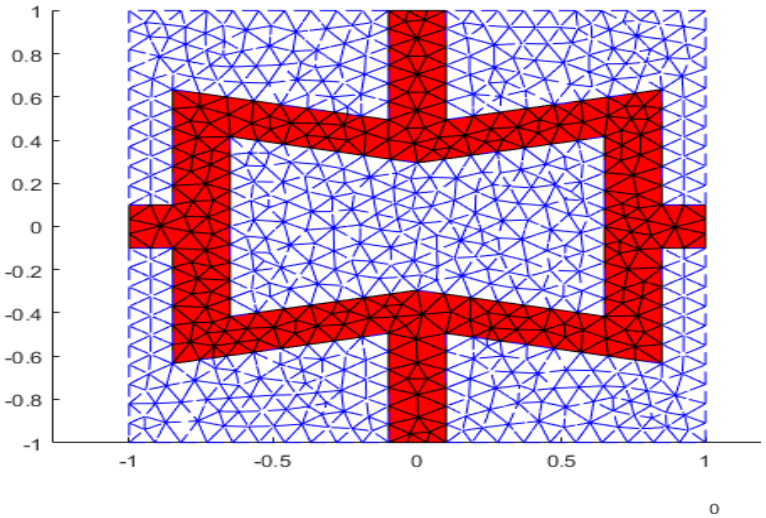
Optimization problem for band gap analysis

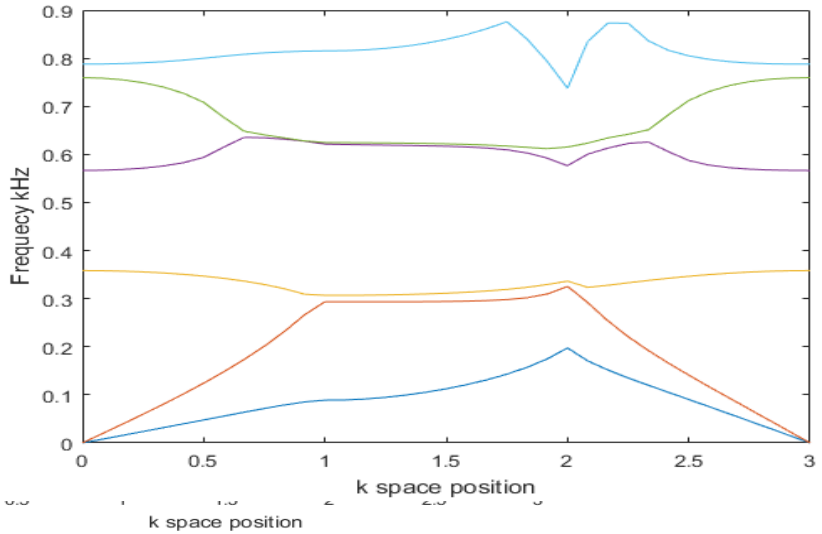
Objective Function

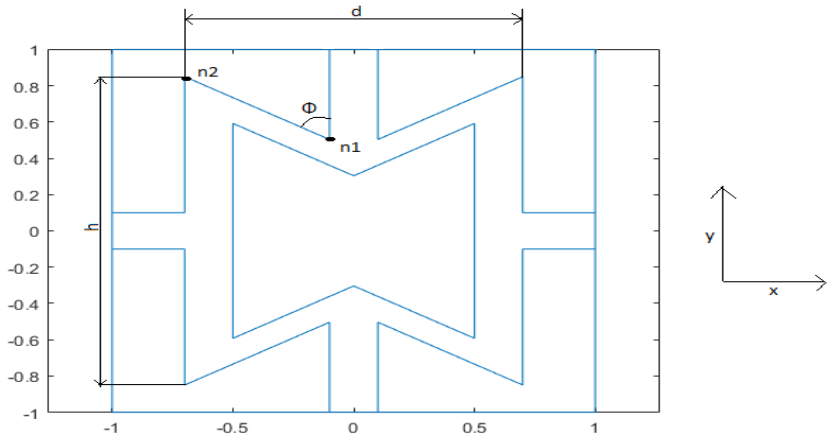
Maximize the Band Gap Area

Constraints

Symmetry design constraints
e.g. at y axis: n2<1
at x axis: n1<0, etc.







