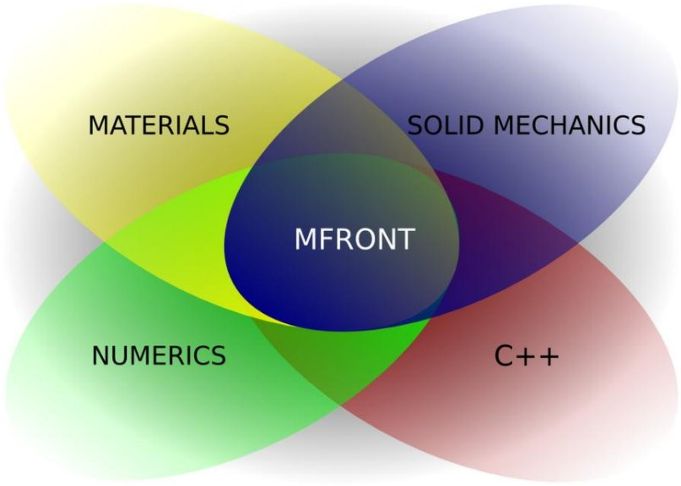


# Microstructurally-based anisotropic hyperelastic FE model of the human abdominal wall

L. Astruc[1], A. Morch[1], G. Dufaye[2], J.-F. Witz[1], P. Lecomte[1], M. Brieu[3]

[1]Univ. Lille, CNRS, Centrale Lille, FRE 2016 – LaMcube – Laboratoire de mécanique multiphysique multiéchelle, Lille, France
[2]SATT Nord, Lille, France
[3]California State University, Los Angeles, United States

# Framework & objectives

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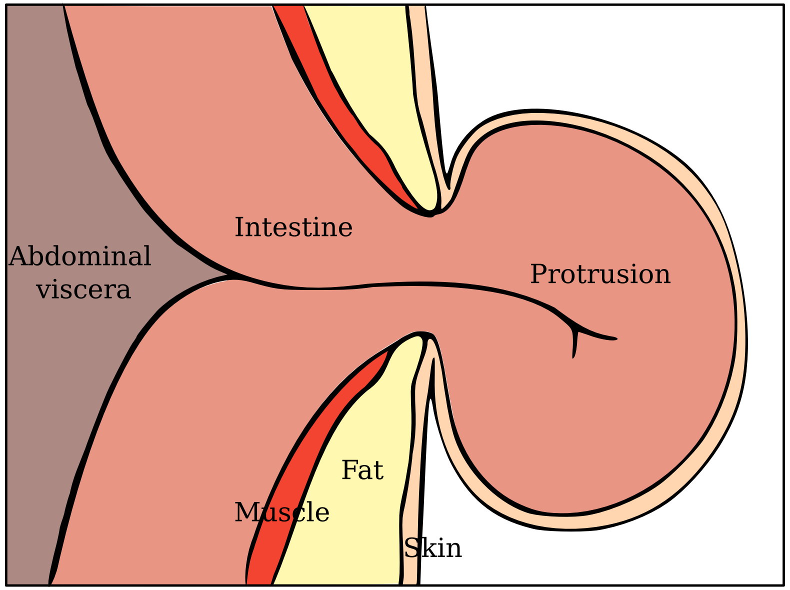
Hernia: protrusion of abdominal wall

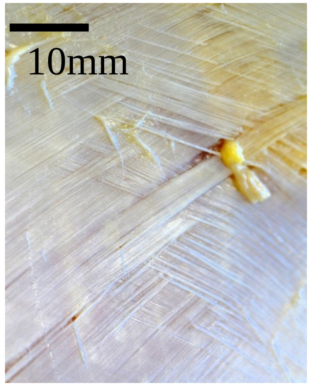
Most common worldwide surgical operation

~ 20% incidence [Bedewi2011]

~ 20-60% recurrence rate [Luijendijk,2000]

⇒ Improvement of medical care solutions




[Astruc,2018]

Connective tissues: highly oriented structure, with collagen and elastin fibers

⇒ Impact on the mechanical behavior [Korenkov,2001]

