SIRAMM

Structural Integrity and Reliability of Advanced Materials obtained through additive Manufacturing

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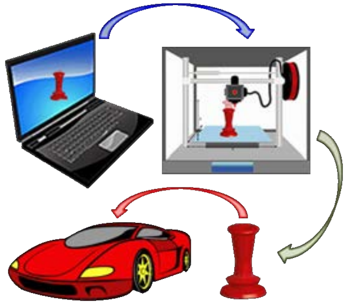


1st Winter School on

Trends on Additive Manufacturing for Engineering Applications

24-28 January 2021

Universitatea Politehnica Timişoara

The process of fracture in soft materials

ALMA · UNIVERSITAS · STUDIORUM · PARMENSIS A.D. 962

Michele Terzano, PhD

Department of Engineering & Architecture, University of Parma

Soft materials

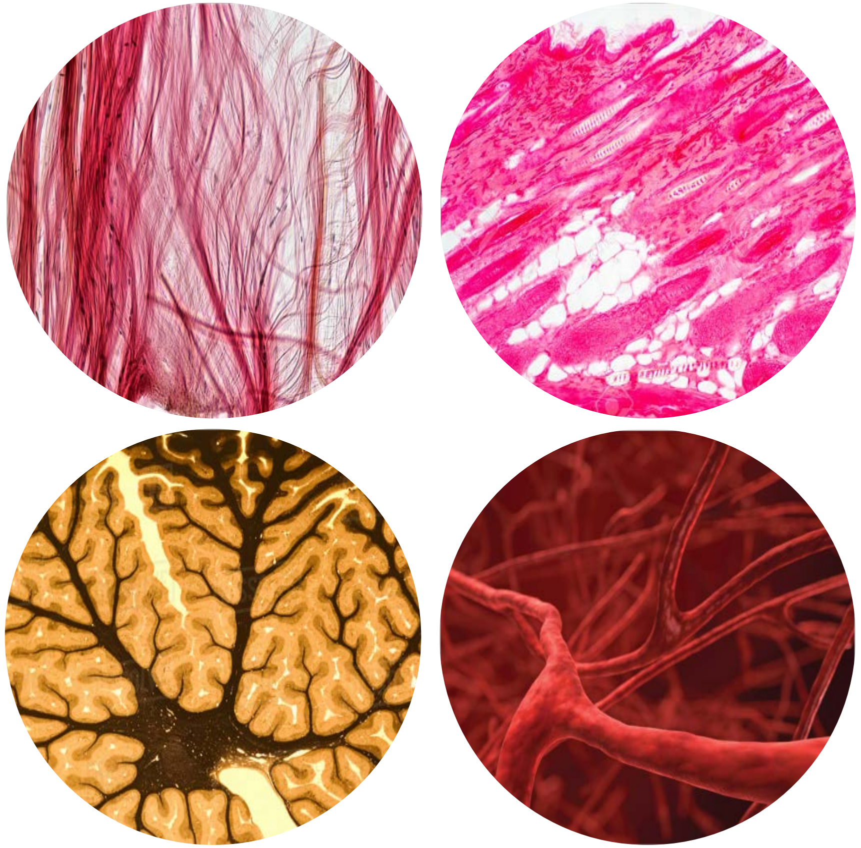
What is **soft matter?**

Soft polymers

elastomers, colloids,
liquid-crystals polymers,
hydrogels, foams …

Soft tissues

skin, muscles, tendons,
blood vessels, organs …



- Soft materials have …

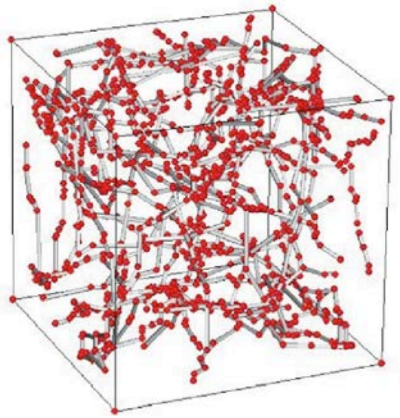
  - low initial elastic modulus
  - high ultimate tensile strain
  - nonlinear stress-strain relationship
  - time dependent behaviour

- and, in addition, soft tissues show …

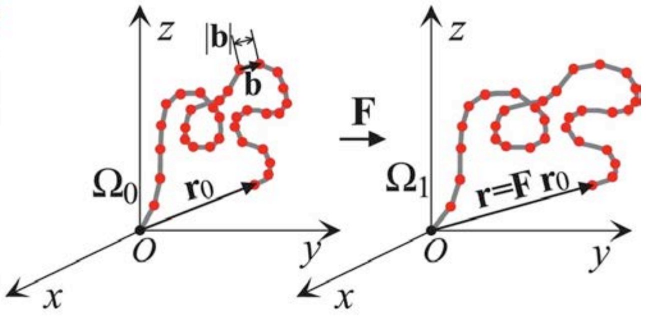
  - strain hardening
  - biphasic nature
  - anisotropic behaviour