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Design Variables:
Heigth: h ϵ [0.2, 1.9]
Width: d ϵ [0.2, 1.9]
Angle: Φ ϵ [50^{o}, 120^{o}]

Microstructures: Analytic homogenization

Lead to homogenized mechanical properties (orthotropic etc)

Can be tailored (graded

Microstructures: Numerical homogenization

Lead to homogenized mechanical properties (orthotropic etc)
Can be tailored (graded materials, better than classical composites, suitable for AM)
In dynamics: band gap properties

Lead to mechanical metamaterials

Open questions: defects during construction, a lot of investigation related to 'missing ribs' etc
Technology limitations

Microstructures: Functionally graded

Lead to homogenized mechanical properties (orthotropic etc)
Can be tailored (graded materials, better than classical composites, suitable for AM)
In dynamics: band gap properties

Lead to mechanical metamaterials

Open questions: defects during construction, a lot of investigation related to 'missing ribs' etc
Technology limitations

Microstructures: Missing ribs etc

Lead to homogenized mechanical properties (orthotropic etc)
Can be tailored (graded materials, better than classical composites, suitable for AM)
In dynamics: band gap properties

Lead to mechanical metamaterials

Open questions: defects during construction, a lot of investigation related to 'missing ribs' etc
Technology limitations

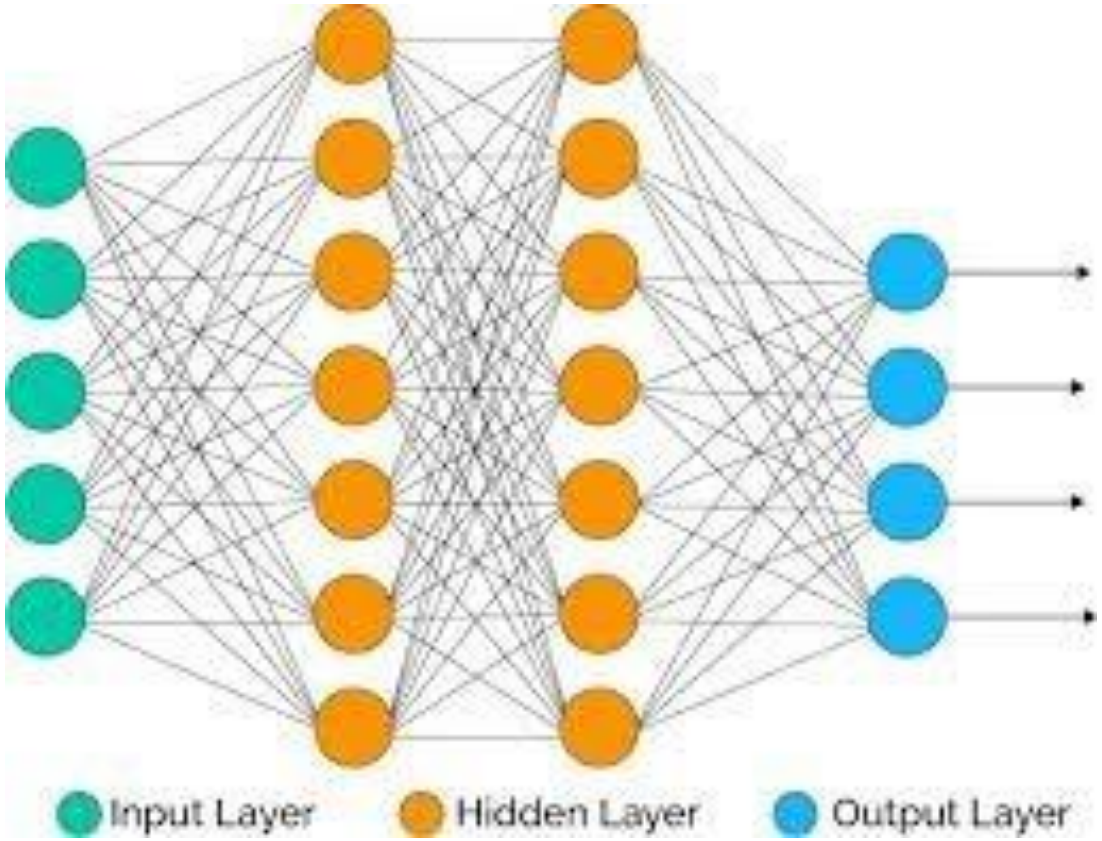
Models vs Data

- Models have concrete mathematical structure
- Models allow for classical approximation
- Data are uncorrelated quantities
- Data require processing and possibly extraction of knowledge
- Hybrid scheme: integrate within a model data
- Example: material relations in Finite Elements