**Link between the histological microstructure and the mechanical behavior**

⇒ Constitutive model with a reduced number of parameters

# Abdominal wall connective tissues



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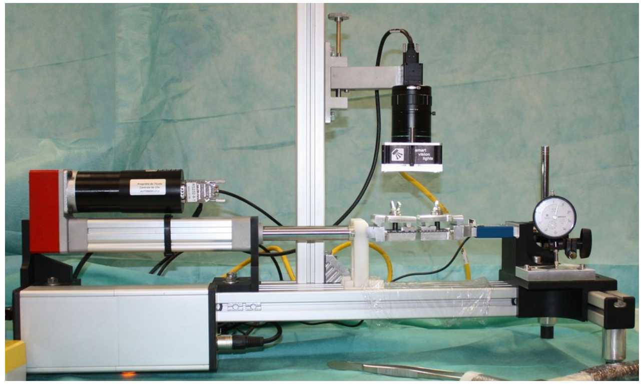
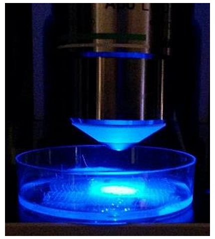
Sheathing tissue = connective tissues

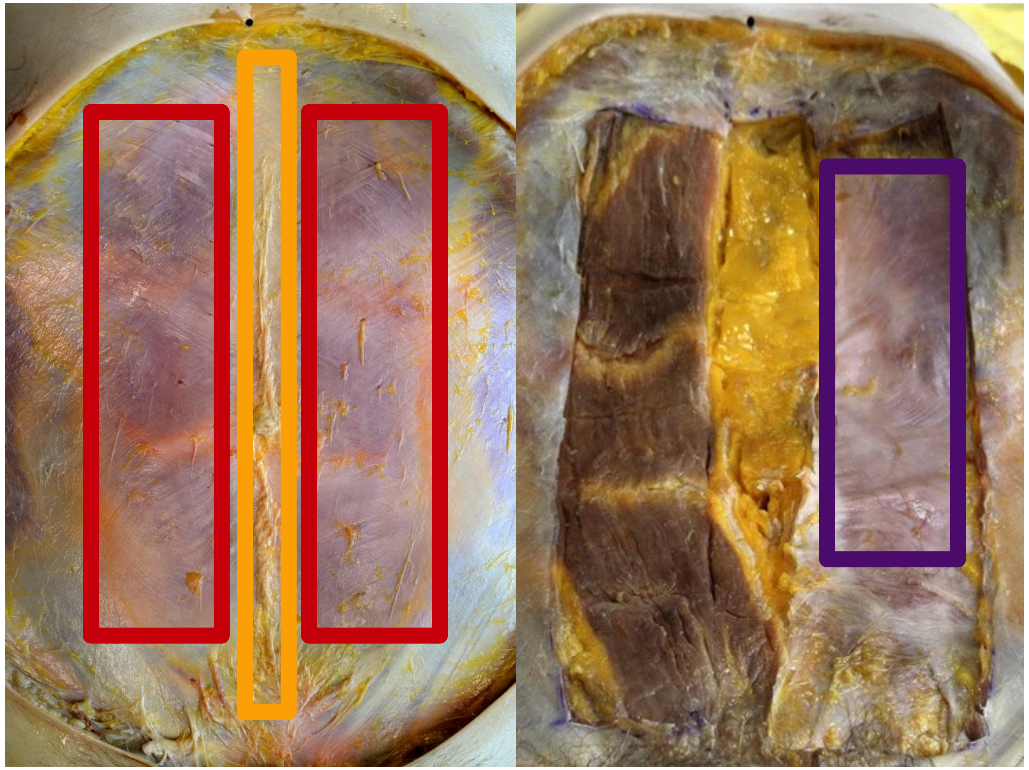
Linea alba (LA)
Anterior rectus sheath (ARS)
Posterior rectus sheath (PRS)



ivtv
INGÉNIERIE ET VIEILLISSEMENT DES TISSUS VIVANTS



Mechanical characterization in 3 directions
Multiphotonic confocal microscopic observation



[Astruc,2018]