- The key feature of soft matter is **entropic elasticity**

Brighenti et al. (2017), *Int. J. Mech. Sci.*, **130**, 448-457



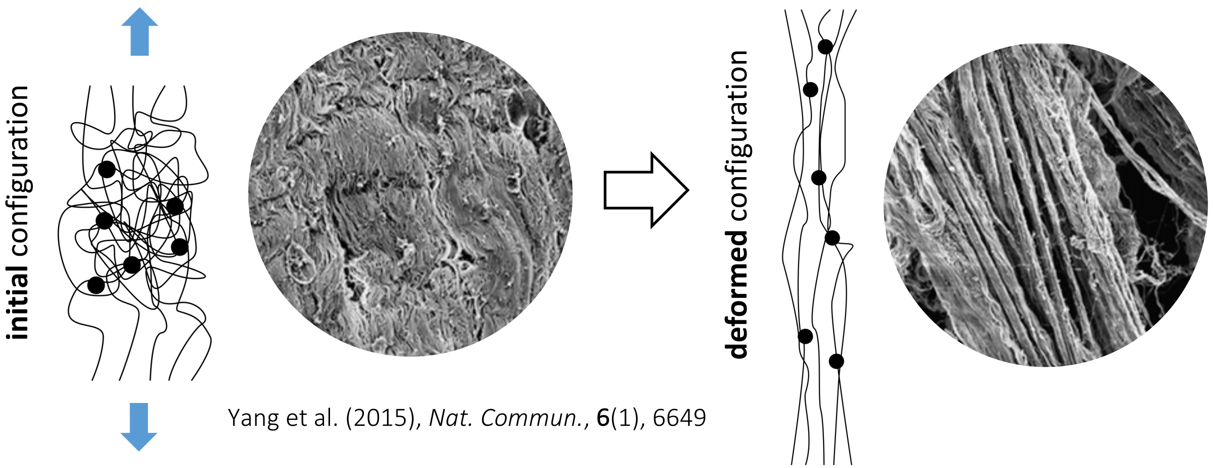
3D amorphous microstructure



single polymeric chain (**before** and **after** stretching)

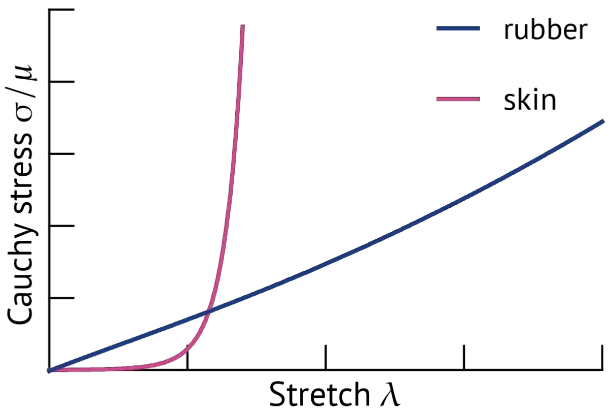
  - the **entropy** of a single chain is derived from a Gaussian probability density function, as a function of the end-to-end distance **r**
  - elasticity arises through entropic **straightening** of polymeric chains, related to the variation of **entropy**
- by contrast, in **hard solids** …
  - elasticity arises from variation of **internal energy** due to change in interatomic attractions (**energetic elasticity**)

An example: the **behaviour of skin**



Yang et al. (2015), *Nat. Commun.*, **6**(1), 6649

uniaxial stress-strain curve



- the dermis layer is made of **elastin** and **collagen**
- limited chain extensibility (**non-Gaussian** statistical theory)
- **J-shaped** stress-strain curve

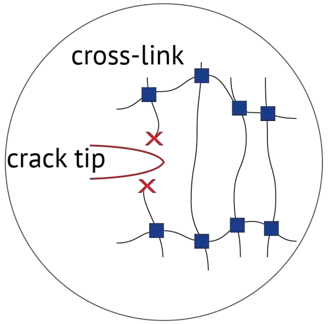
Fracture process in soft matter

What happens when we **tear** soft materials?

- at the **mesoscale**:
  microscopic mechanisms of fracture include disentanglement by chain pull-out and bond rupture

Fracture energy | $\Gamma = nbN^{3/2}U_b$

monomer length (b), bond energy (U_b), density of chains (n), number of monomers (N)

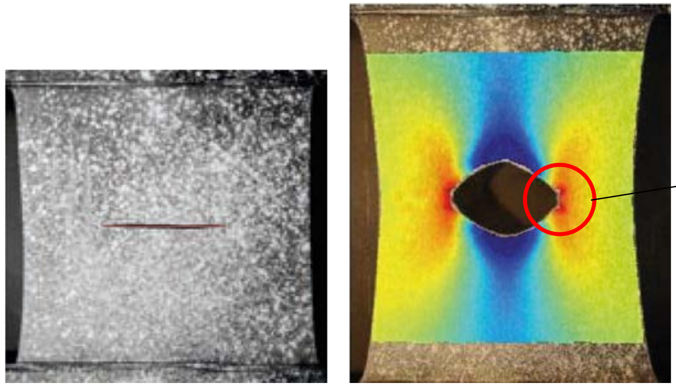


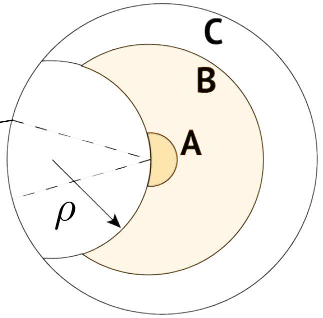
- at the **macroscale**:
  - **crack blunting:** cracks are severely deformed upon loading
  - the **natural crack-tip radius** is the fundamental length scale defining soft materials by the point of view of fracture mechanics

