Proprietà Meccaniche dei Materiali Bioispirati

Federico Bosia

Dipartimento di Fisica, Università di Torino

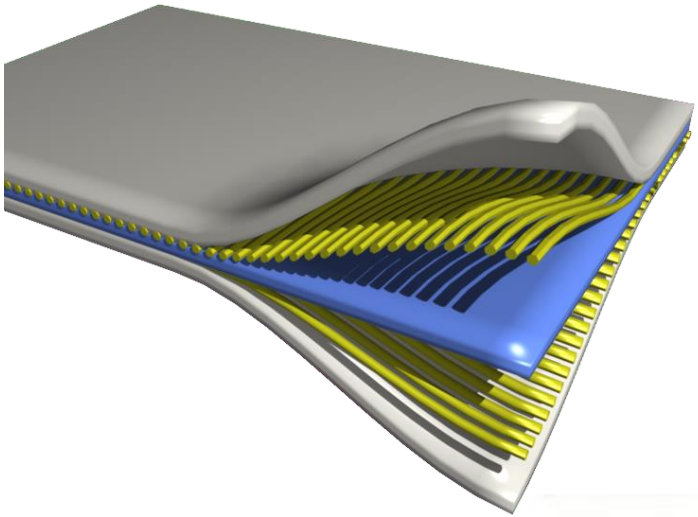
federico.bosia@unito.it

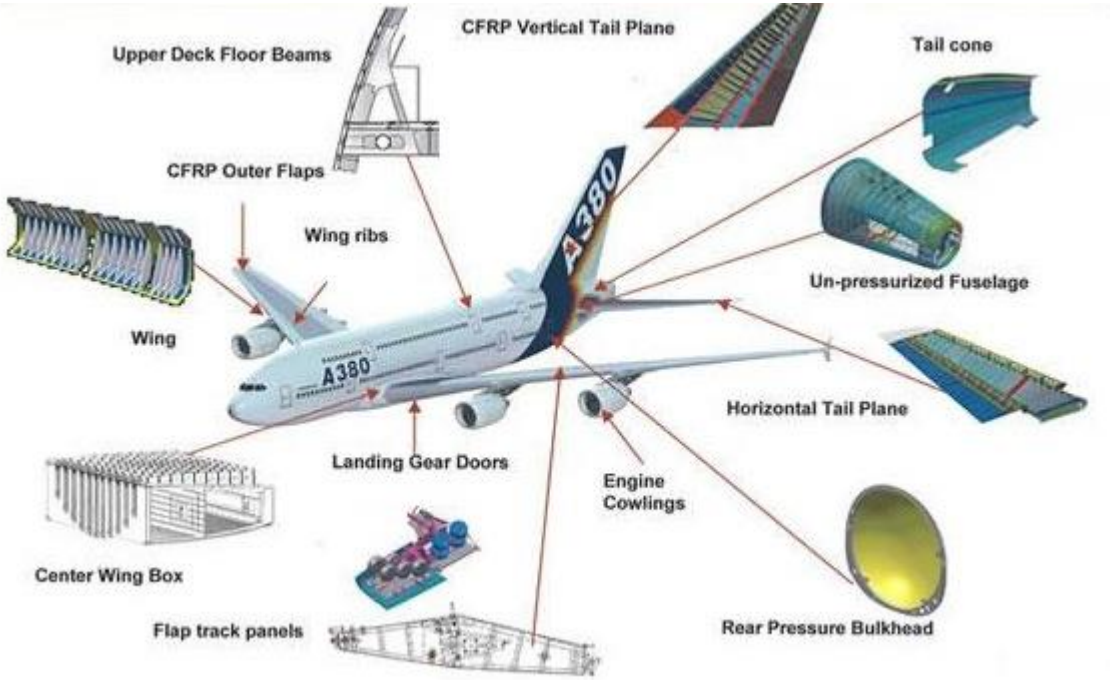
Outline

- **Biological structural materials vs. Composite materials**
- **Bioinspiration**
  - ✓ **Adhesion**
  - ✓ **Strength/toughness**
  - ✓ **Friction**
  - ✓ **Waves and Vibrations: metamaterials**

  - ✓ **Tesi**

Composite materials

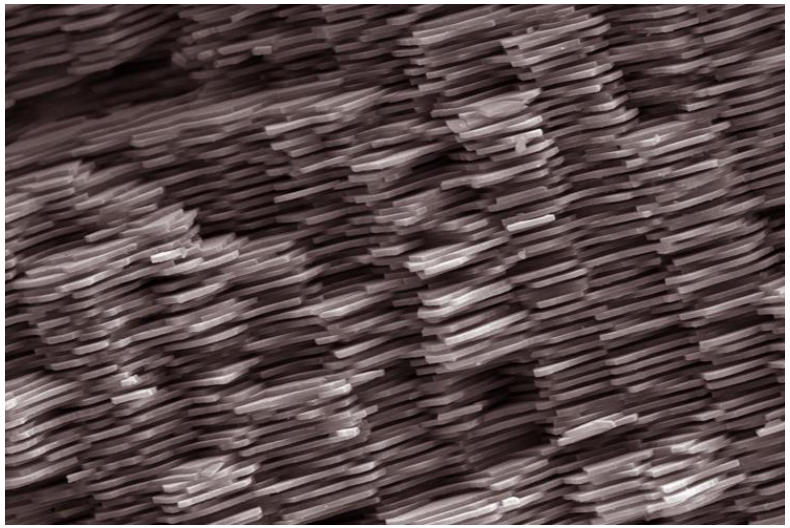




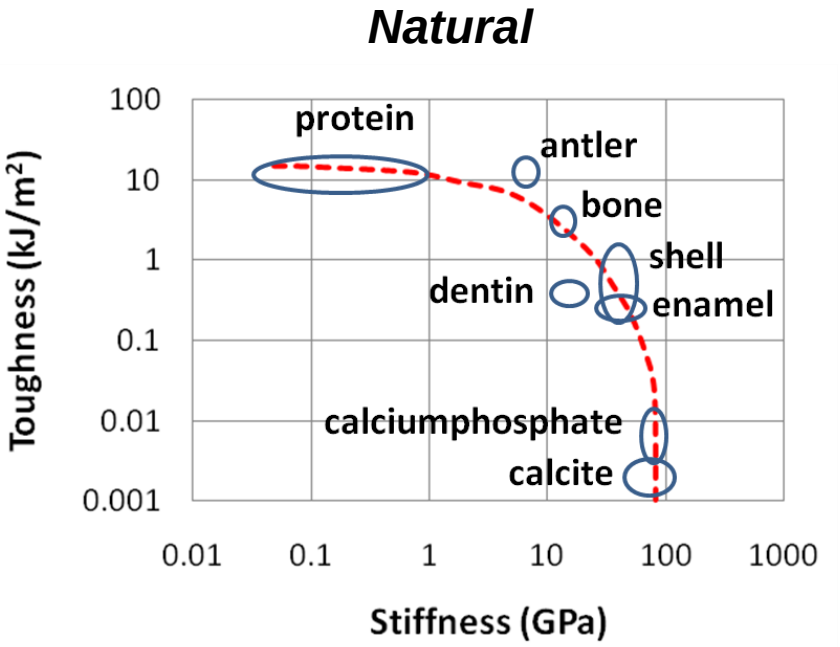
Composite materials

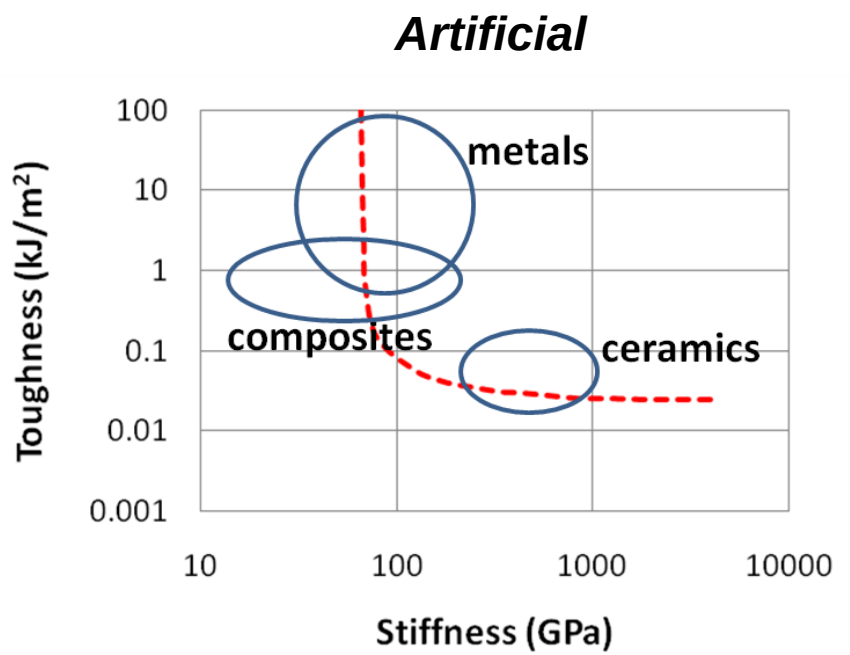
room for improvement…

Biological composite materials



Optimization of mechanical properties



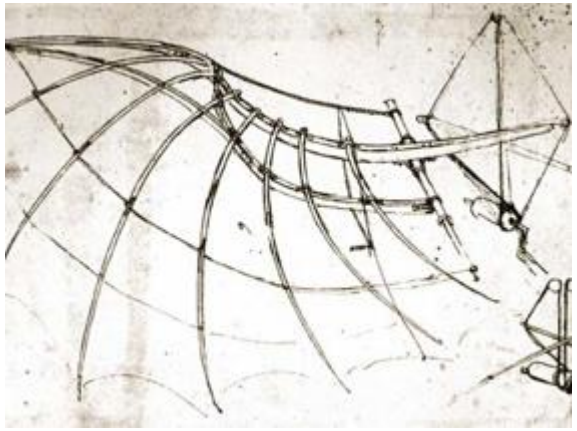


[Buehler, **Int. J. Appl. Mech.** 1 (2009)]

- **Strength/Stiffness vs. toughness**
- **Strength/stiffness vs. density**
- **Adhesion/antiadhesion**
- **Hydrophily/hydrophobility**
- **…**

Bioinspiration & biomimicry

Biological structures are a constant source of inspiration for solving a variety of technical challenges in **architecture**, **aerodynamics**, **mechanical engineering**, **materials science…**



Wing design by Leonardo da Vinci

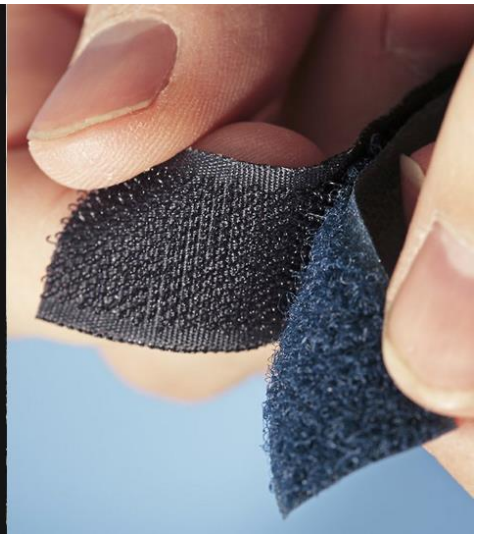
Bioinspired vs. biomimetic

“A methodology in which biological systems (processes and elements) are studied to draw analogies to be applied to human design and industrial challenges”

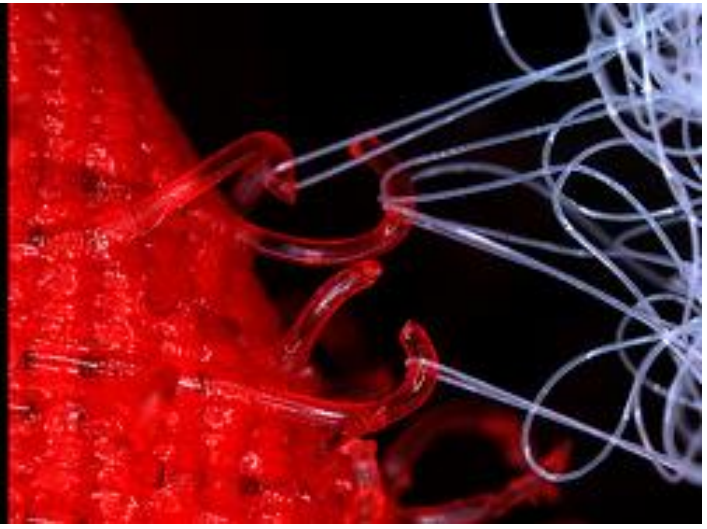
Bioinspiration & biomimicry

Materials

Arctium L.

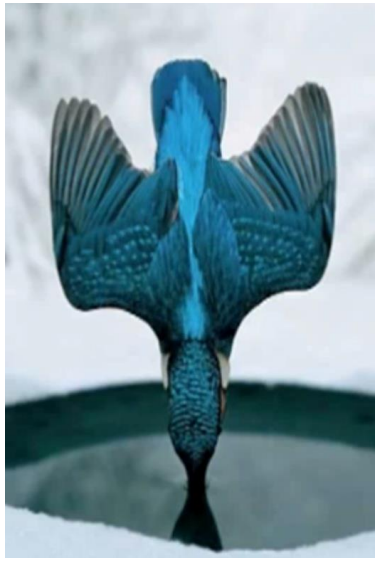


Velcro



Bioinspiration & biomimicry

Transport



Kingfisher

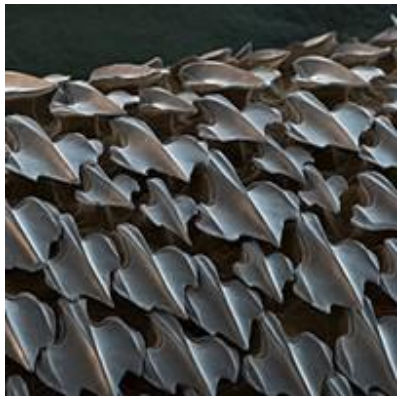
Shinkkansen bullet Train
(West Japan Railway Company)

Box fish

Mercedes Bionic car

Bioinspiration & biomimicry

Sport and leisure



Shark skin

Speedo Body swimsuit

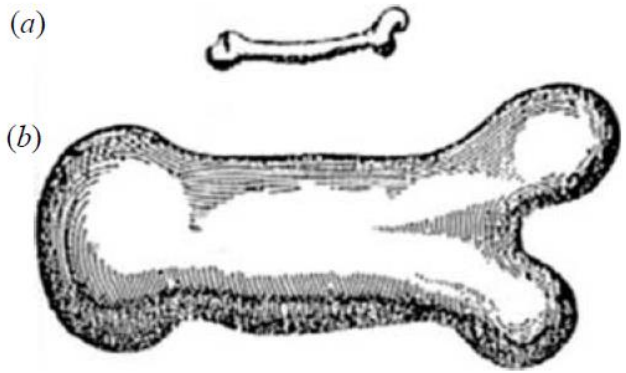
Bioinspiration: how?