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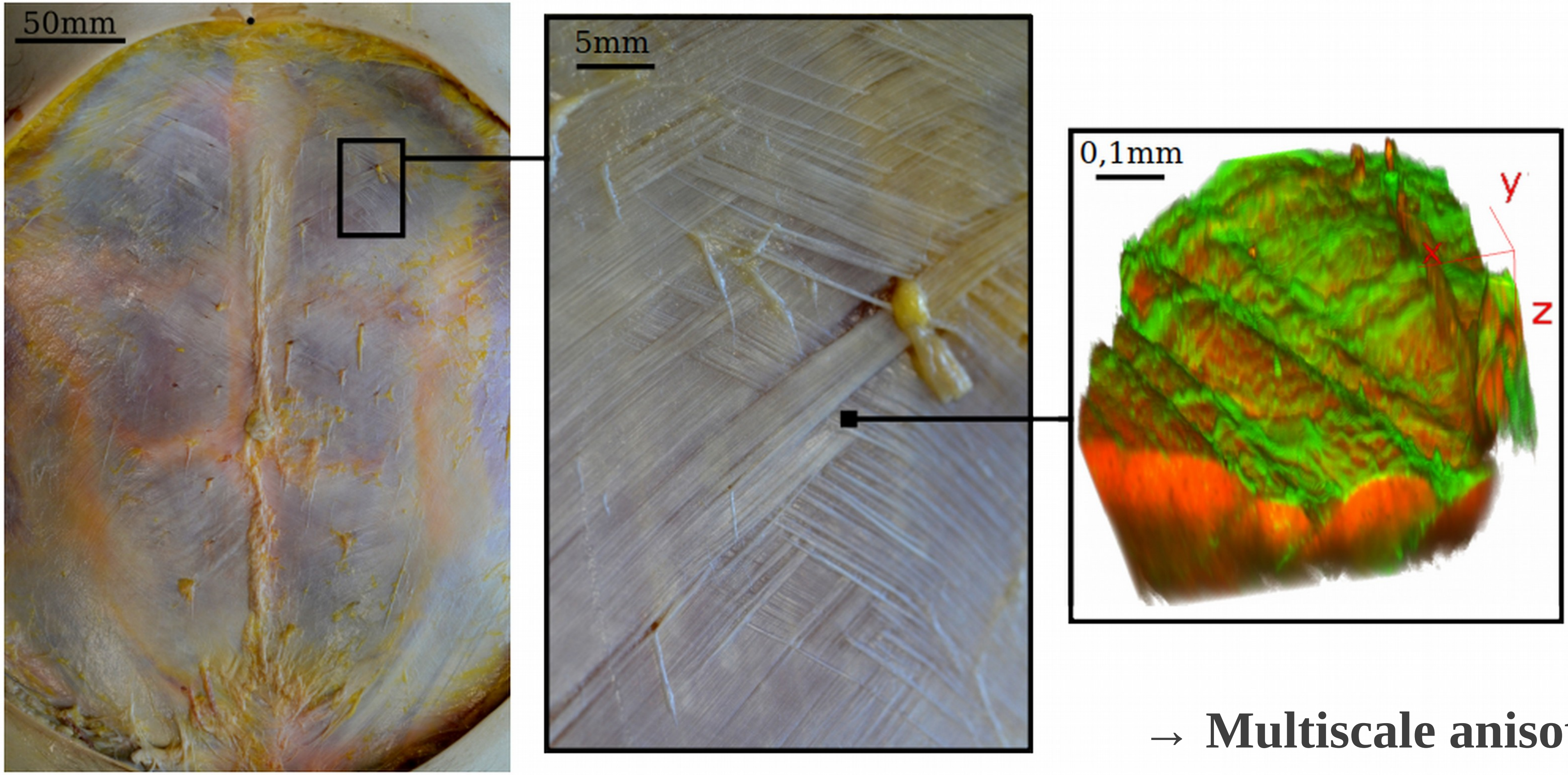
# Multiscale microstructure