natural crack-tip radius | $\rho \propto \frac{\Gamma}{W_c}$

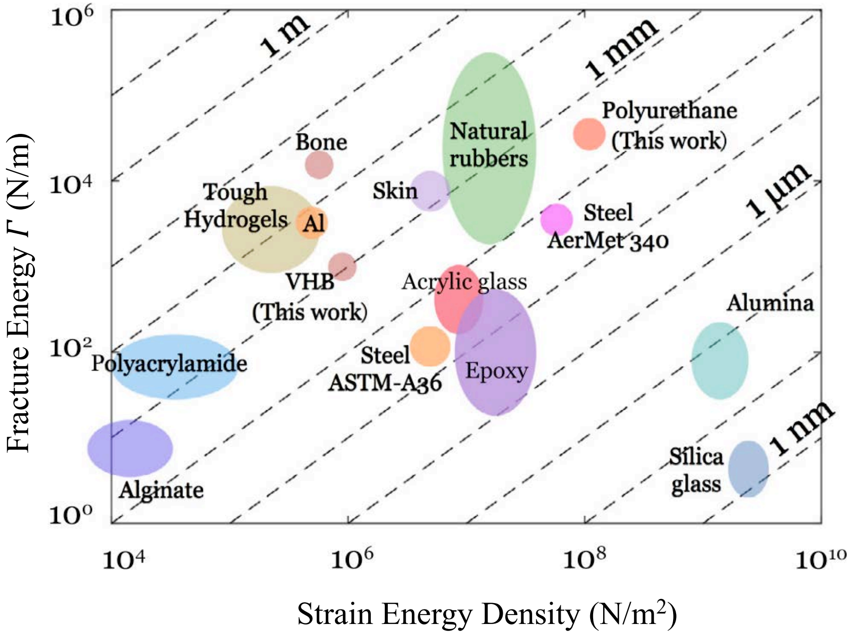
Strain energy density (W_c)