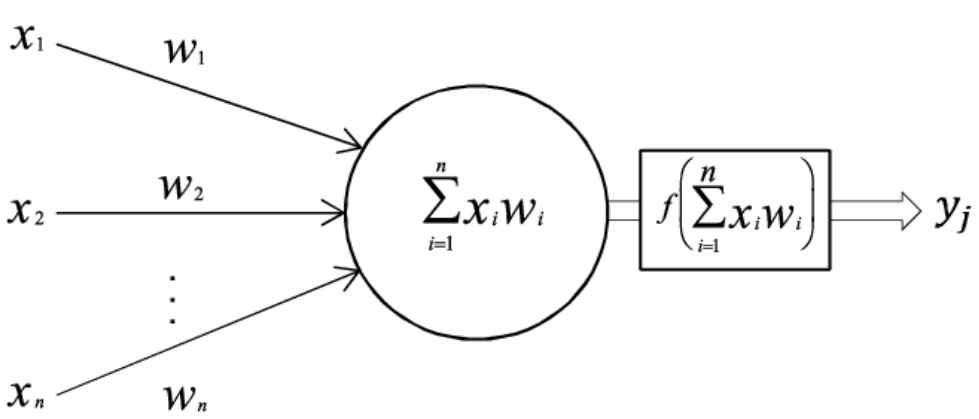
Neural networks, Deep Learning, Artificial Intelligence, Big Data Analytics

- Model-free estimators
- Exploitation of big data, from experiments or numerical simulation
- Suitable for: direct analysis (replacement of material constitutive law), inverse analysis (structural health monitoring)
- Next step: Digital Twin