→ **Multiscale anisotropy**

# Directional constitutive modeling



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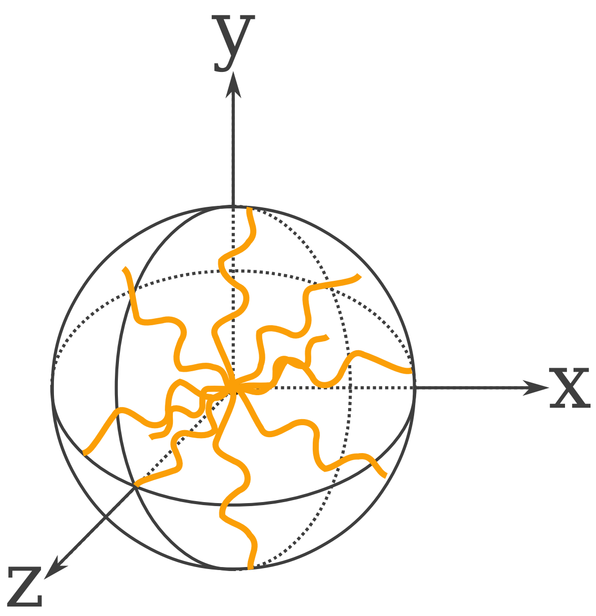
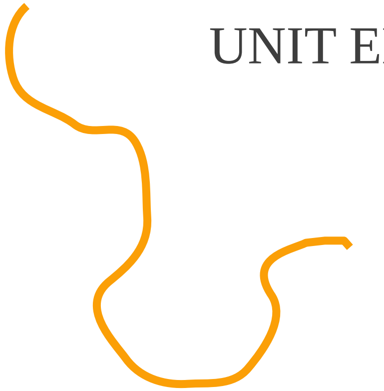
→ DESIGN OF A MICROSTRUCTURALLY-BASED **HYPER-ELASTIC** MODEL




Fibers = spatial network of macro-molecules

⇒ **Microsphere approach** [Diani2004, Kuhl2006, Brieu2016]



UNIT ELEMENT with 2 parameters (C,N)

C : rigidity of the chain
N : average length of the chain

$$\mathcal{W}(\nu) = CN\left(\beta\frac{\nu}{\sqrt{N}} + \ln\left(\frac{\beta}{\sinh(\beta)}\right)\right) \quad \text{with } \beta = \mathcal{L}^{-1}\left(\frac{\nu}{\sqrt{N}}\right)$$

[Kuhn1942]

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# Modeling of hyperelastic isotropic material

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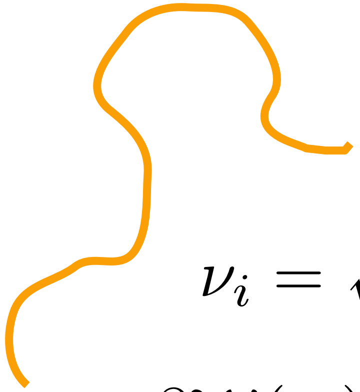
Application on rubber [Diani2004] and vagina [Brieu2016]

$$\boldsymbol{C} = \begin{pmatrix} \lambda^2 & 0 & 0 \\ 0 & \frac{1}{\lambda} & 0 \\ 0 & 0 & \frac{1}{\lambda} \end{pmatrix}_{(\vec{e_1},\vec{e_2},\vec{e_3})}$$



$$\nu_i = \sqrt{\underline{u_i}.\boldsymbol{C}.\underline{u_i}}$$

$$\frac{\partial \mathcal{W}(\nu_i)}{\partial \nu_i} = C_i \sqrt{N_i}\beta$$

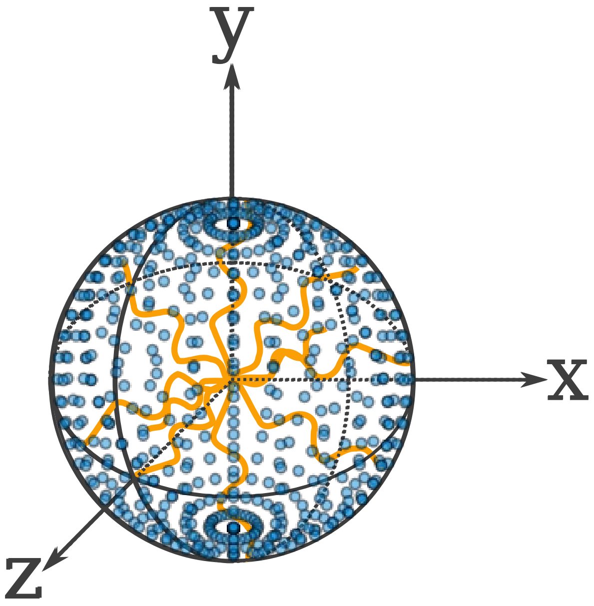
$$\boldsymbol{S} = 2\sum_{i=0}^{M} \omega_i \frac{\partial \mathcal{W}(\nu_i, C_i, N_i)}{\partial \boldsymbol{C}} + \boldsymbol{S}^{vol}$$