"*If bone is the answer, what is the question?*" Rik Huiskes

e.g. which mechanical property(ies) has been optimized?

→ understand the structure–function relationship

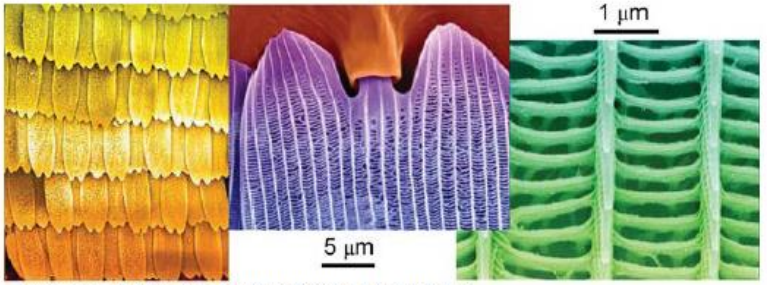
(+ multifunctionality)



Galileo's description of bones from (a) small and (b) large animals

Bioinspiration

✓ Complex constitutive behaviour emerges from simple components (e.g. Hierarchy)



J. Genzer, A.Marmur, MRS Bulletin 33 (2008) 742.

✓ Metamaterials

✓ Structure → Function

✓ Adhesion/friction

✓ Strength/low density

✓Damping

Adhesion

➢**The most adhesive: the Tokay Gecko**

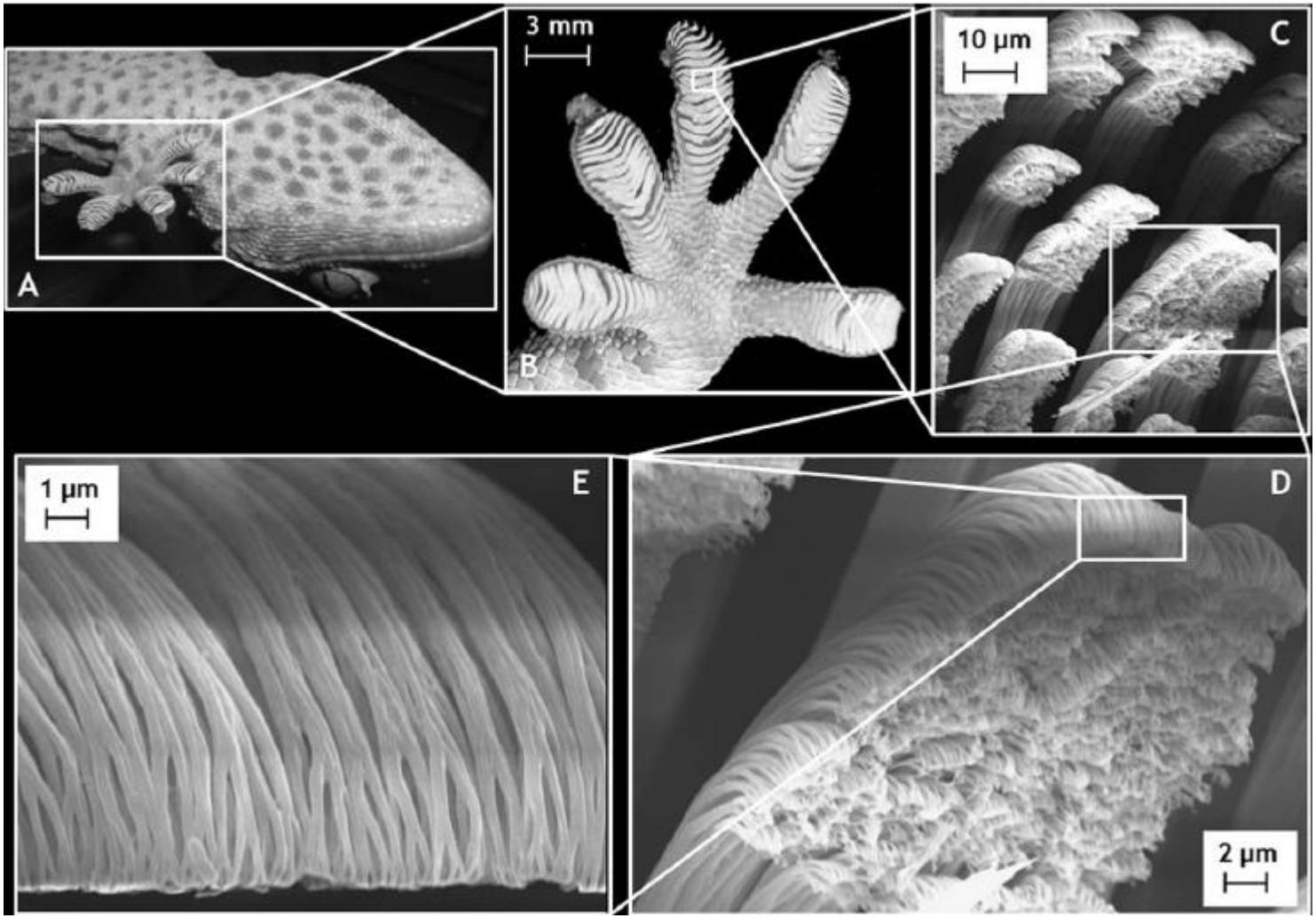
Adhesion due to van der Waals and capillary forces;

Adhesion strength of about 1 MPa, i.e. 10 times its body weight

3 requirements:

- Strong adhesion
- Easy detachment
- Self-cleaning mechanisms

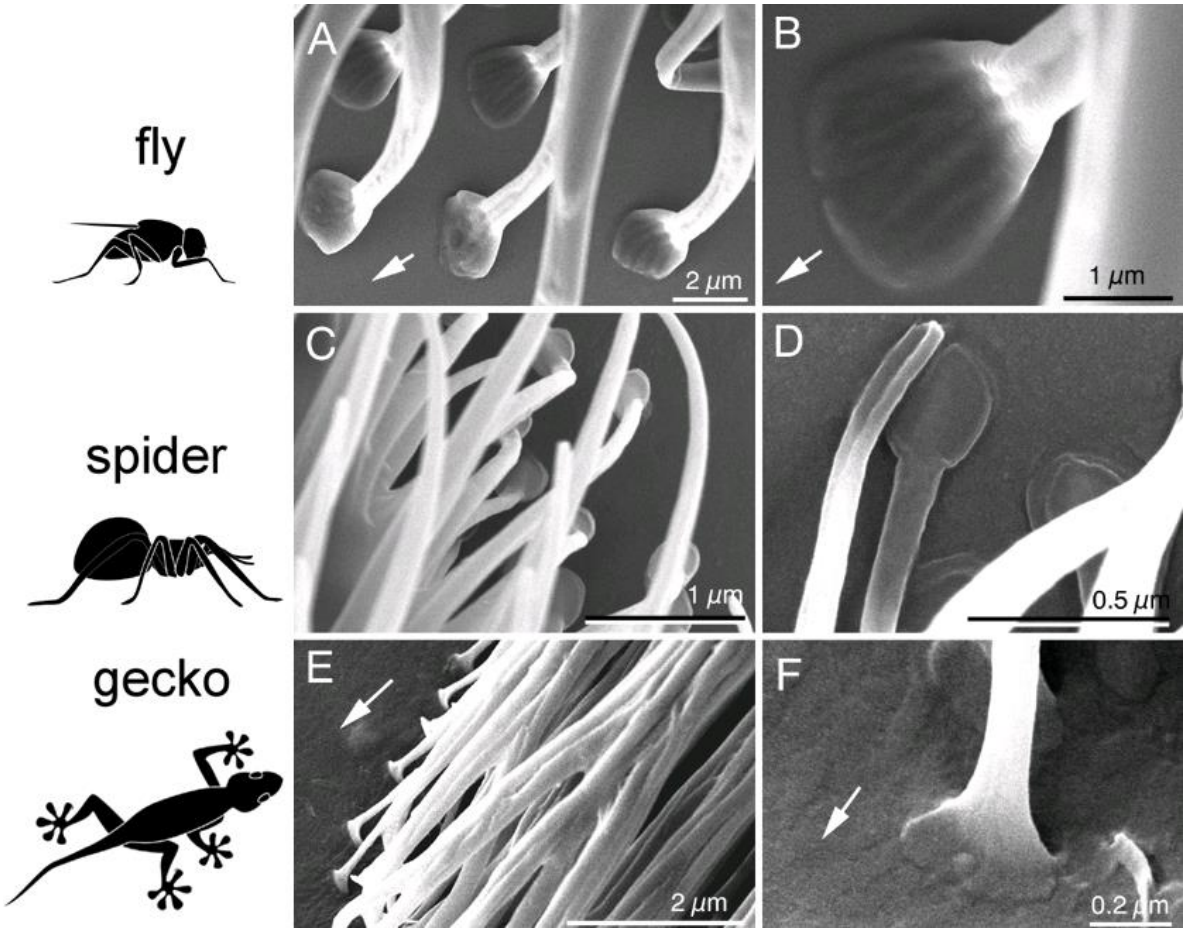
Adhesion

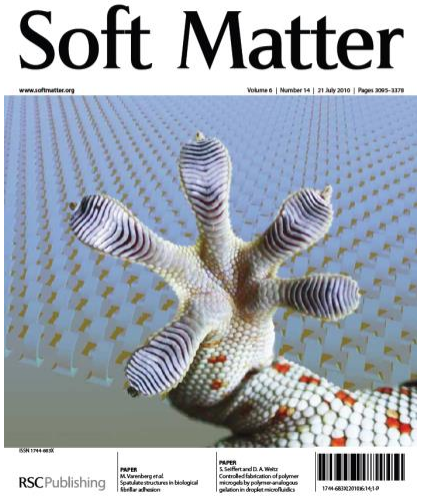


HIERARCHICAL NANO-ARCHITECTURES

E.Lepore, F.Pugno, N.M. Pugno (2011):
The Journal of Adhesion, 88:10, 820-830

Adhesion



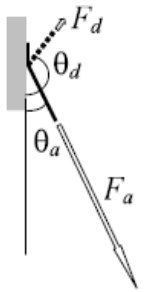


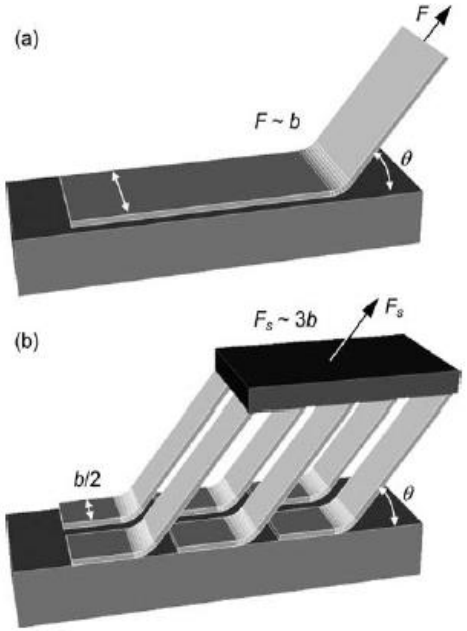
M.Varenberg, N.M.Pugno, S.N.Gorb
Soft Matter, 2010,6, 3269-3272

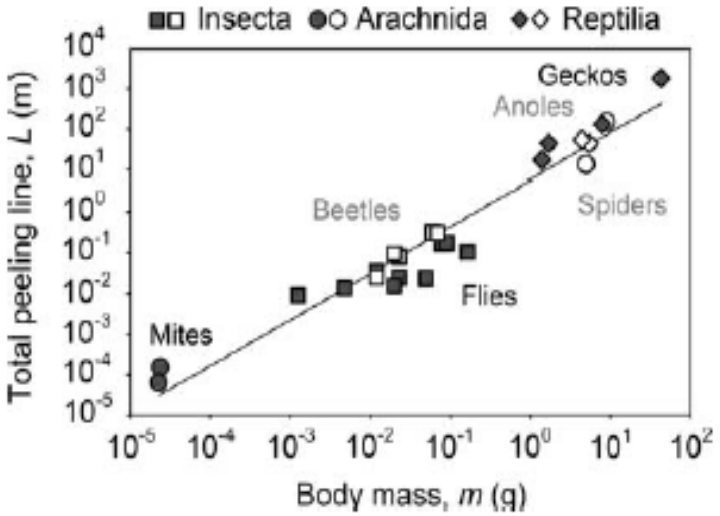
SPATULAE: TERMINAL CONTACT UNITS
Similar tape-like geometries (thus the detachment is due to “peeling”), but of different sizes (3 billions of contacts in geckos)

Optimization of Adhesion

Principle of contact splitting







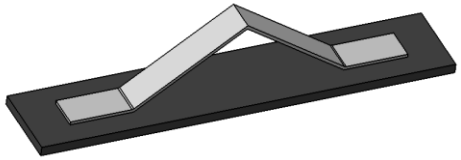
3 "ingredients":

1) Super-adhesion by nanocontacts: $F \propto b$ **(*b* total peeling line)**

2) Easy detachment by controlling the peeling angle: $F \propto 1/(1-\cos\theta)$

3) Self-cleaning → "Lotus effect" (Hierarchical architectures)

Optimization of Adhesion



❖ Multiple peeling

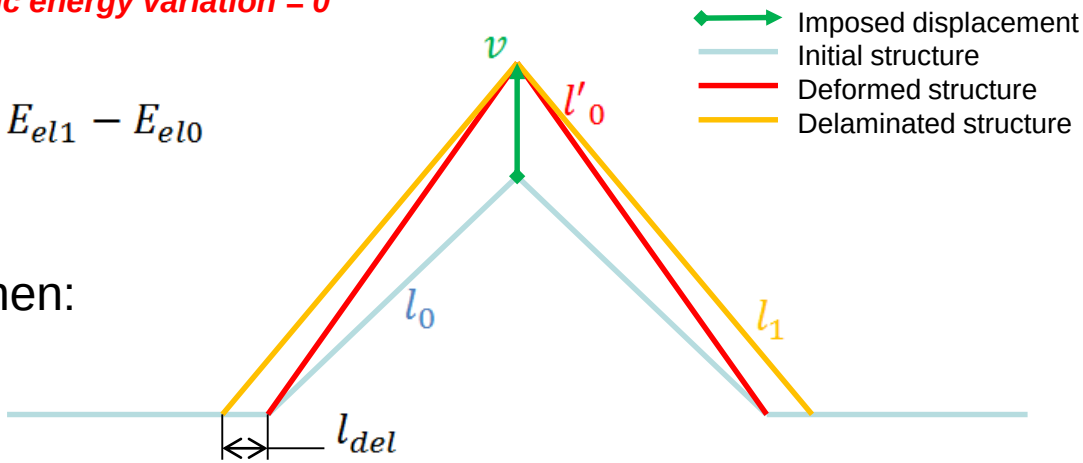
Energetic formulation between deformed & delaminated states:

Surface energy + Work variation + Elastic energy variation = 0

$$E_{el} = \frac{1}{2} Ytb \frac{(l' - l)^2}{l}, \qquad \Delta E = E_{el1} - E_{el0}$$