Spagnoli, **Terzano** et al. (2019), *Appl. Sci.*, **9**(6), 1086

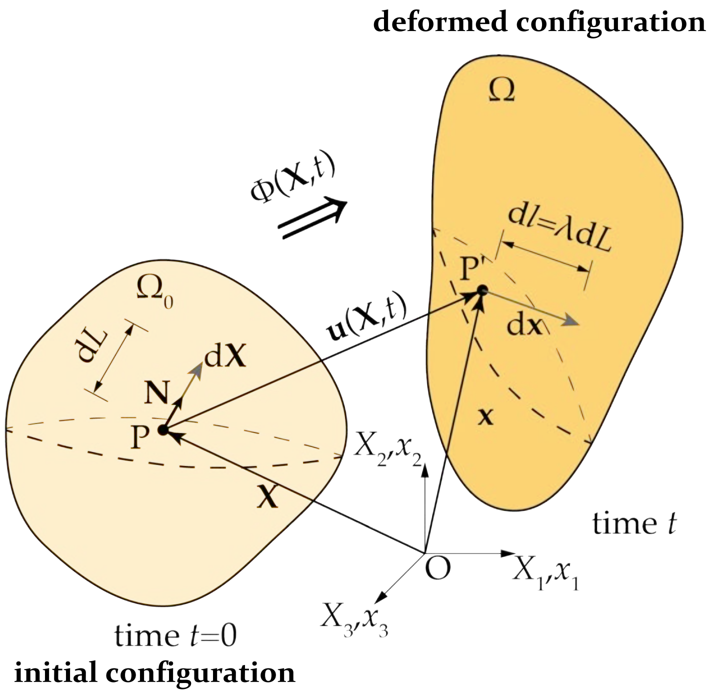




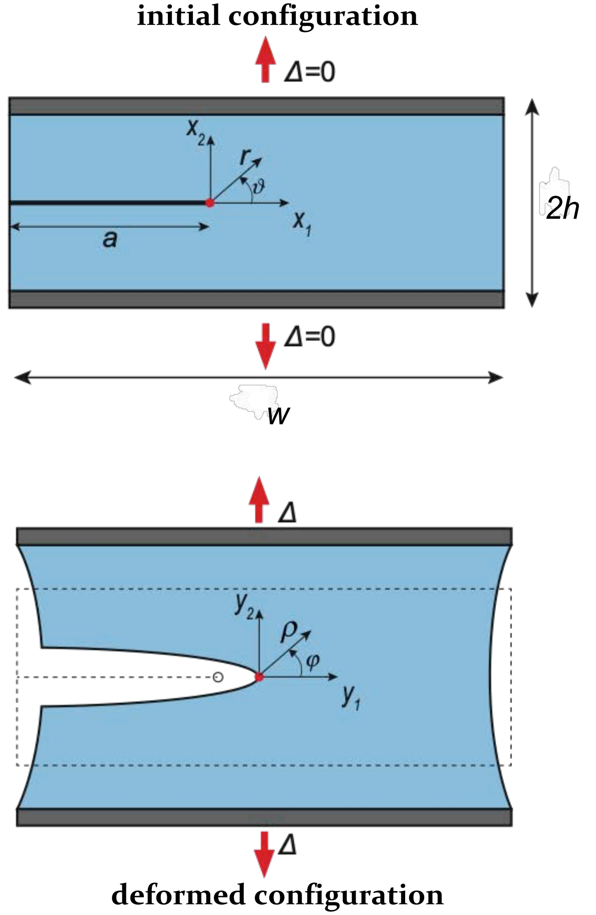
Chen et al. (2017), *Extrem. Mech. Lett.*, **10**, 50-57



Analysis of the local crack-tip stresses in soft materials



current coordinates	$\mathbf{x}=\mathbf{X}+\mathbf{u}(\mathbf{X},t)$
deformation gradient	$\mathbf{F}=\dfrac{\partial \mathbf{x}}{\partial \mathbf{X}}$
left Cauchy-Green strain tensor	$\mathbf{b}=\mathbf{F}\mathbf{F}^T$
first strain invariant	$I_1=\mathrm{tr}\mathbf{b}=\lambda_1^2+\lambda_2^2+\lambda_1^{-2}\lambda_2^{-2}$
Cauchy stress tensor	$\boldsymbol{\sigma}=-p\mathbf{I}+2\dfrac{\partial W}{\partial I_1}\mathbf{b}$



neo-Hookean strain energy density	$W(I_1)=\dfrac{\mu}{2}(I_1-3)$
GNH strain energy density	$W(I_1)=\dfrac{\mu}{2b}\left\{\left[1+\dfrac{b}{n}(I_1-3)\right]^n-1\right\}$
exponential strain energy density (Fung model)	$W(I_1)=\dfrac{\mu}{2b}\left[\exp b\left(I_1-3\right)-1\right]$

hp:

isotropic **hyperelastic incompressible** behaviour

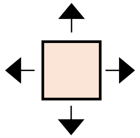
pure shear geometry:

$$w,a \gg h \quad \mathbf{F}\sim\begin{bmatrix}\lambda & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & \lambda^{-1}\end{bmatrix}$$