ISOTROPY

$$C_i = C \quad N_i = N$$

Material parameters

$$\boxed{\underline{\boldsymbol{M}} = \begin{pmatrix} C \\ N \end{pmatrix}}$$



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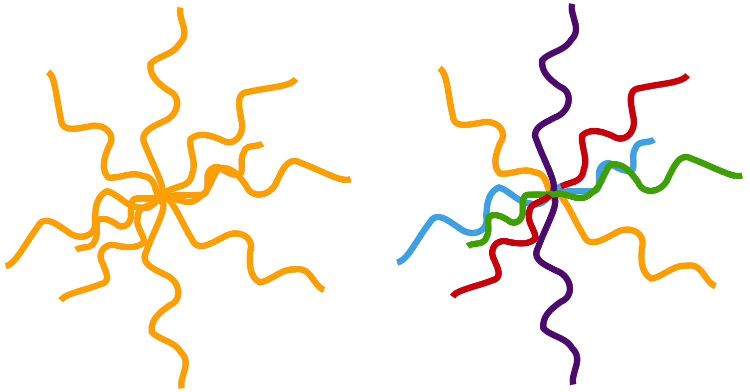
# Consideration of the anisotropy

## Application on embedded biological prosthesis [March2019]

### MATERIAL APPROACH

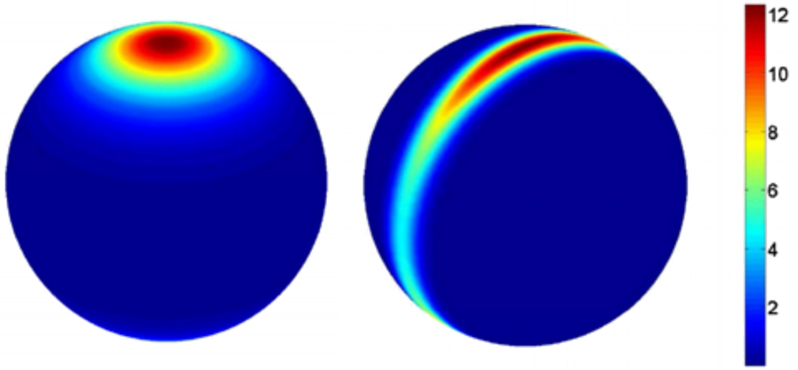
isotropy anisotropy



Material parameters

$$\boxed{\underline{M} = \begin{pmatrix} C_i \\ N \end{pmatrix}}$$

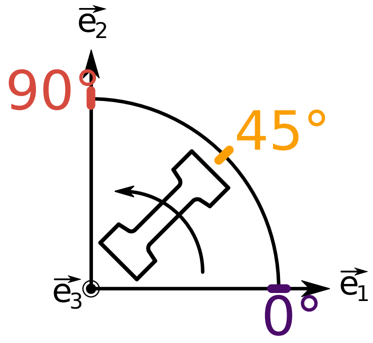
→ **Stresses** penalization

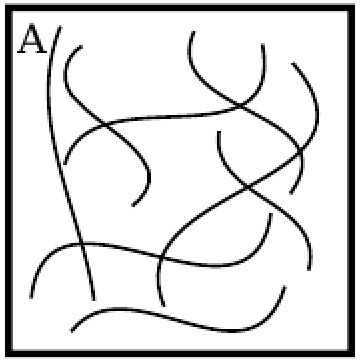


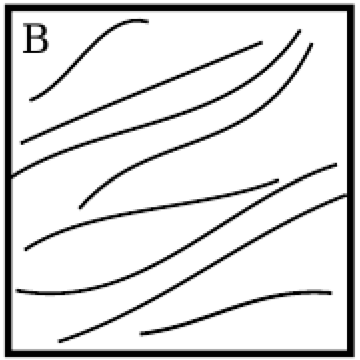

[Alastrué,2010]

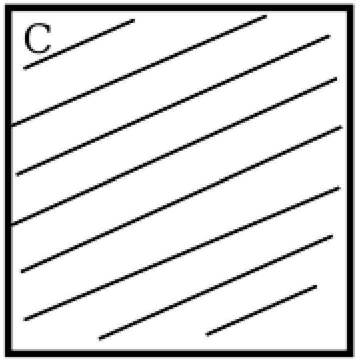
$$\boldsymbol{S} = 2\sum_{i=0}^{M} \omega_i \omega_i^A \frac{\partial \mathcal{W}(\nu_i, C, N)}{\partial \boldsymbol{C}} + \boldsymbol{S}^{vol}$$