Delamination takes place when:

$$\Delta E > 2bR$$

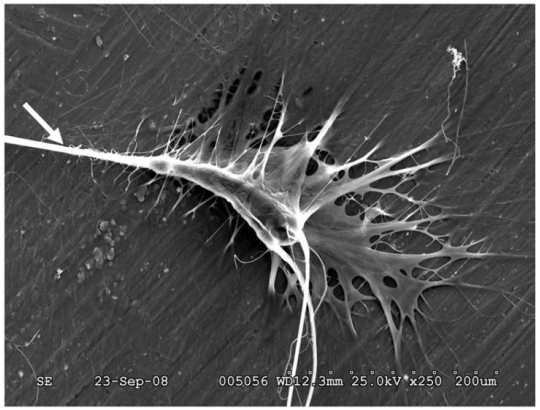


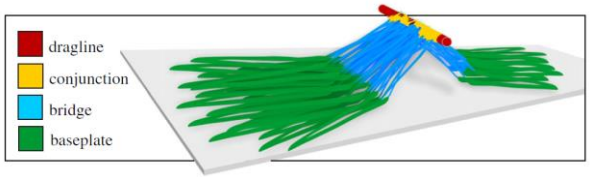
- K. Kendall, J. Phys, (1975), 8

16

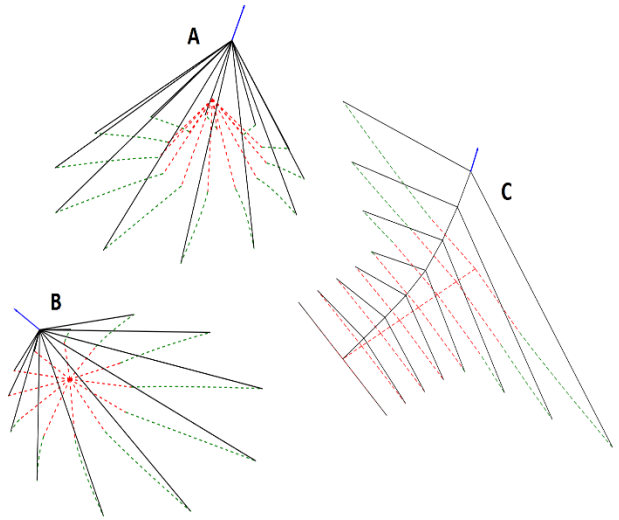
Optimization of Adhesion

THEORY OF MULTIPLE PEELING, TO DESIGN GECKO-INSPIRED ADHESIVES

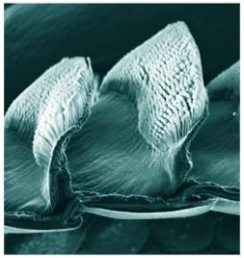


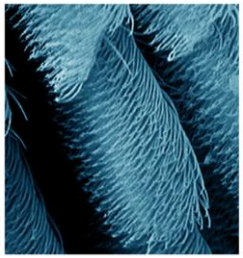


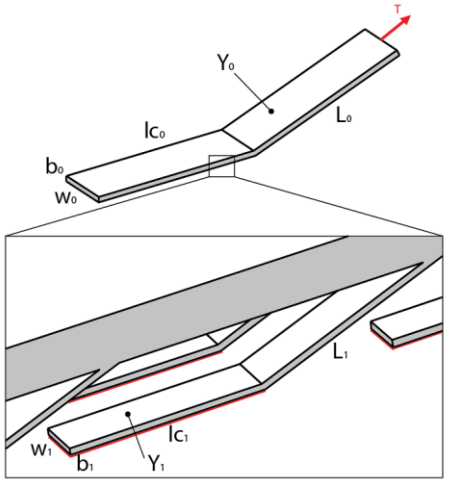
$$T = Ybw\left(\cos\theta - 1 + \sqrt{(1-\cos\theta)^2 + \frac{4\gamma}{Yb}}\right)$$

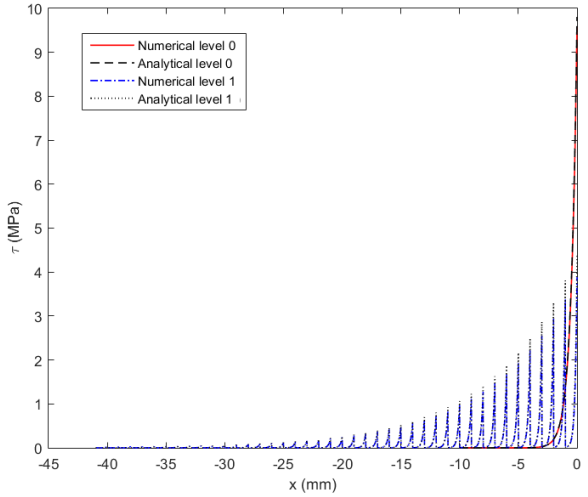


HIERARCHICAL ANCHORAGES









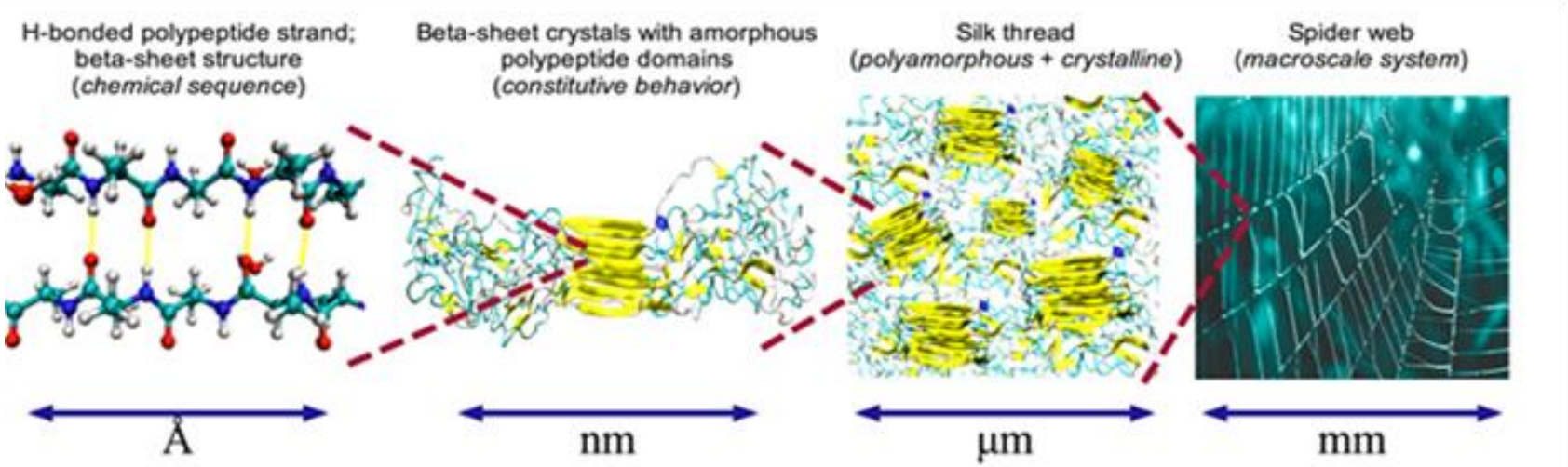
Bioinspired adhesion

Design of “Spiderman suit”:

- **Nano-fibres**
- **Hierarchical design**
- **“Tapered” spatula**

Spider silk

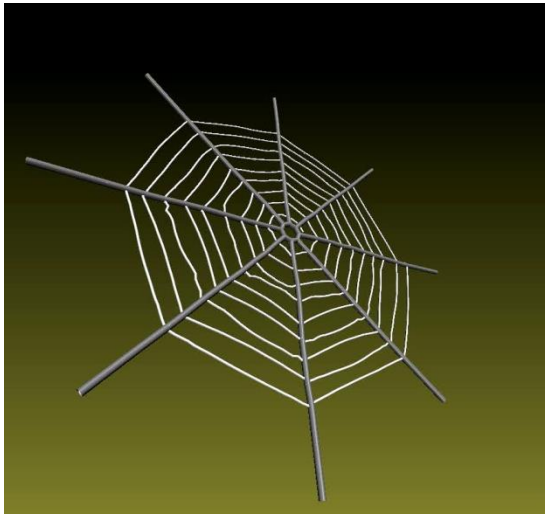
- **Hierarchical structure in spider silk** **STRENGTH ≈1 GPa, STRAIN >750%**

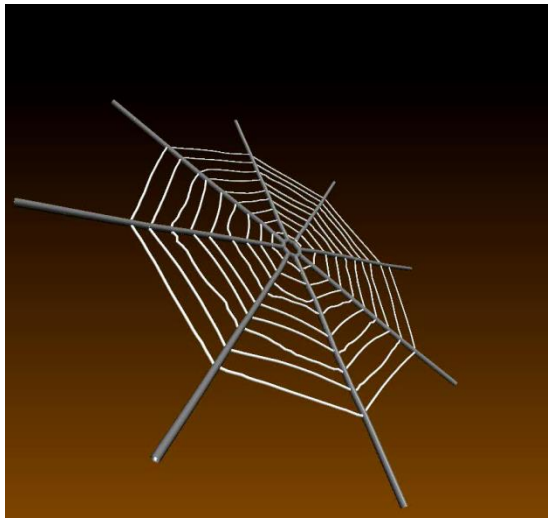


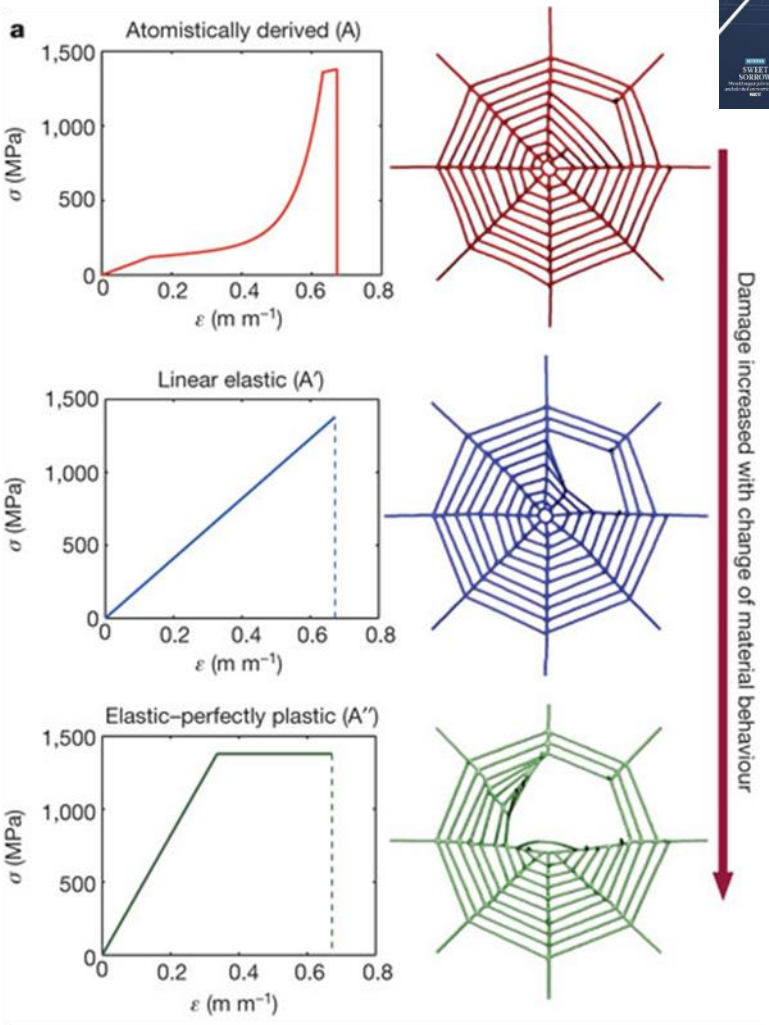
A.Nova, S.Keten, N.M.Pugno, A.Redaelli and M.J. Buehler, **Nanoletters** 10, 2626–2634 (2010)

Spider webs

LOCALIZED LOAD



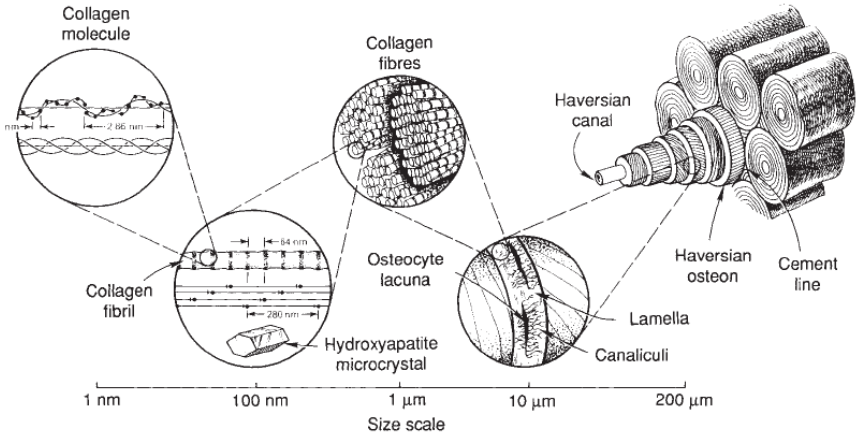




S.W.Cranford, A.Tarakanova, N.M.Pugno, and M.J. Buehler, **Nature** 482, 72–76 (2012)