$$\lambda=1+\Delta/h$$

Analysis of the local crack-tip stresses in soft materials

- In **linear elastic** materials



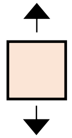
power of singularity

$$\sigma_{11} = \frac{K_I}{\sqrt{2\pi}} r^{-1/2} f_{11}(\vartheta)$$

$$\sigma_{22} = \frac{K_I}{\sqrt{2\pi}} r^{-1/2} f_{22}(\vartheta)$$

$$\sigma_{12} = \frac{K_I}{\sqrt{2\pi}} r^{-1/2} f_{12}(\vartheta)$$

- In hyperelastic **neo-Hookean** materials



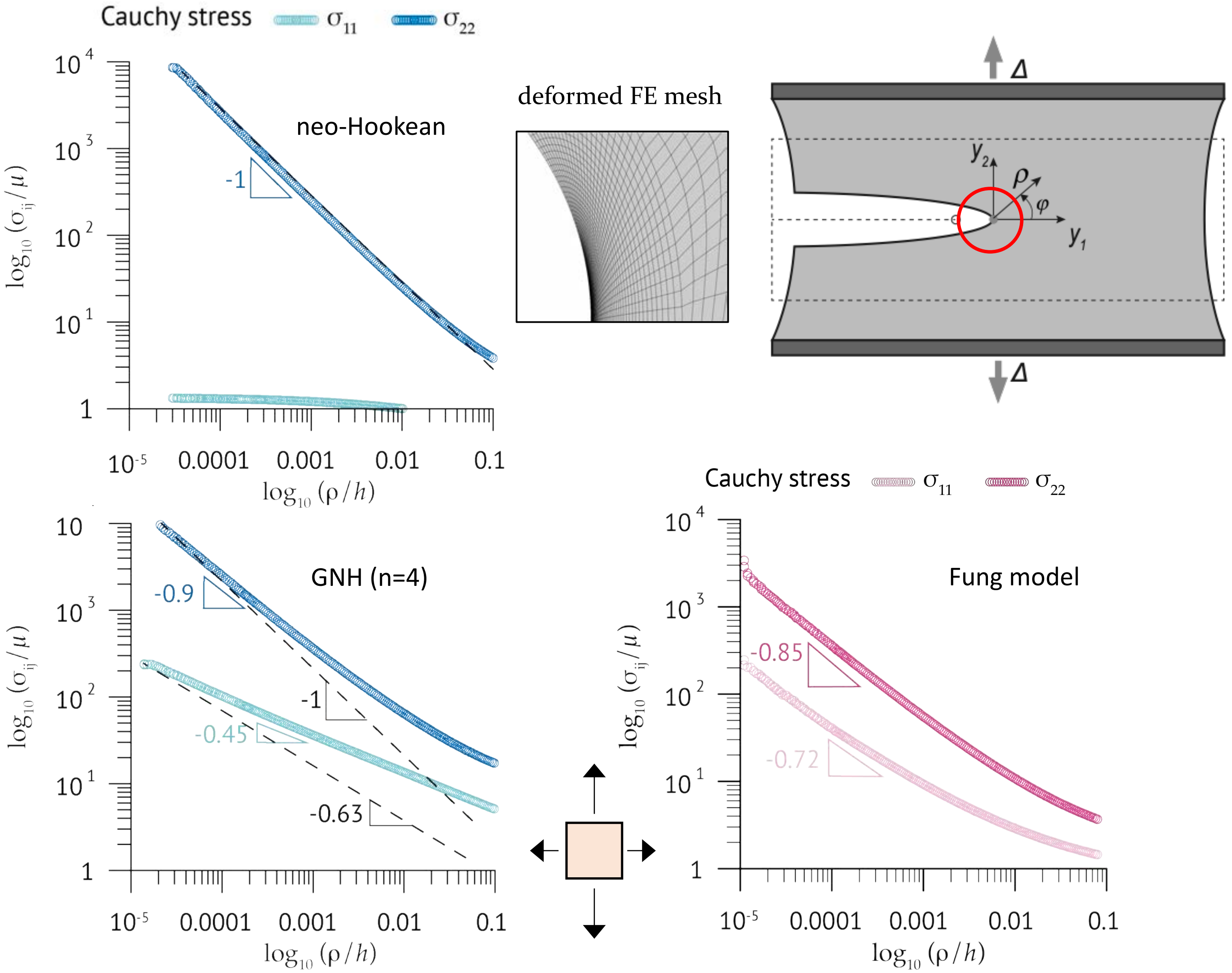
$$\sigma_{11} = \mu C_1^2$$

$$\sigma_{22} = \frac{\mu}{4} C_1 C_2^2 \rho^{-1} f_{22}(\rho,\varphi)$$

$$\sigma_{12} = \mu C_1^{3/2} C_2 \rho^{-1/2} f_{12}(\rho,\varphi)$$

- In hyperelastic **strain-hardening** materials, the singularity depends on strain hardening

Crack-tip stress fields from FE analysis



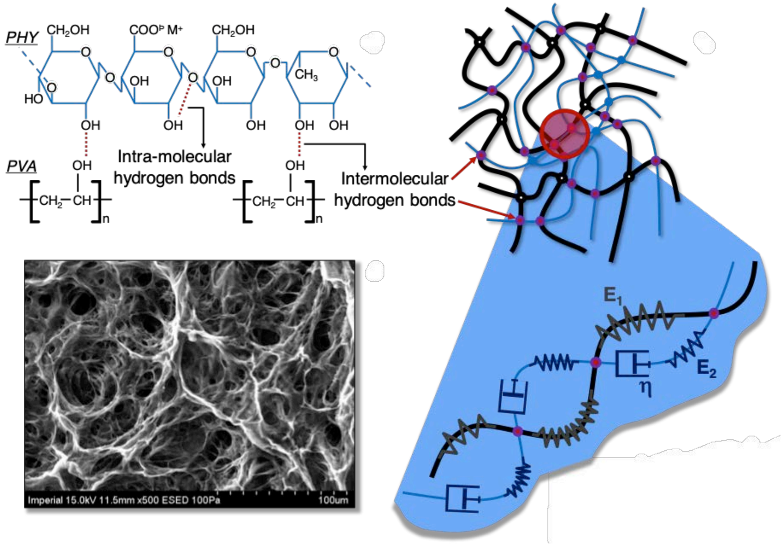
Fracture in fluid-saturated soft materials

Analysis of the fracture process in the brain tissue and mimicking hydrogels

- the brain tissue is a **soft porous** solid, characterised by a very low stiffness (~ 1 kPa) and complex **time-dependent behaviour**
- hydrogels ca be used as **synthetic mimicking materials**

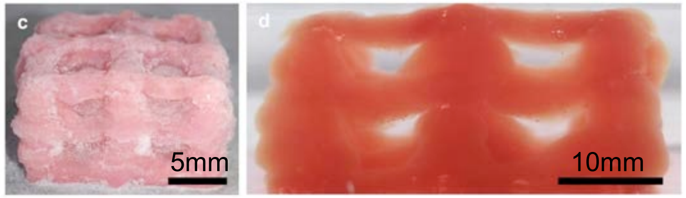
composite hydrogel (CH)
(poly-vinyl-Alcohol (PVA) + Phytagel (PHY))