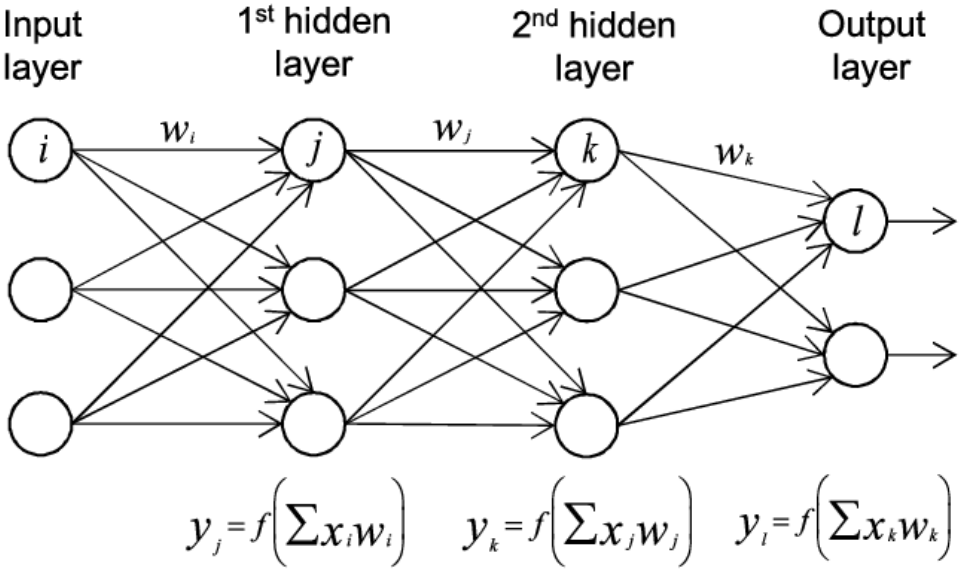
Backpropagation NN



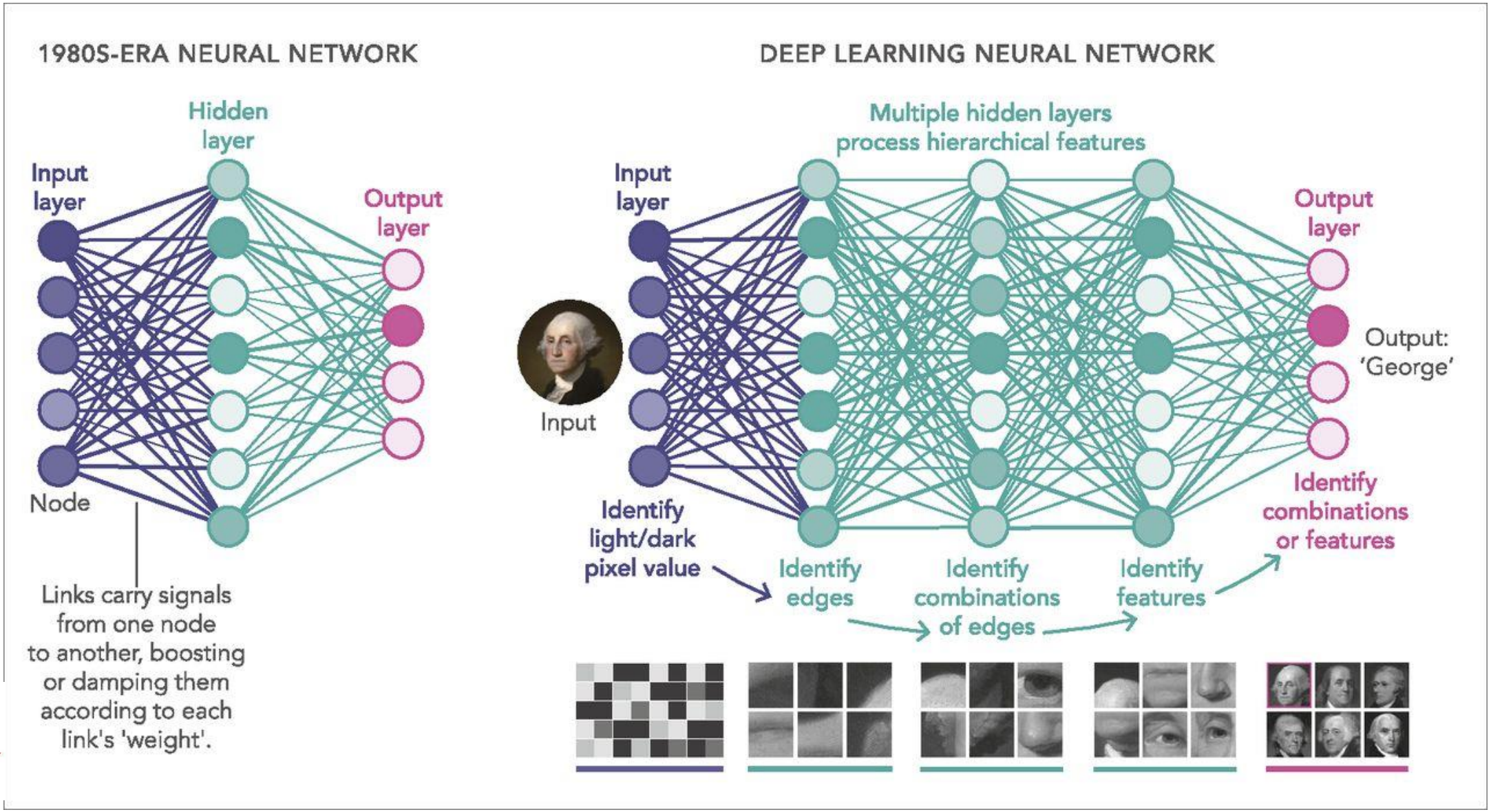
(a)



(b)