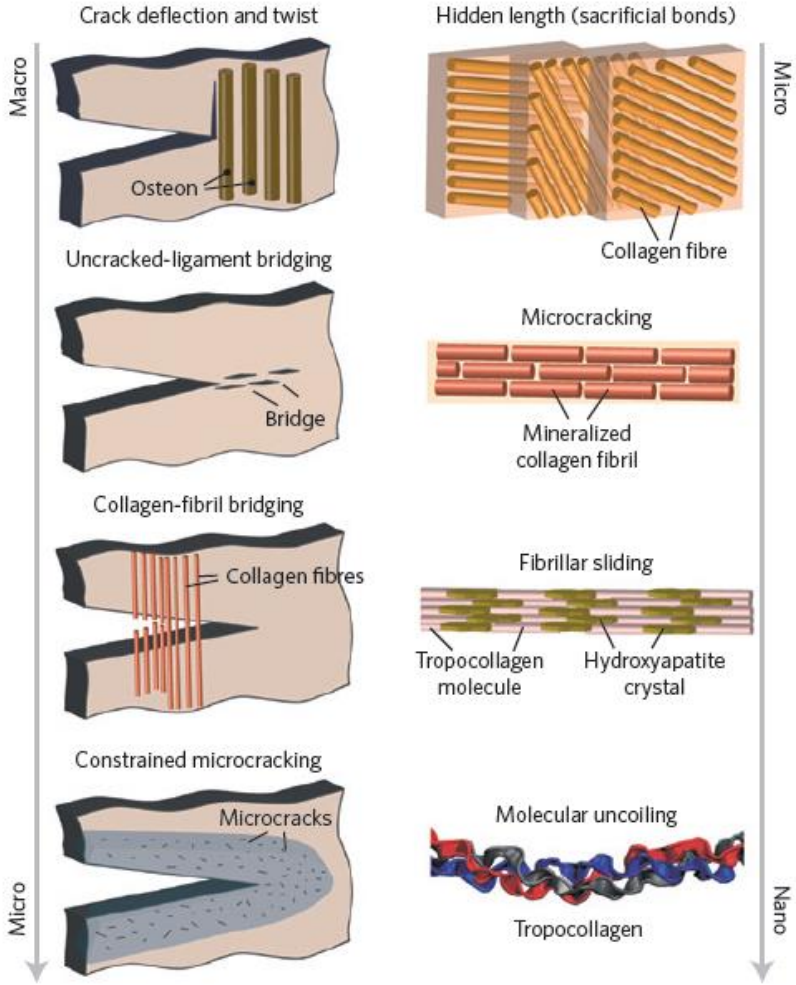
Bone

- **Hierarchical structure in human compact bone**



Lakes (1993): **Nature**, 361, 511

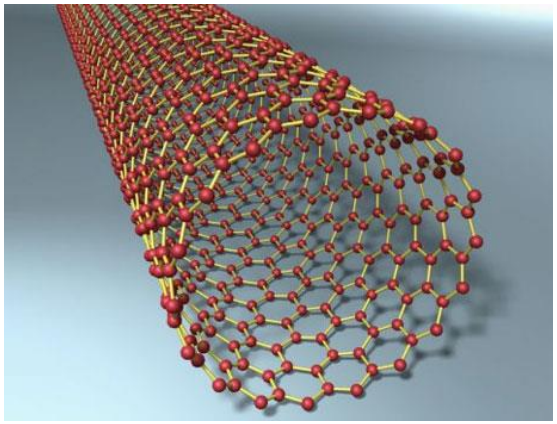
- **Multiphase**
- **Multiscale**
- **Hierarchical**
- **Fibre-based**
- **Self-healing**



Ritchie, **Nat. Mat.** 10, 820 (2011)

Carbon nanomaterials

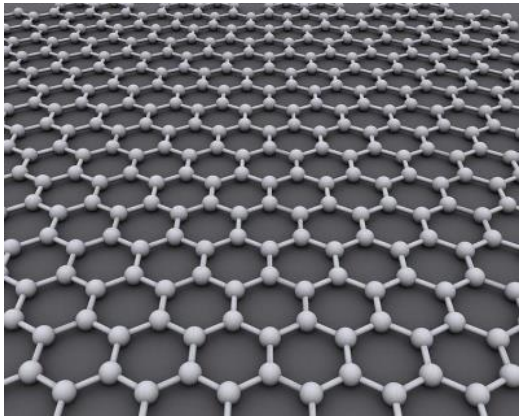
CARBON NANOTUBES (CNT)



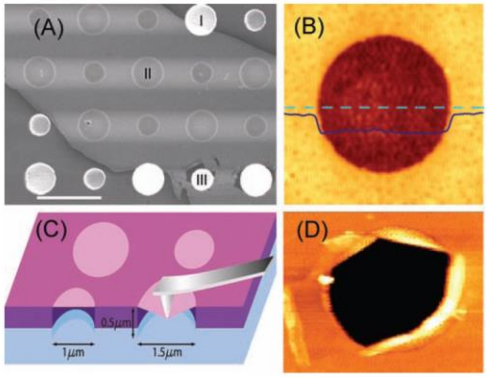
Theoretical strength $\sigma \approx 100$ **GPa**

Measured strength $\sigma \approx 60$ **GPa**

GRAPHENE

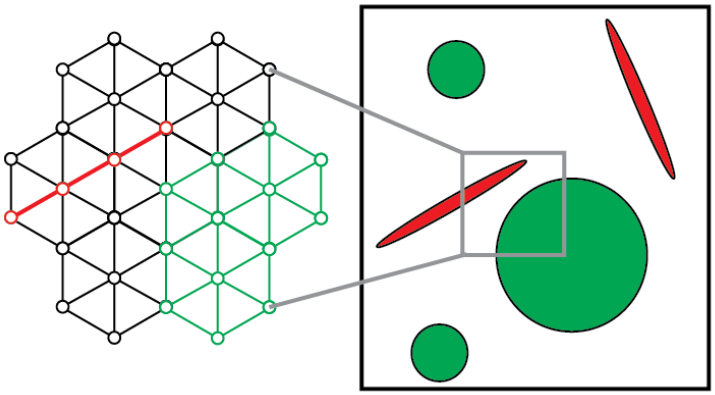


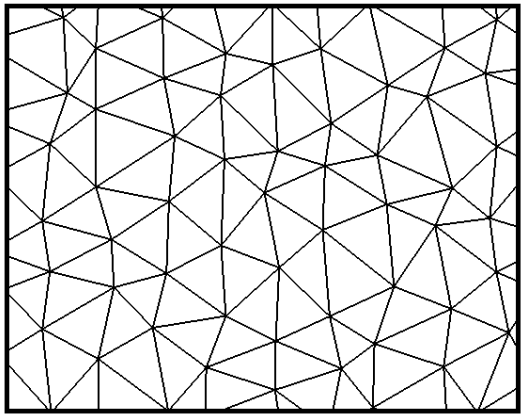
Intrinsic strength: $\sigma = (130 \pm 10)$ GPa

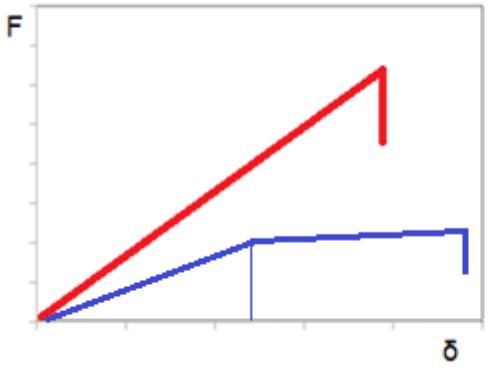


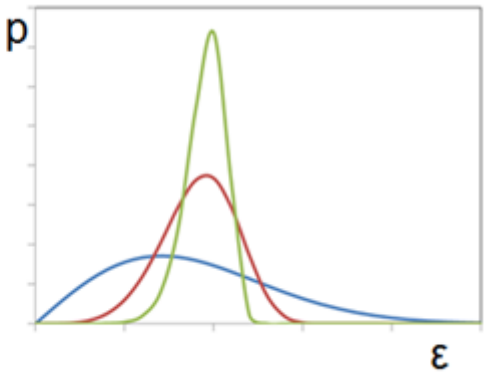
[Lee et al. **Science** 321, 385 (2008)]

Lattice Spring Model







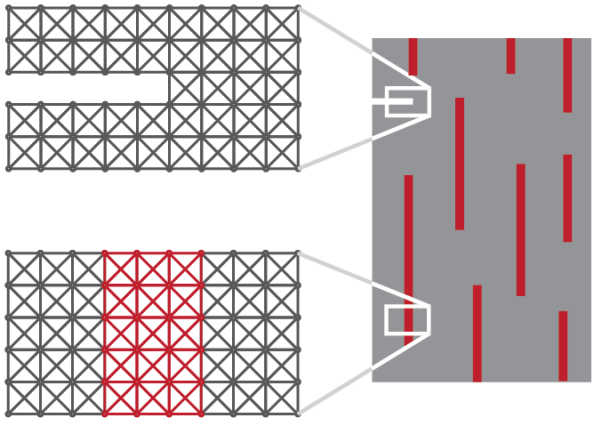


Distributions on maximal bond elongation : Weibull

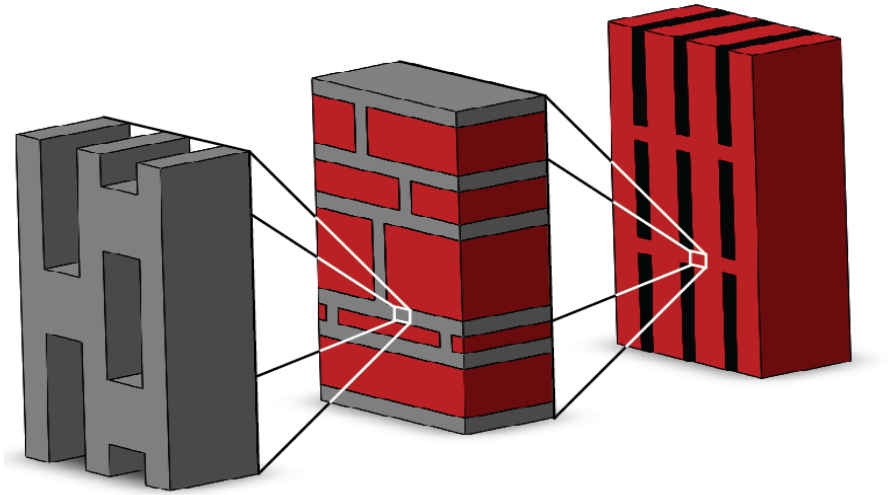
$$f(x;\lambda,k) = \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-(x/\lambda)^k}$$

Hierarchy

- **Influence of defects and reinforcements**
- **Development of crack propagation**
- **Crack shielding and stress concentrations**



Discontinuities



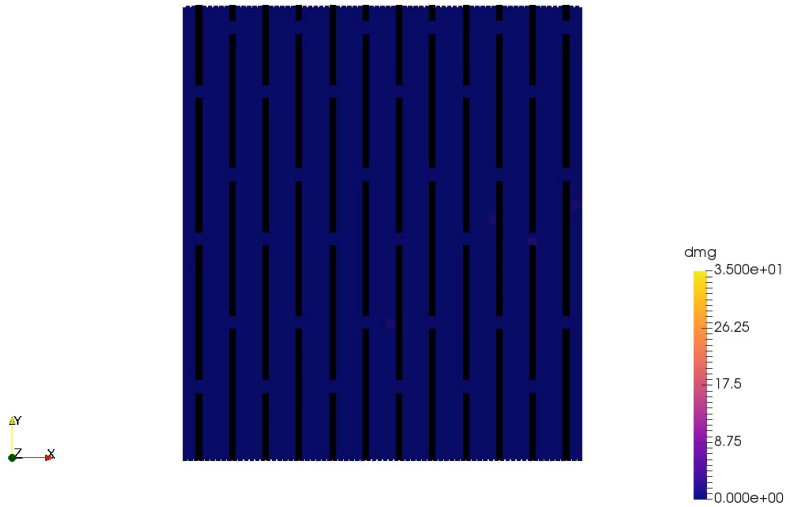
Hierarchy

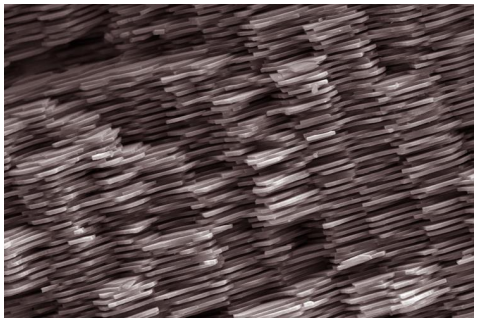
[Brely et al., **Frontiers in Materials**, 2:51 (2015)]

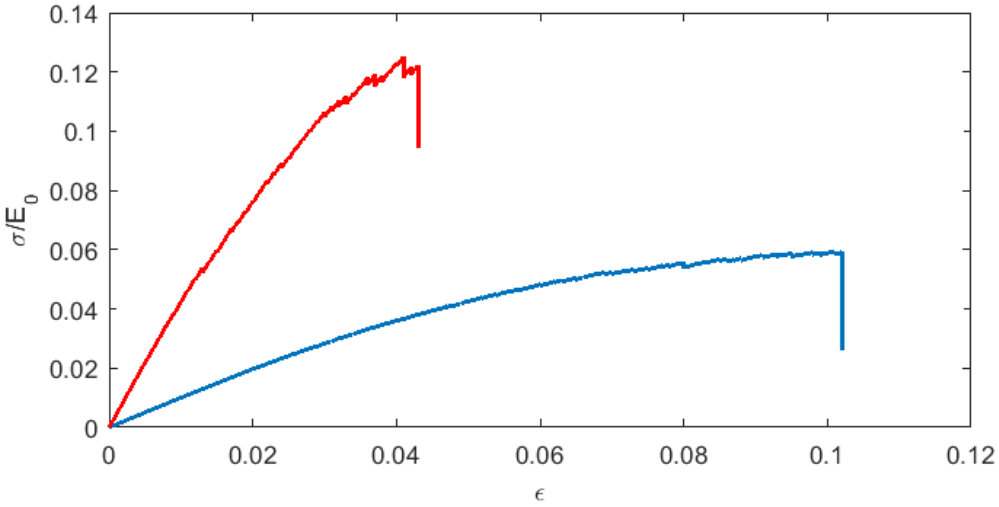
Simulations

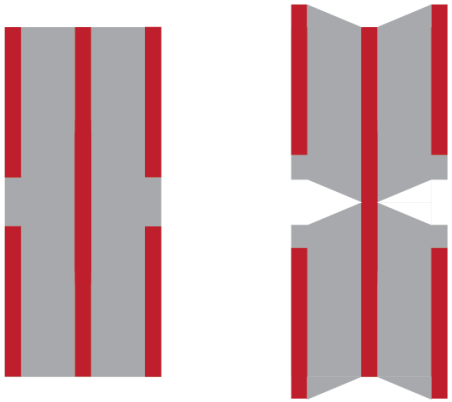
25

Simulations





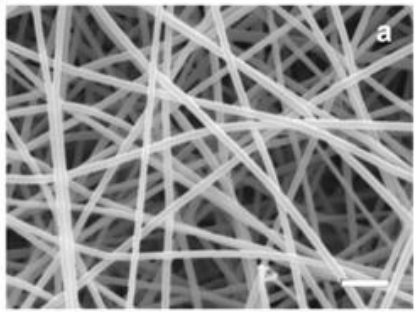


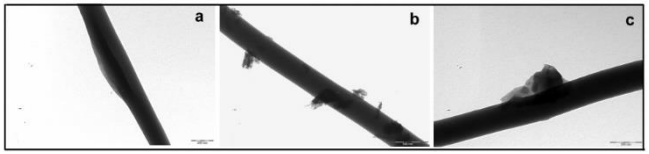


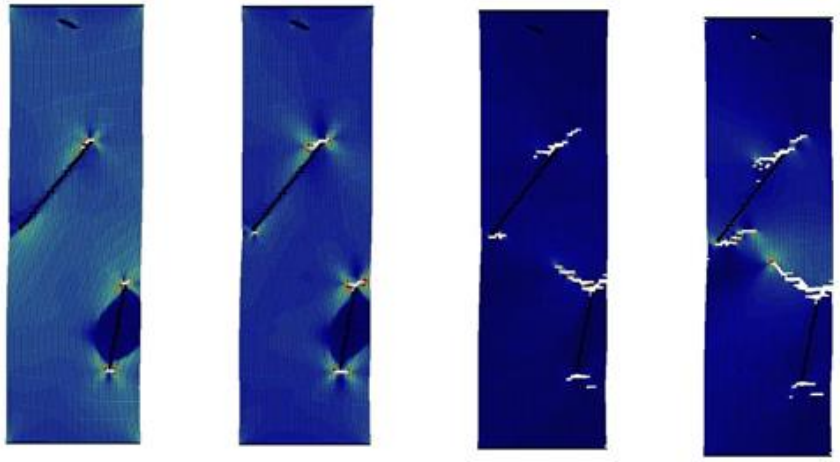
26

Simulations on Graphene composites

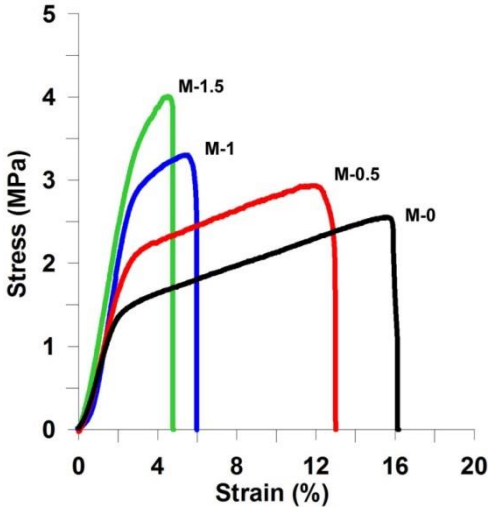
- **GO-gelatin composites (fibre mats and films)**