⇨ can be obtained by **cryogenic 3D printing**



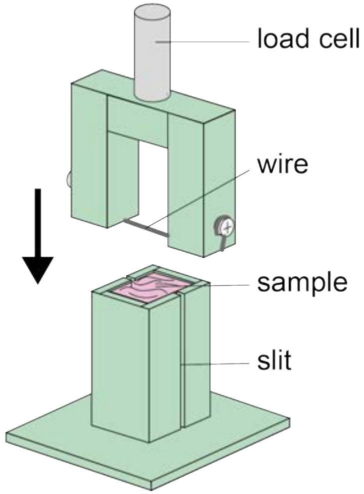
Forte et al. (2016), *Mater. Des.*, **112**, 227-236

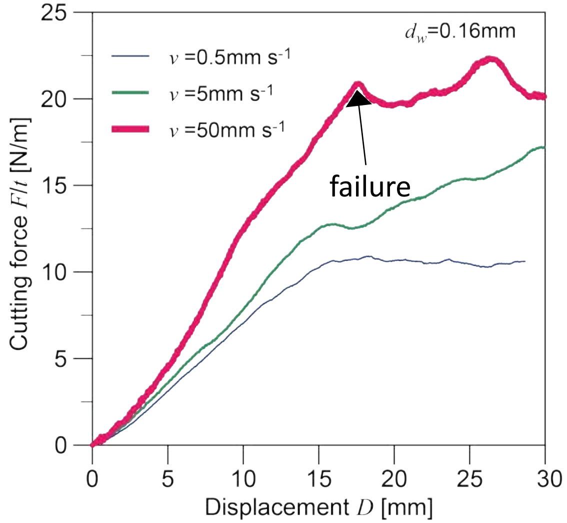
- **extrusion-based** technique
- liquid to solid phase change of a hydrogel ink
- freeze-thaw cycle forms physical crosslinks
- resolution: 200 μm



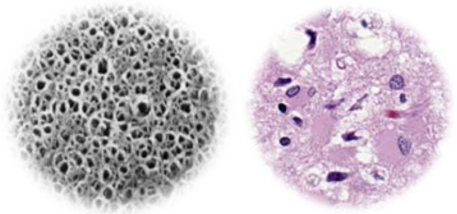
Tan et al. (2017), *Sci. Rep.*, **7**(1), 16293

Wire-cutting experiments (brain tissue)





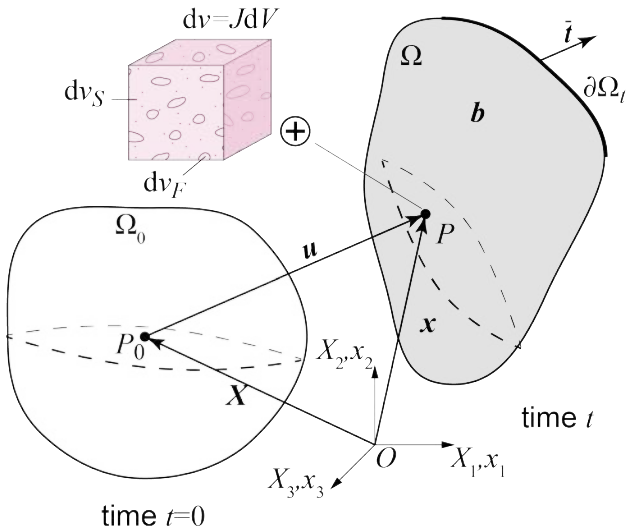
- we have employed wire-cutting experiments to test the **fracture properties** of:
  - porcine brain tissue
  - composite hydrogels
  - gelatine



Fracture in fluid-saturated soft materials

Analysis of the fracture process in the brain tissue and mimicking hydrogels

Terzano, M., Spagnoli, A. *et al.*, submitted, "Fluid-solid interaction in the rate-dependent failure of brain tissue and biomimicking gels"



hp: **finite strain** model
hyperelastic compressible material
incompressible viscous fluid (water)
saturated conditions

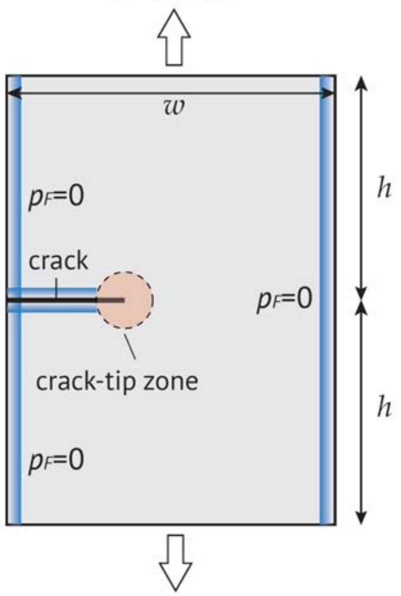
modified principal stretch $\bar{\lambda}_i = J^{-1/3}\lambda_i$