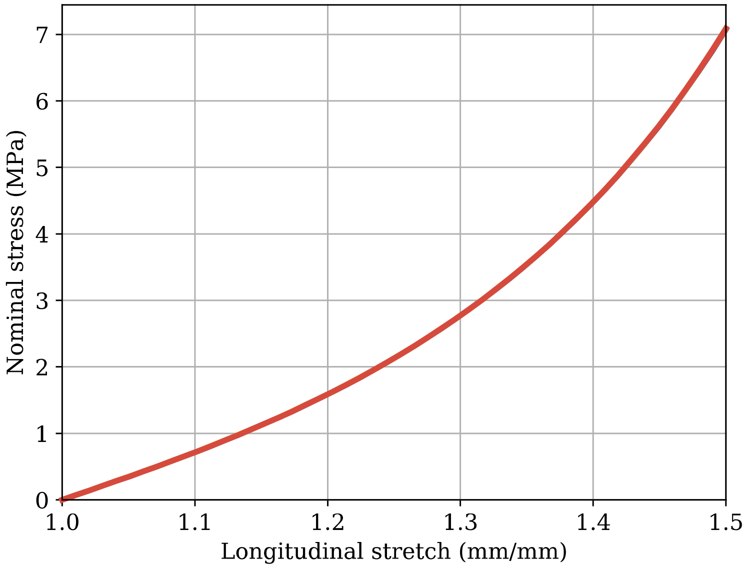
# Results

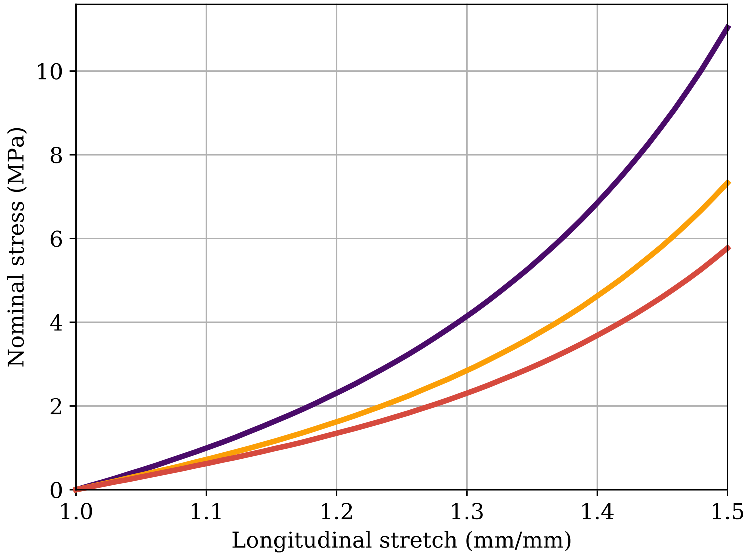


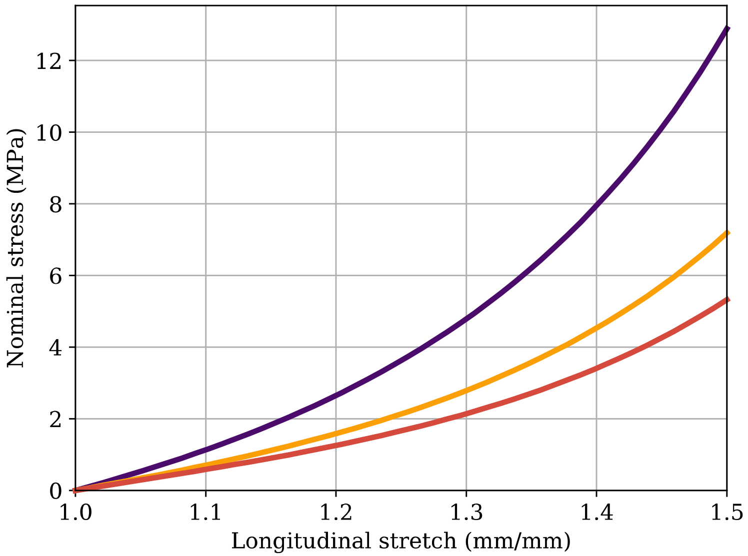



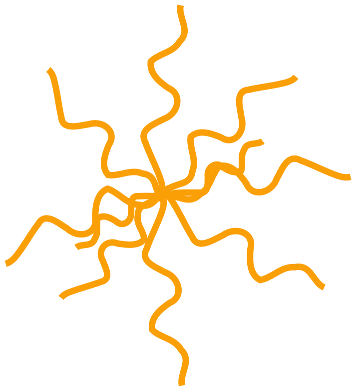

Need to consequently increase the number of integration points with the anisotropy