Deep Learning



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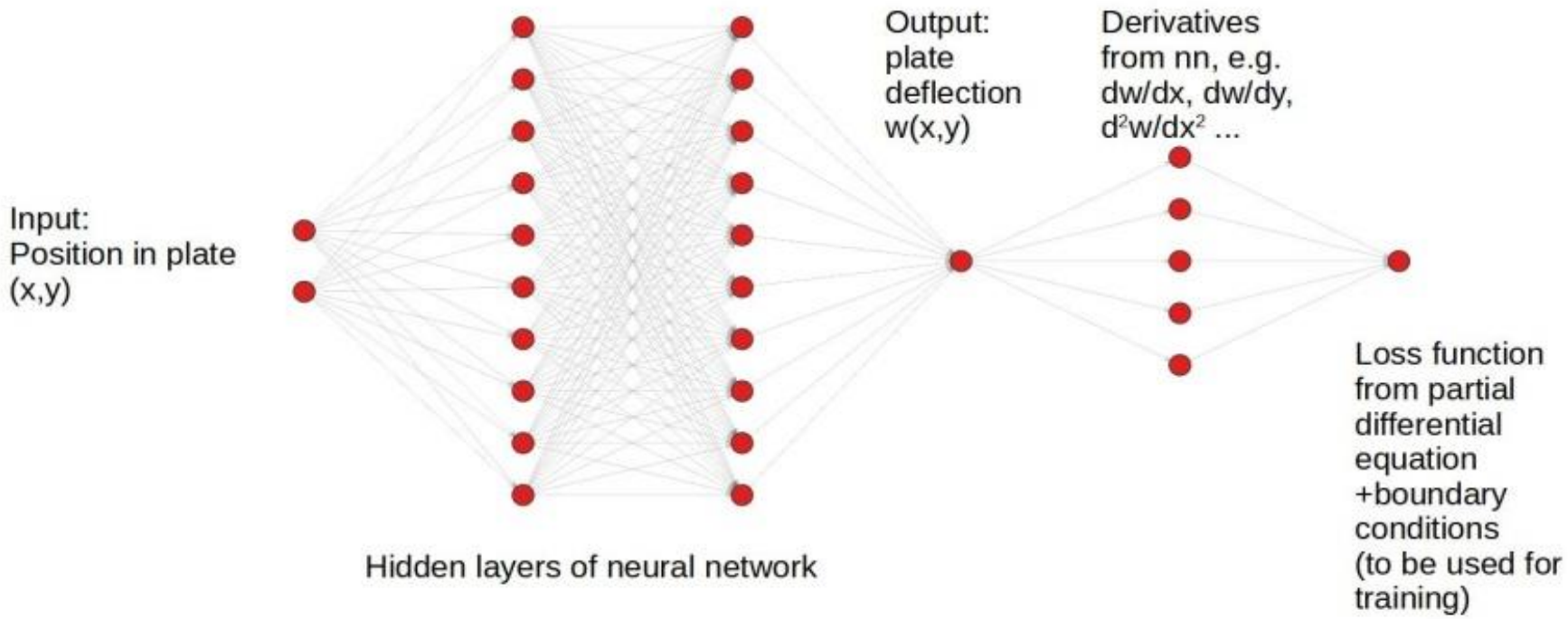
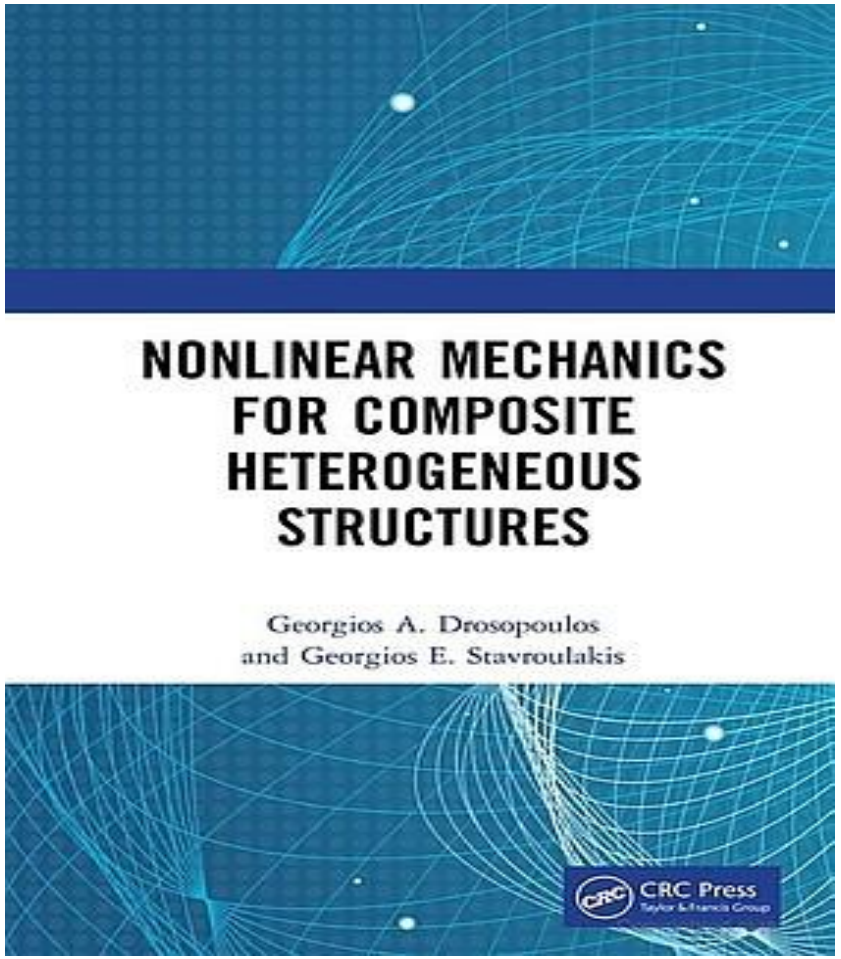
Neural network architecture

The artificial neural network architecture, used in this work is illustrated below.



Our recent book



MATLAB codes for 2-D examples (homogenization, neural network integration, XFEM, data-driven)

PYTHON version in preparation

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Thank you very much for your attention!

Computational Mechanics and Optimization Laboratory

Email: gestavroulakis@tuc.gr

Web: http://www.comeco.gr

For more information you can visit the website

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