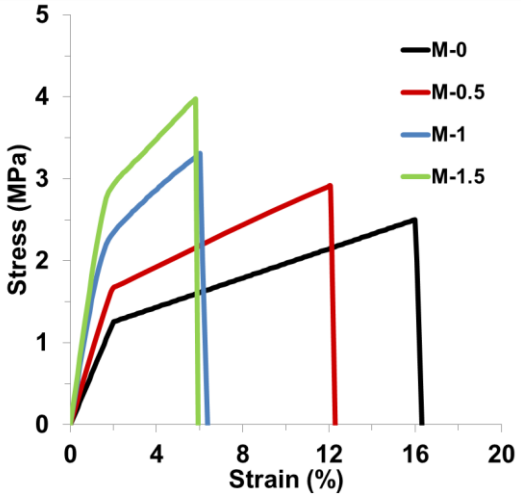






- **Stress-strain behaviour for varying reinforcement content**

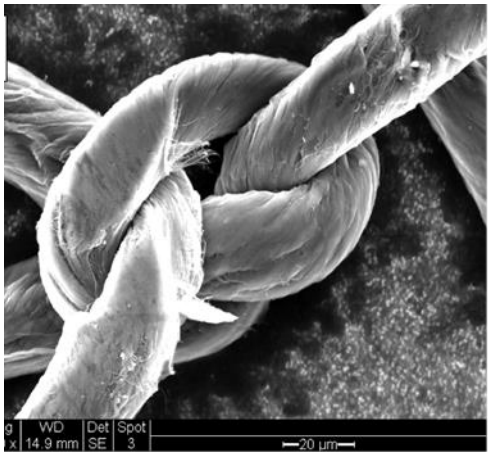


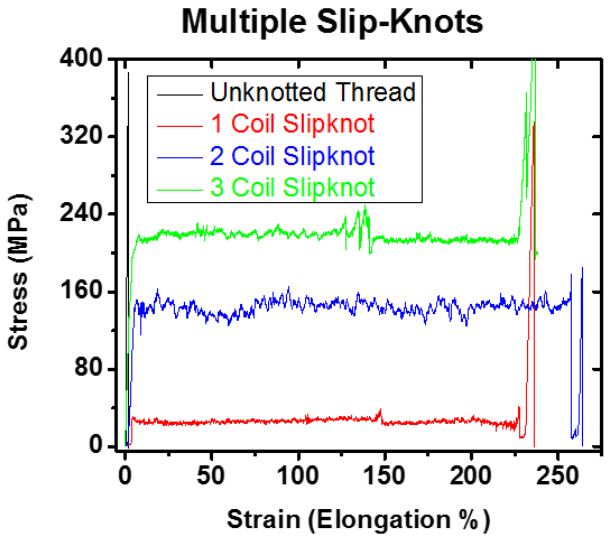


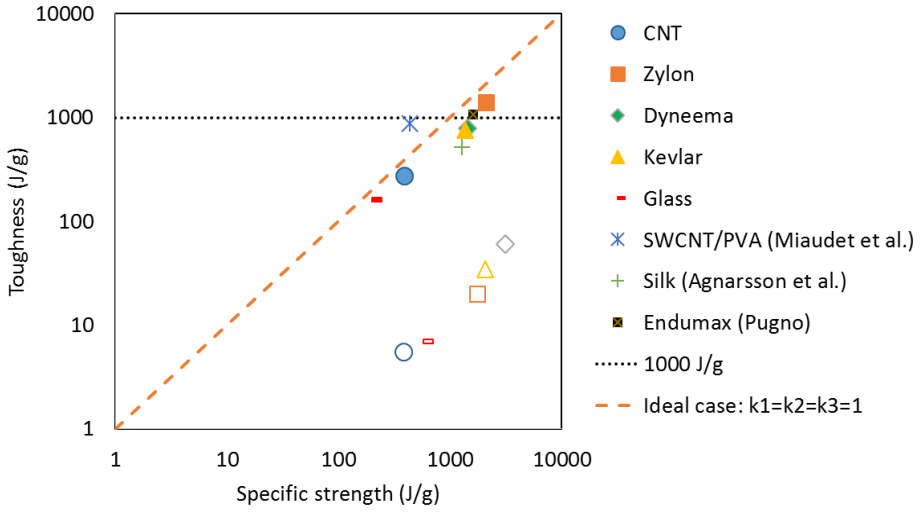
[S. Panzavolta et al., **Carbon,** 78, 566 (2014)]

Strength vs. toughness

- **Synthetic polymeric microfibers and CNT fibres**



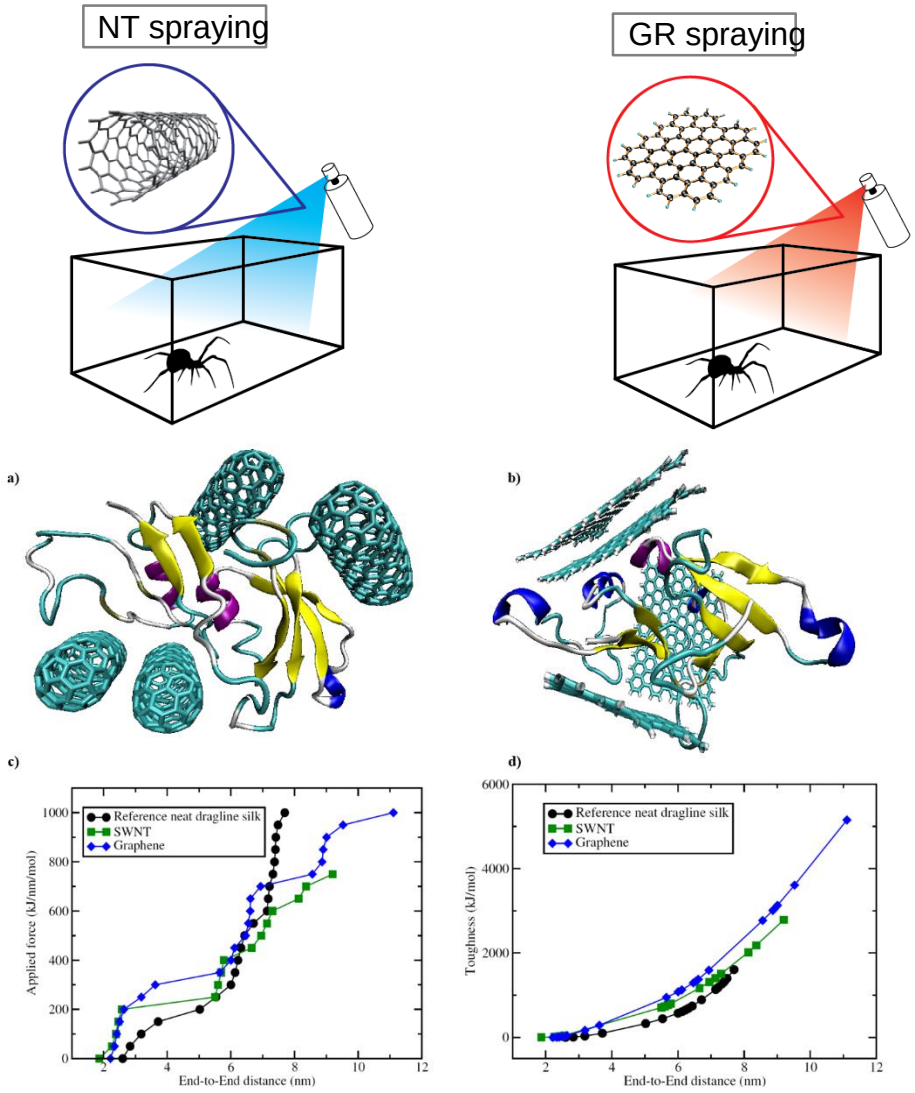


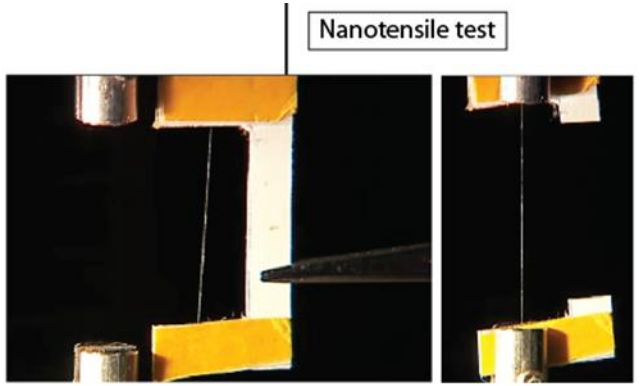


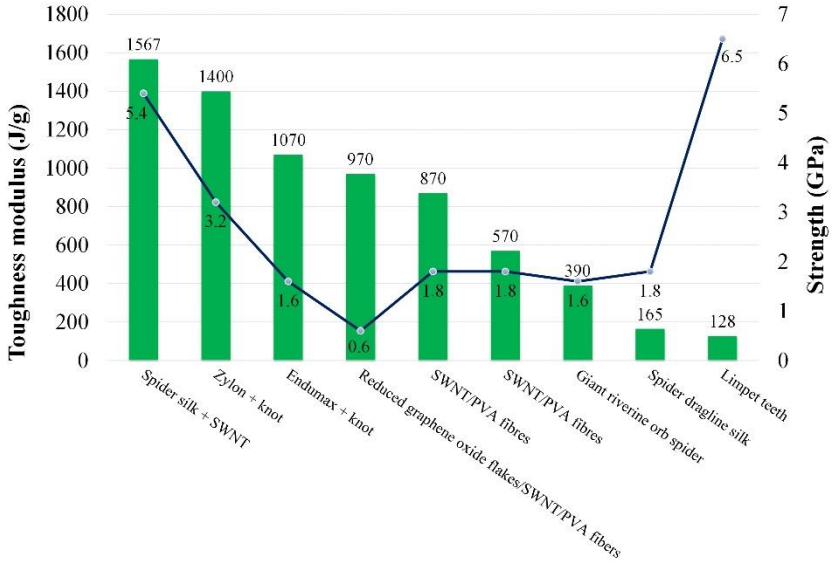
[F.Bosia et al., Carbon. (2015)]

“Bionic” nanocomposites

- **Nano-reinforced spider silk**







[E. Lepore et al., **Arxiv:1504.06751** (2015)]

Self-healing in artificial materials

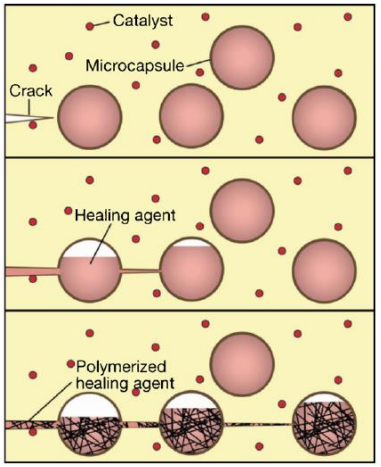
MICROCAPSULE HEALING

(a) damage → crack formation in the matrix;

(b) ruptures of microcapsules, release of liquid healing agent into crack plane;

(c) polymerization upon contact with embedded catalyst

[White et al. **Nature** 409:794–7 (2001)]

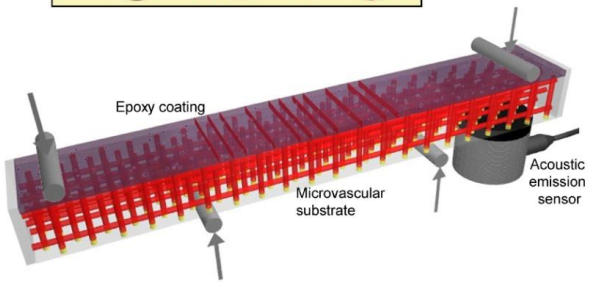


VASCULAR SYSTEMS

- autonomous repair after repeated damage events

- 3-D microvascular networks

[Toohey et al. **Nat.Mat.** 6 : 581 (2007)]