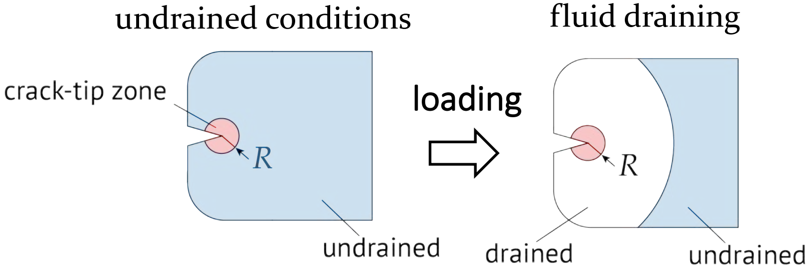
total and effective P-K stress $\mathbf{S} = \mathbf{S}' - J p_F \mathbf{C}^{-1} \qquad S_i' = \dfrac{1}{\lambda_i}\dfrac{\partial W'(\bar{\lambda}_i)}{\partial \lambda_i}$

Ogden's compressible model $W' = \sum_{i=1}^{N} \dfrac{2\mu_i}{\alpha_i^2}\left(\bar{\lambda}_1^{\alpha_i} + \bar{\lambda}_2^{\alpha_i} + \bar{\lambda}_3^{\alpha_i} - 3\right) + \sum_{i=1}^{N}\dfrac{1}{D_i}(J-1)^{2i}$

relative fluid velocity $\mathbf{w}(\mathbf{x},t) = n_F(\dot{\mathbf{u}}_F - \dot{\mathbf{u}})$

Darcy's law $J\mathbf{F}^{-1}\mathbf{w} = -\dfrac{k}{\gamma_F}\mathbf{I}\nabla p_F$





Fluid pressure contours $\lambda = \lambda_0$

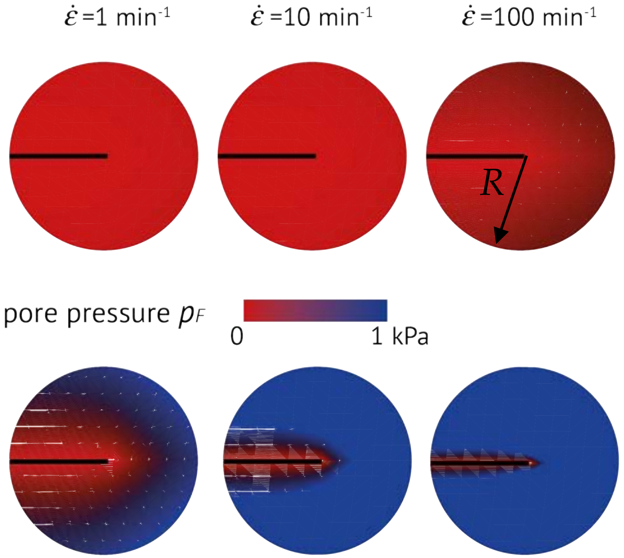
hydraulic conductivity (LT^{-1})

$k = 1.25 \cdot 10^{-6}$ m/s

gelatine 10% w/w

$k = 1.25 \cdot 10^{-9}$ m/s

brain tissue



Numerical simulation of curved insertion paths of needles in tissue mimicking hydrogels

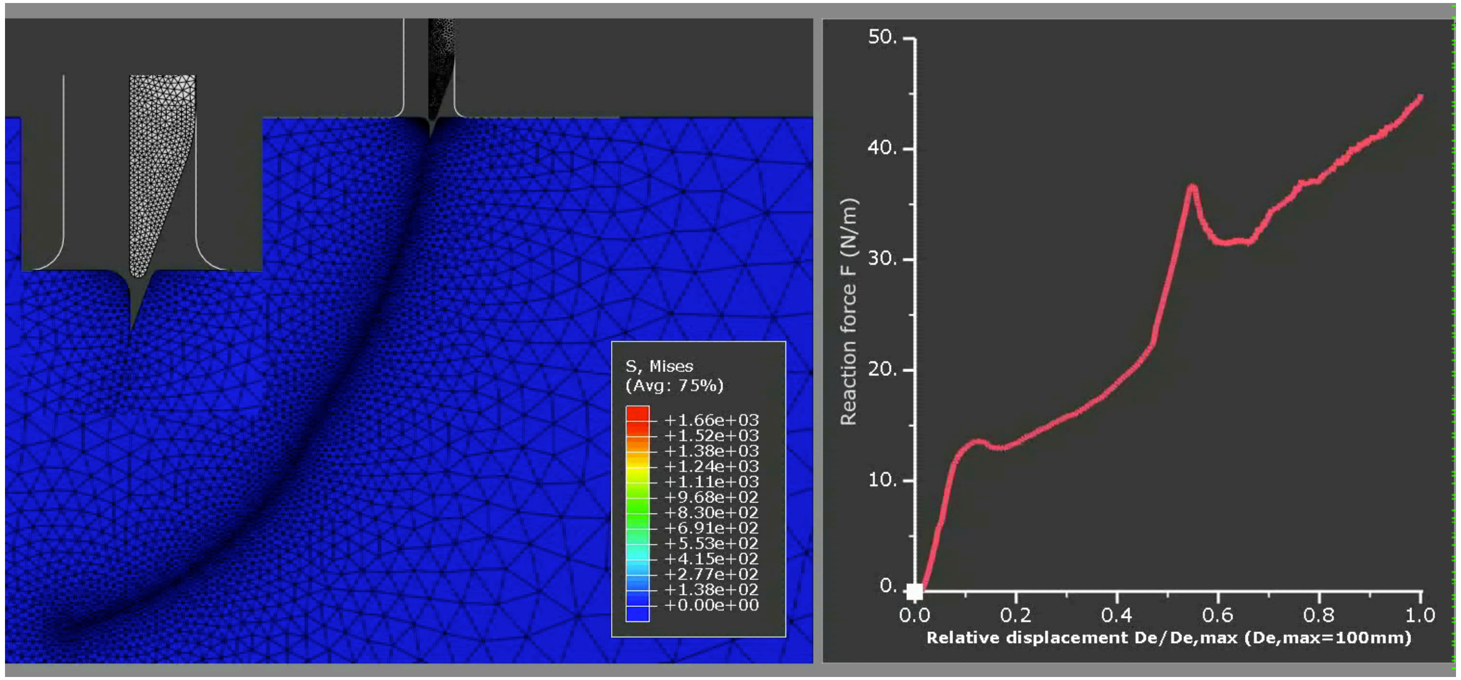
Terzano, M., Dini, D. *et al.*, 2020,
"An adaptive finite element model for steerable needles"