# New micro-structural approach

Application on abdominal wall connective tissues [Astruc,2019]

## STRUCTURE APPROACH

isotropy



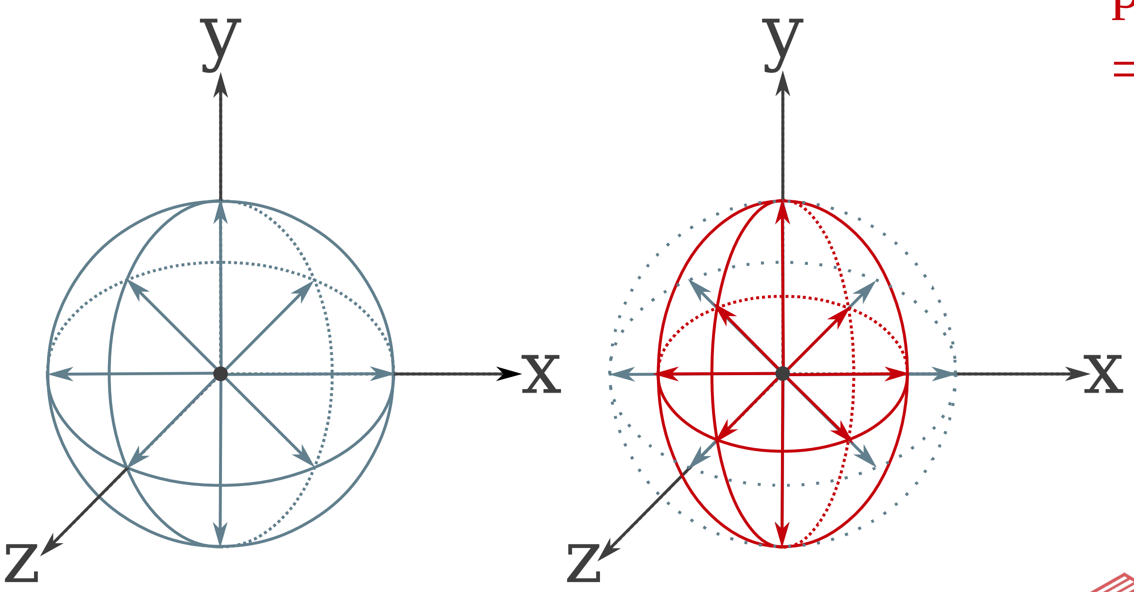
anisotropy

→ Anisotropy = **specific** fibers arrangement

$$\underline{M} = \begin{pmatrix} C \\ N \end{pmatrix}$$

Material parameters = INTRINSIC

**Deformations** penalization




Microstructure parameters = EXTRINSIC

$$\underline{A} = \begin{pmatrix} \theta \\ \varphi \\ R \end{pmatrix}$$

# Deformations penalization

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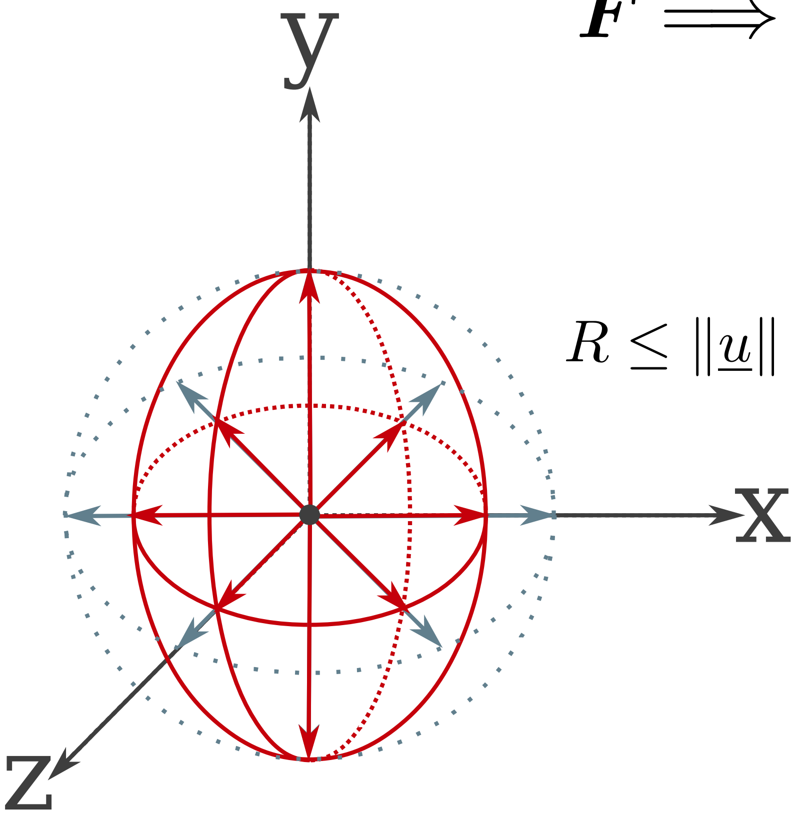
macro deformation