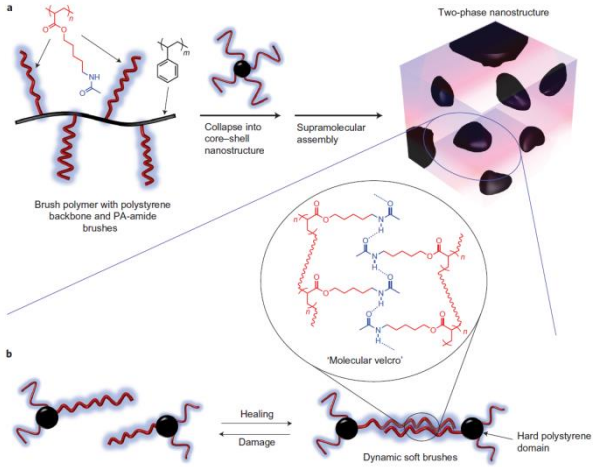
MOLECULAR SYSTEMS

- hydrogen-bonding thermoplastic polymers

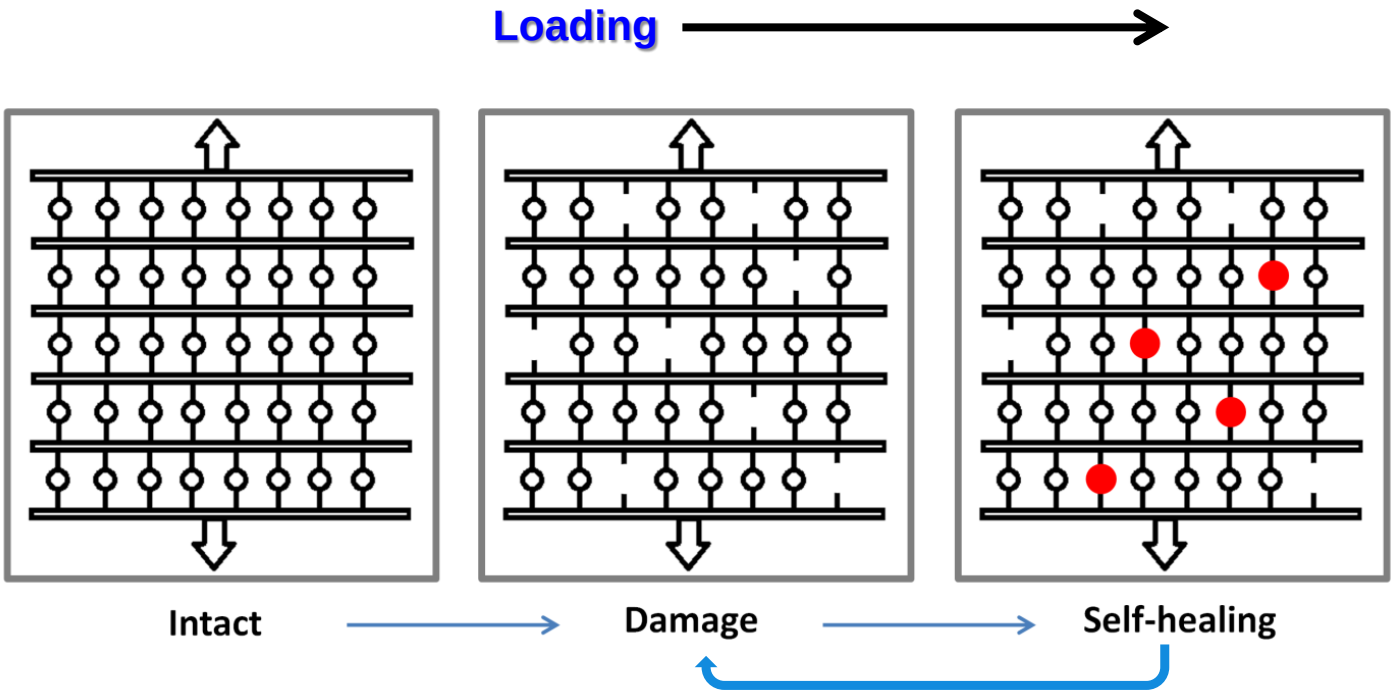
- self-assembled hard–soft microphase-separated system

- spontaneous healing in multiphase supramolecular thermoplastic high-thoughness elastomer

[Chen et al., **Nat. Chem**. 4, 467 (2012)]



Self-healing simulations



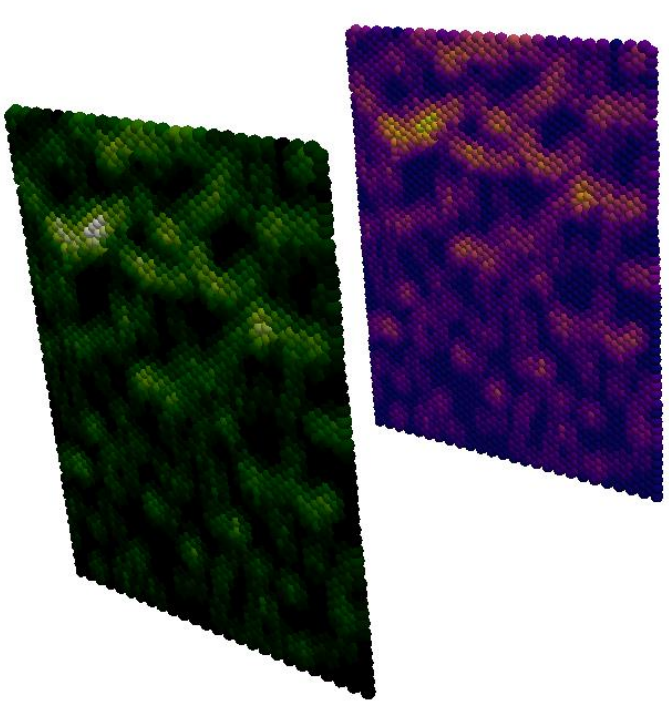
$\eta = \eta(t)$: *ratio between fractured and healed fibres per unit time*

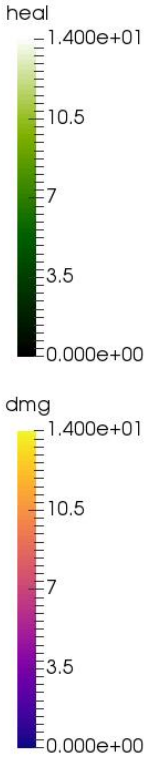
1. **"Distributed healing": replace random fibre at with healing rate η**
2. **"Local healing": replace last fractured fibre with healing rate η**

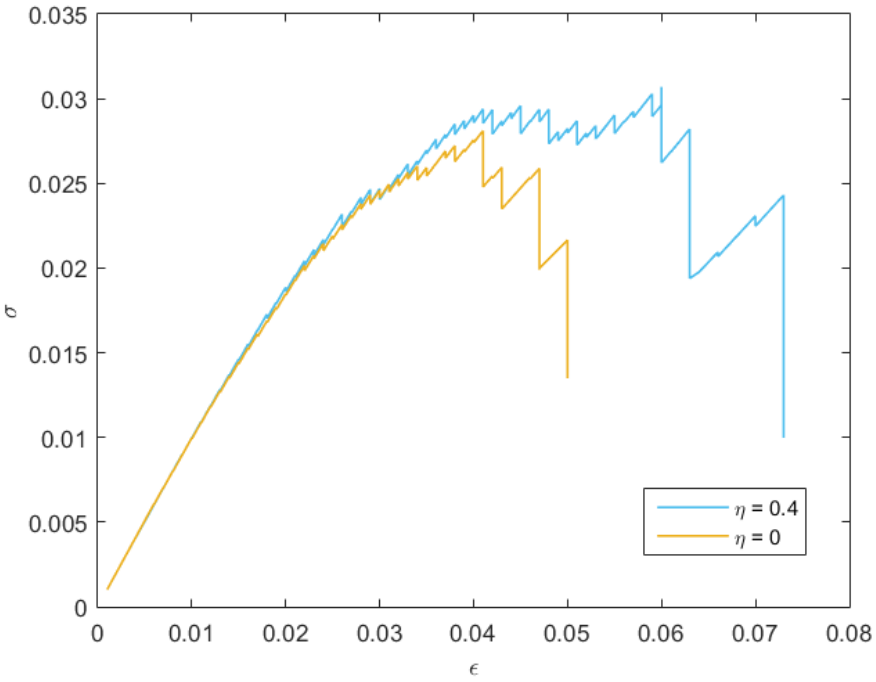
[Bosia et al., **Langmuir** 30, 1123-1133 (2014)]

Self-healing simulations

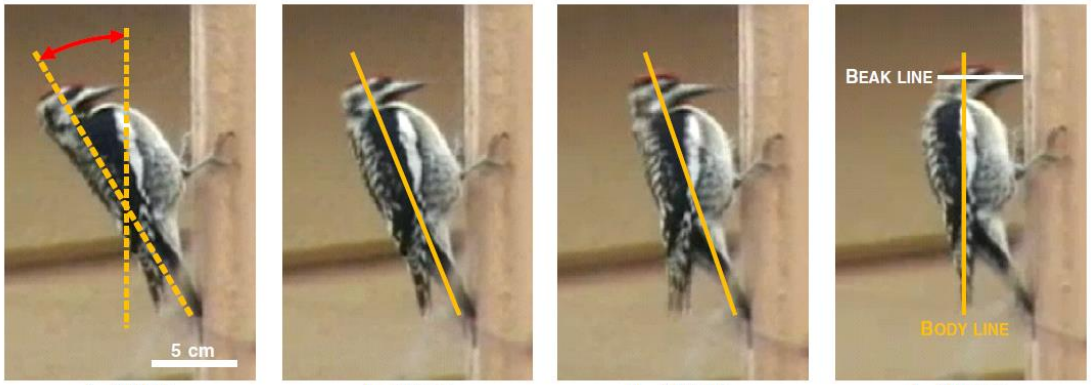
η: SH paramete $\eta = \frac{N_{heal}}{(N_{broken})_{n-p}}$



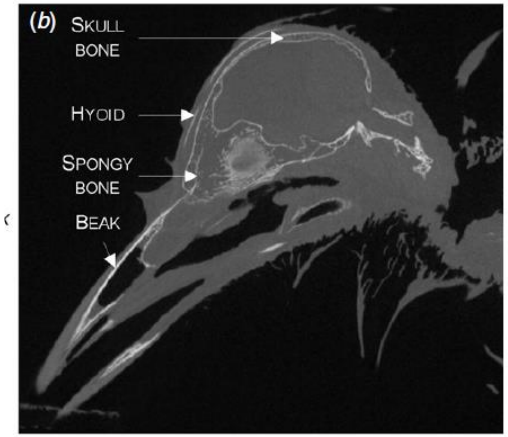


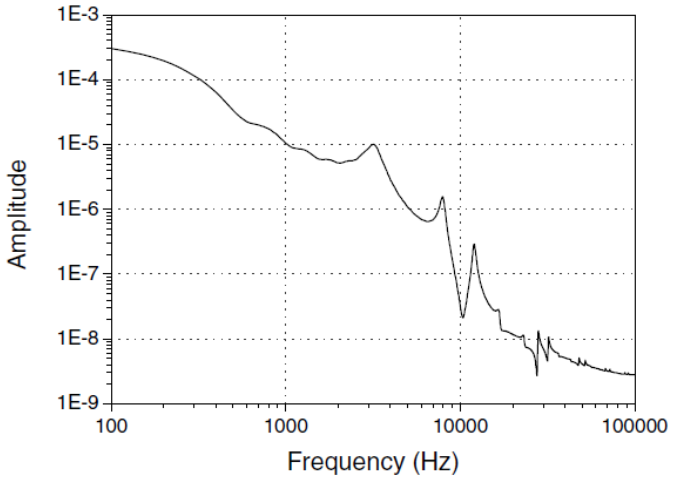


Vibration damping



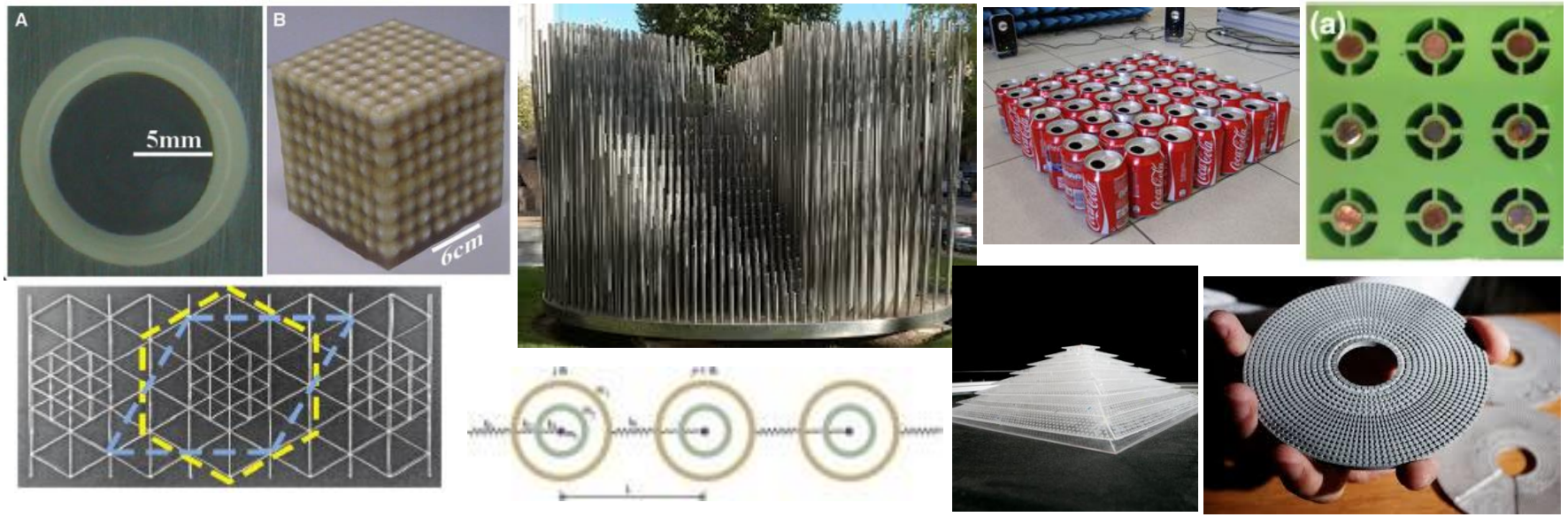
t = 0 msec t = 7 msec t = 13 msec t = 20 msec





Elastic Metamaterials

- **“usual” materials** with **unusual properties**

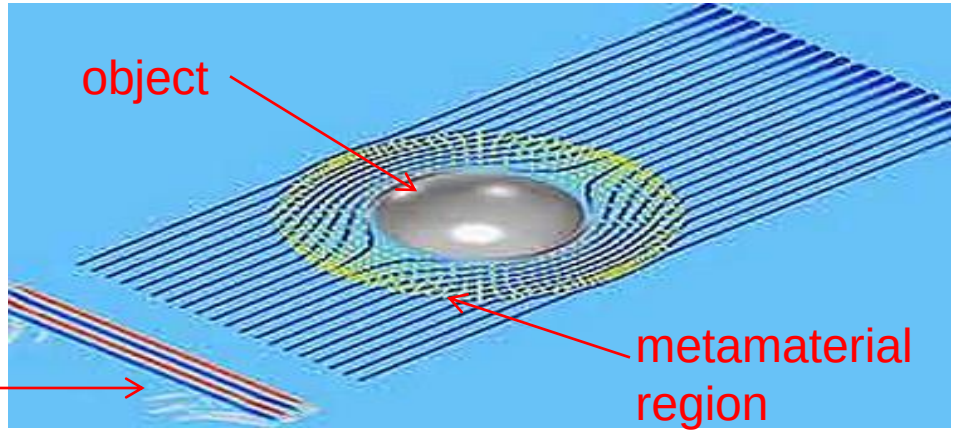


- **Main features:**
  - composite materials: material/air, stiff/soft material, ...
  - periodic structure
  - sizes: from nanometers to meters