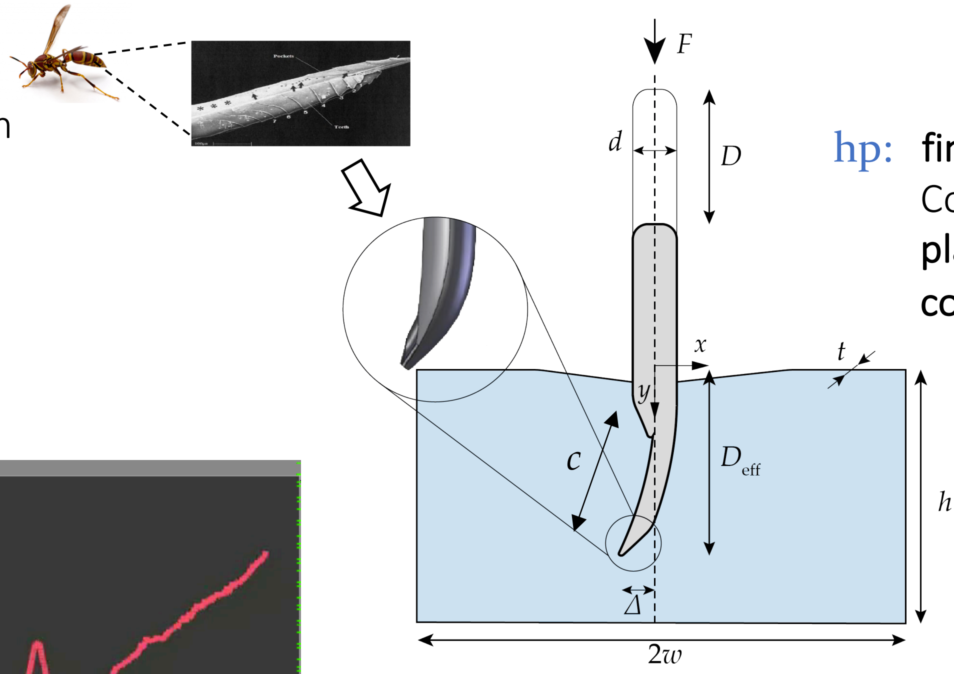
- needle insertion can be treated as a problem of **indentation cutting**
- we consider a bio-inspired thin **flexible needle** with an **asymmetric** tip (programmable bevel-tipped needle, PBN)

KEY-POINT: the propagation path is **unknown in advance**

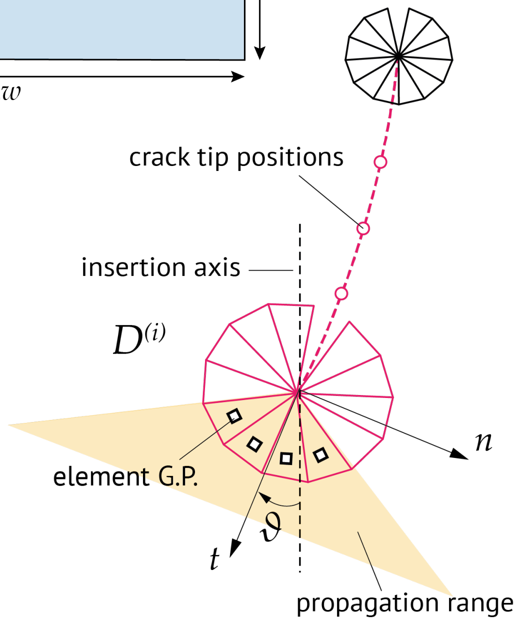
⇩

iterative FE algorithm





hp: **finite strain** elastic model
Coulomb's friction
plane strain conditions
cohesive zone model



Thank you for your attention

Michele Terzano, PhD
Research Fellow
Dept. of Engineering & Architecture, University of Parma

michele.terzano@unipr.it

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