Elastic Metamaterials

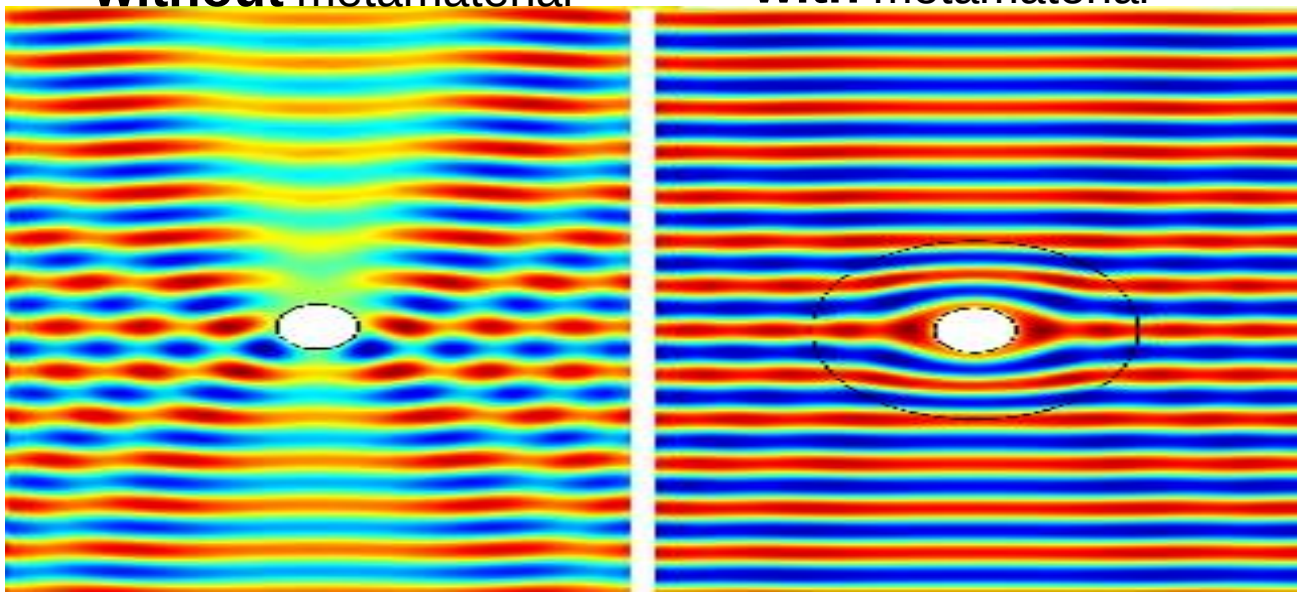
(1) acoustic cloaking

- Cloak objects from sound waves



without metamaterial

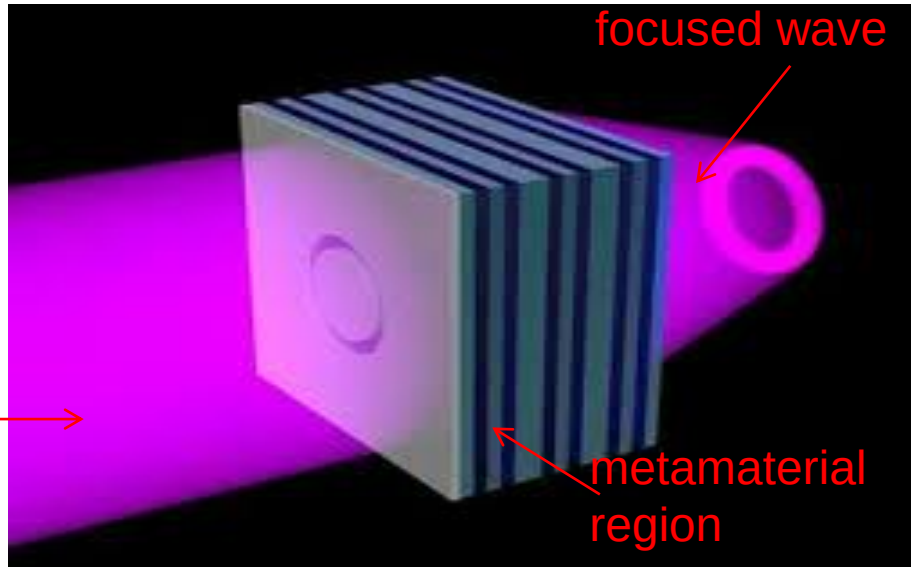
with metamaterial

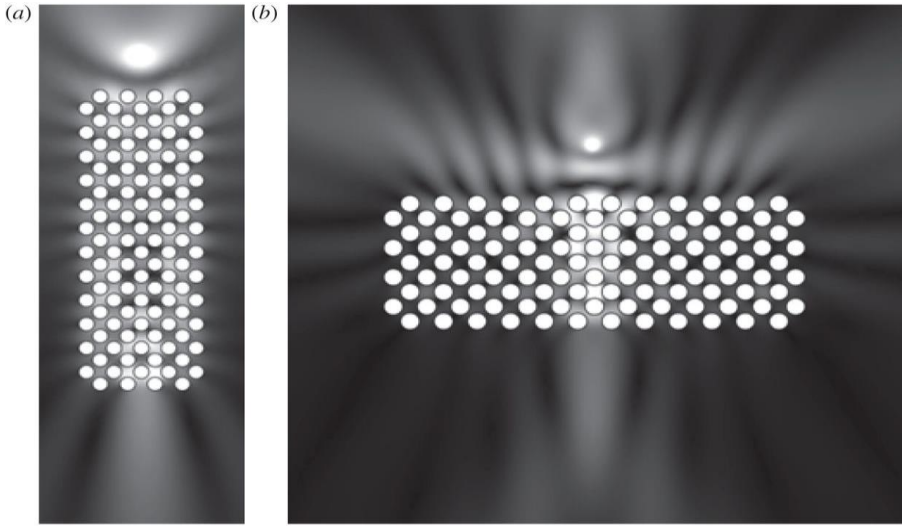


Elastic Metamaterials

(2) wave focusing

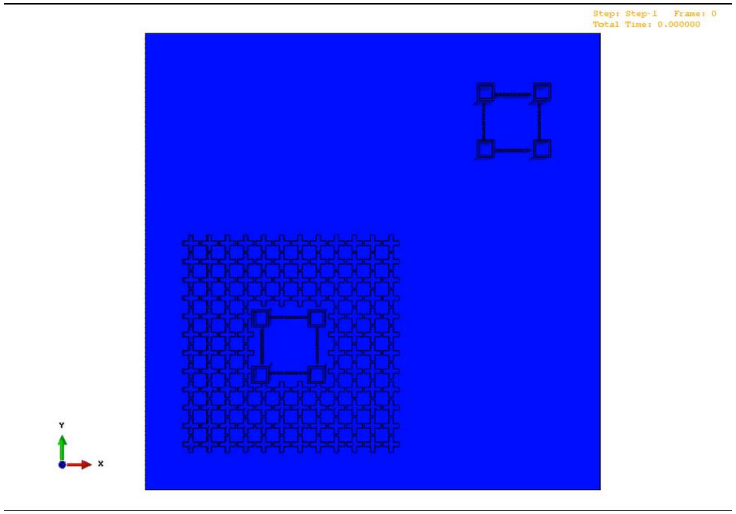
- metamaterial flat lens for wavefocusing

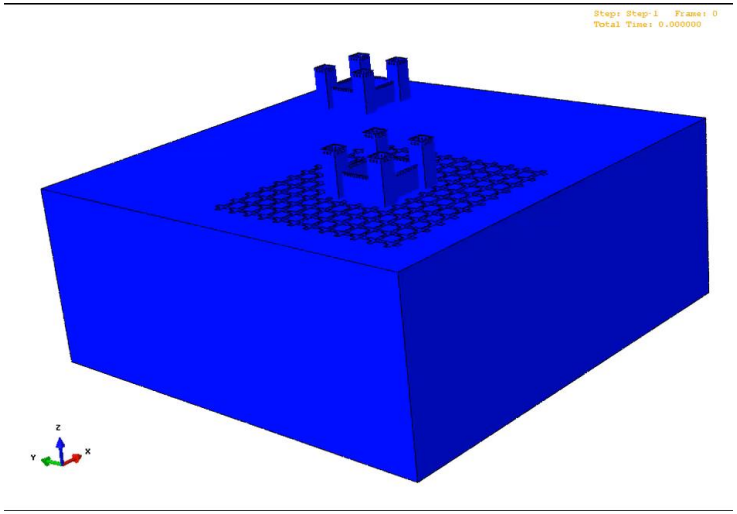


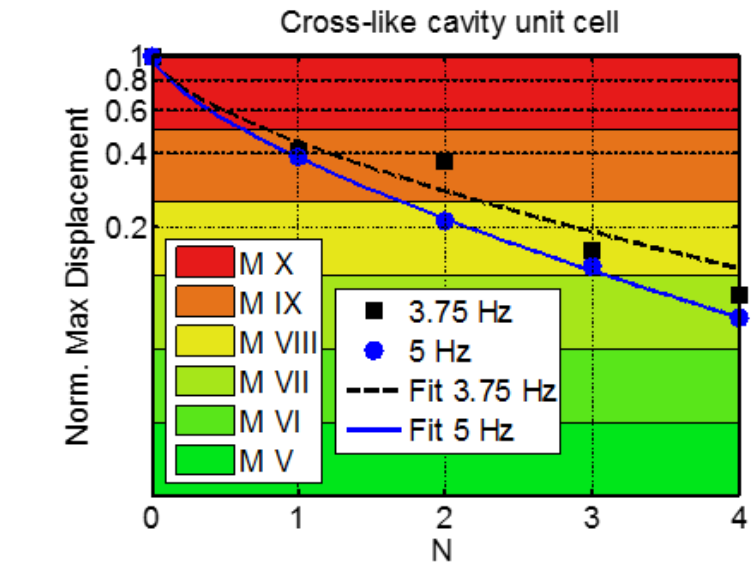


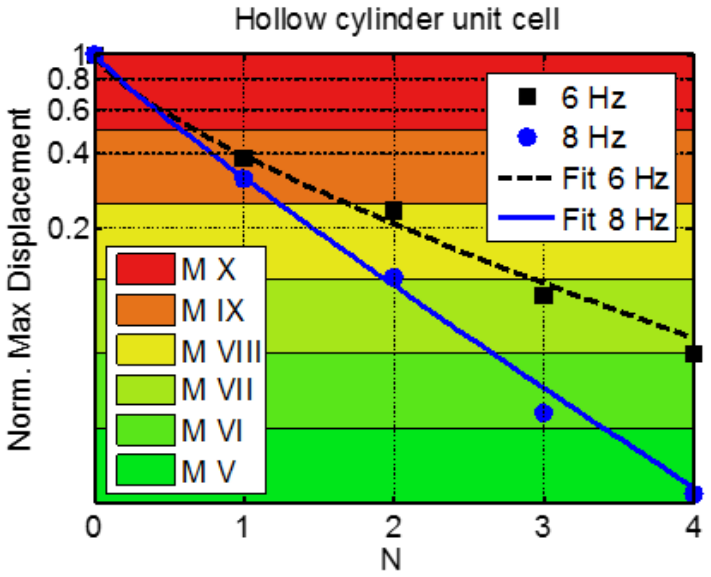
Elastic Metamaterials

- Seismic shielding



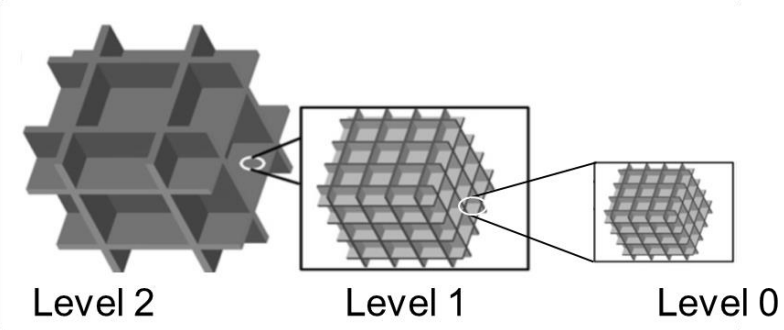


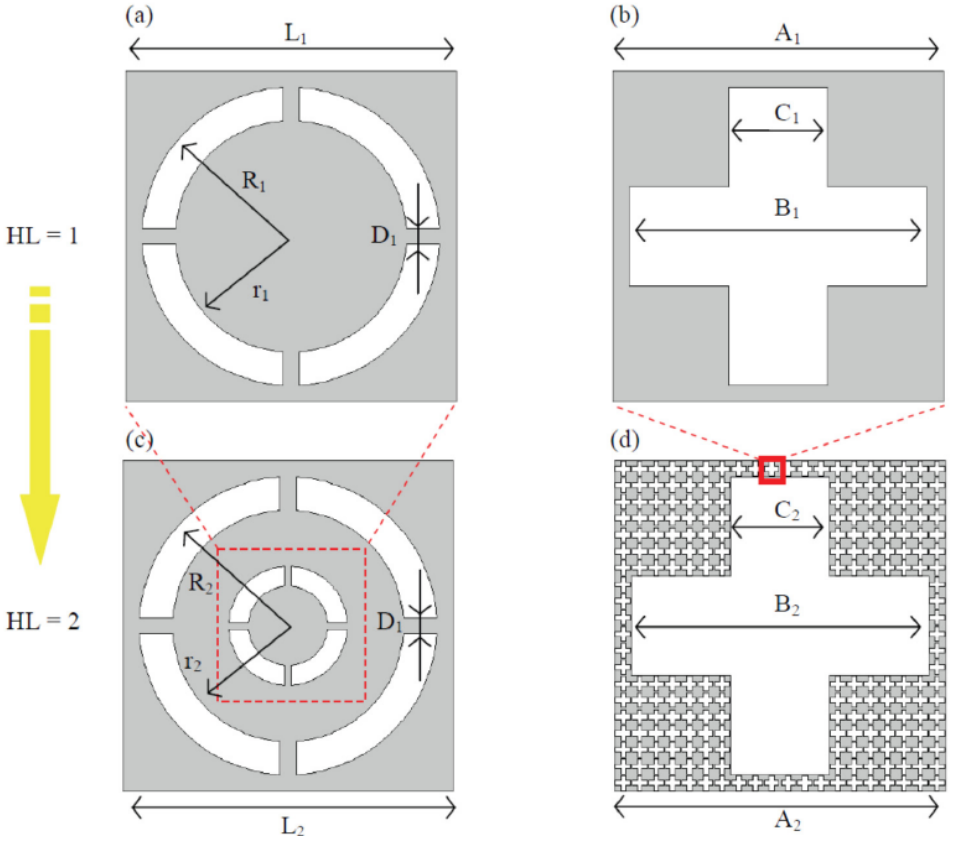




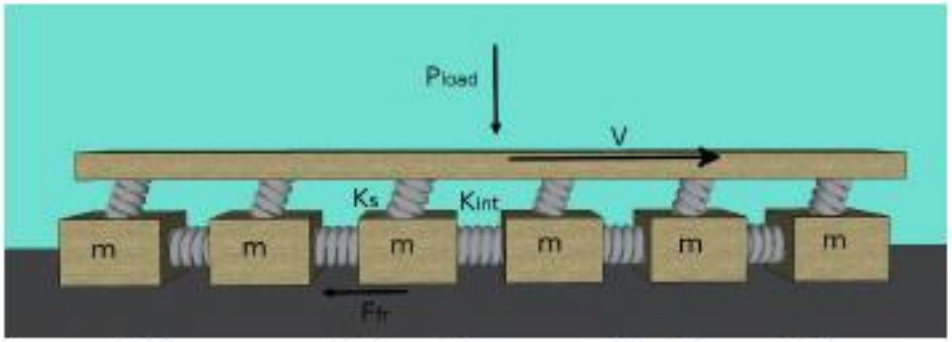
Miniaci et al., New J. Phys. 18 (2016) 083041

Hierarchical Elastic Metamaterials

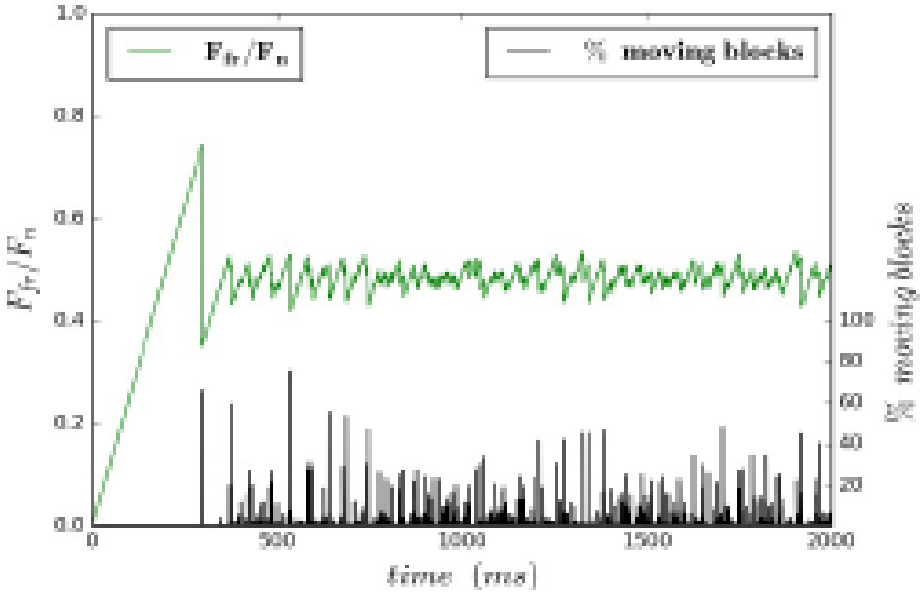




Friction

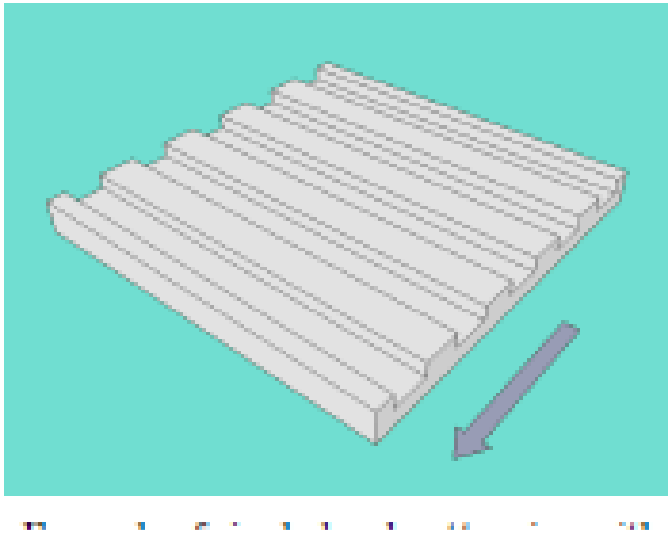


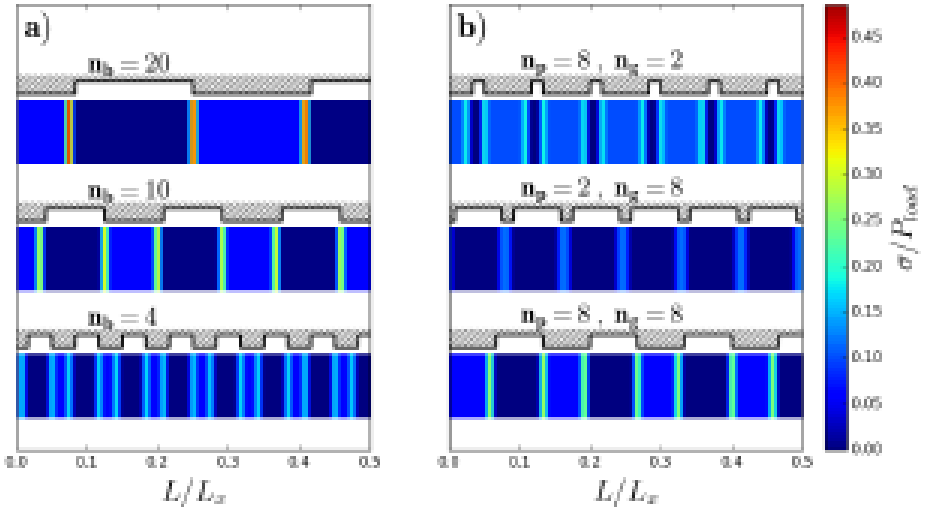
Schematic of the 1-D spring-block model

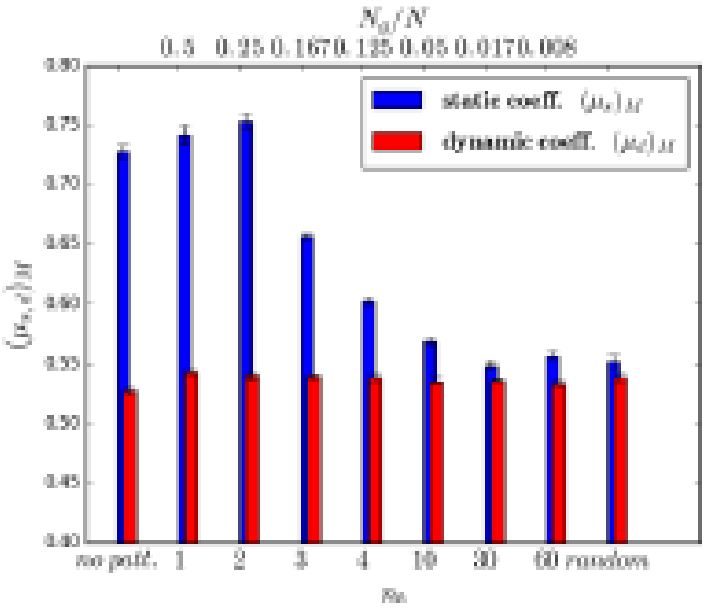


Time evolution of the total friction force

Friction







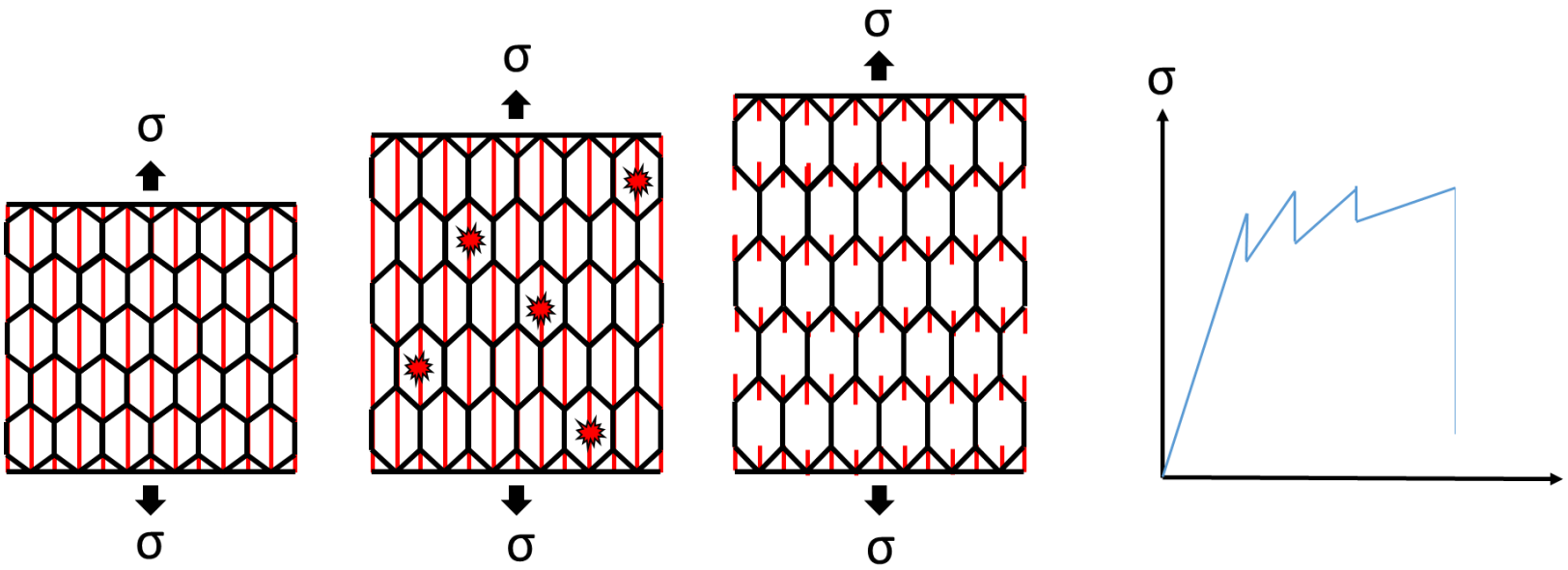
Static and dynamic friction coefficients varying the grooves size expressed in number of blocks

G. Costagliola, F. Bosia, N. M. Pugno, Static and dynamic friction of hierarchical surfaces. Arxiv 1609.08846

Tesi di Laurea

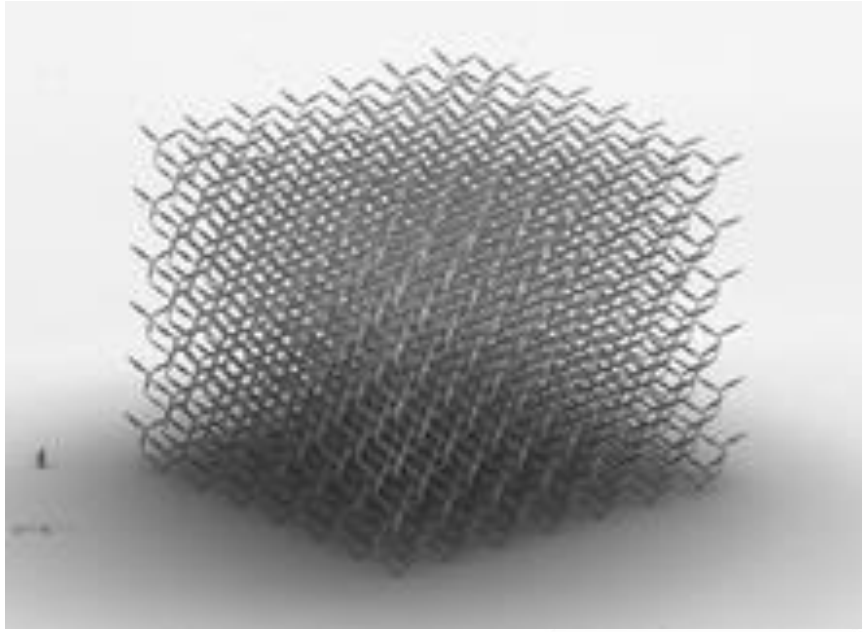
Tesi disponibili:

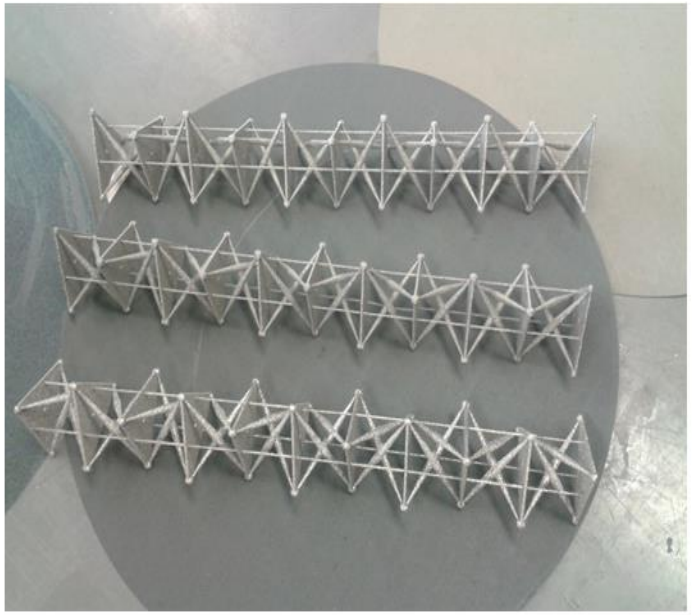
- **1) Simulazione, stampa 3D e caratterizzazione di strutture per massimizzare la dissipazione di energia tramite “sacrificial bonds”**



Tesi di Laurea

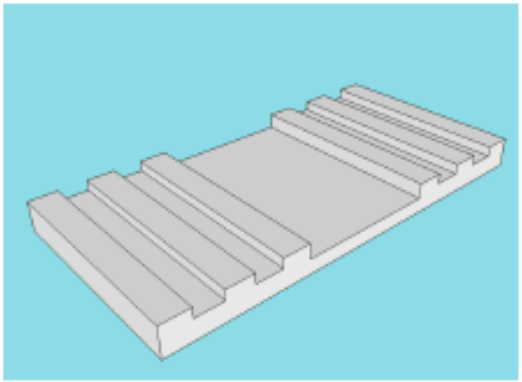
- **2) Metamateriali ultraleggeri: studio della dinamica di varie strutture per attenuazione di vibrazioni a bassa frequenza**

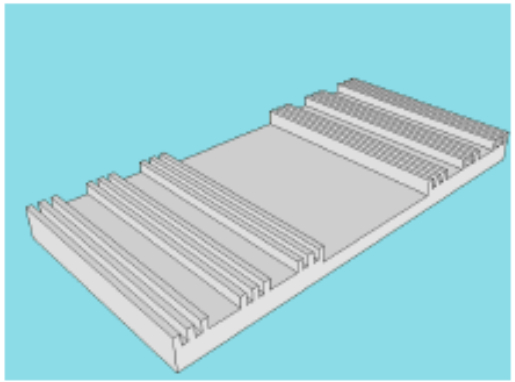


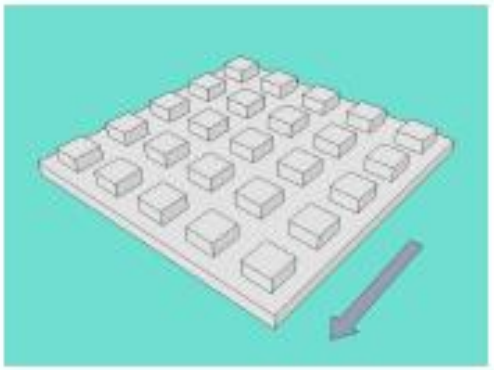


Tesi di Laurea

- **3) Modelli numerici di attrito e adesione su superfici strutturate**







Contatti

Federico Bosia
Dipartimento di Fisica
federico.bosia@unito.it
tel.: 011 670 7889
ufficio: T34 (piano terra istituto vecchio)

http://www.dfs.unito.it/solid/index.html