micro deformation per direction

$$\boldsymbol{F} \Longrightarrow \nu \sim \underline{u}.\boldsymbol{F}.\underline{u}$$




$$R \leq \|\underline{u}\| \leq 1$$

**Sphere**

$$\|\underline{u}\| = 1$$

$$\nu_{\text{sphere}} \sim \underline{u}.\boldsymbol{C}.\underline{u}$$

$$\nu_{\text{sphere}} \sim \frac{L}{L_{0\text{sphere}}}$$

**Ellipsoid**

$$\|\underline{u}\| \leq 1$$

$$\nu_{\text{ellips.}} \leq \nu_{\text{sphere}}$$

$$\frac{L}{L_{0\text{ellips.}}} \leq \frac{L}{L_{0\text{sphere}}}$$

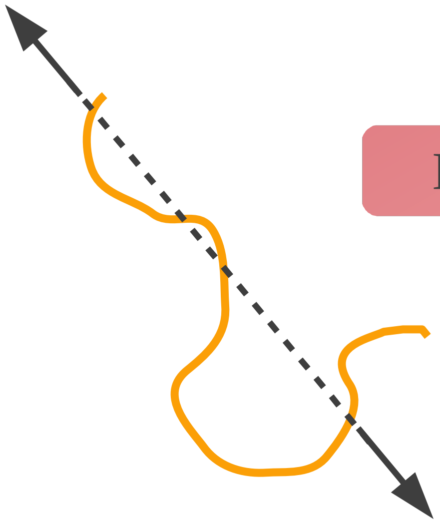
$$L_{0\text{ellips.}} \geq L_{0\text{sphere}}$$

→ anisotropy ≈ angular initial length variation

# Fibers recruitment



Tissue deformation >> Fibers deformation



How to consider the non-complete fibers recruitment?

$$\longrightarrow \nu = (\underline{u}.\boldsymbol{E}.\underline{u})^2 + 1$$

Simplest possible measure [Forest2009]

macro deformation | micro deformation per direction

$$\boldsymbol{F} \Longrightarrow \nu \sim \underline{u}.\boldsymbol{F}^4.\underline{u}$$

$$\boxed{\underline{M} = \begin{pmatrix} C \\ N \end{pmatrix}}$$

Material parameters

Non-affine transformation of the fibers

↓

Decrease in apparent global tissue rigidity

<u>Stiffness</u>

| | |
|---|---|
| Protein | ~ **GPa** |
| Fiber | ~ **MPa** |
| Tissue | ~ **kPa** |

[Sasaki1996,Sherman2015]

→ NON-LINEAR DEFORMATIONS PENALIZATION

# Results



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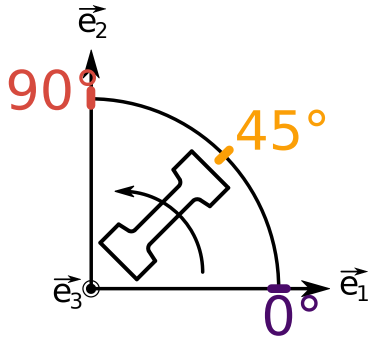


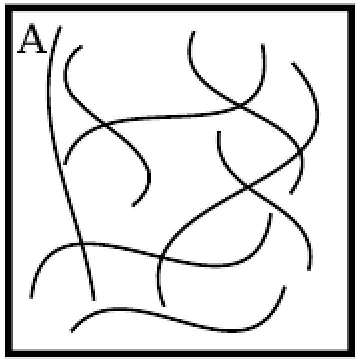


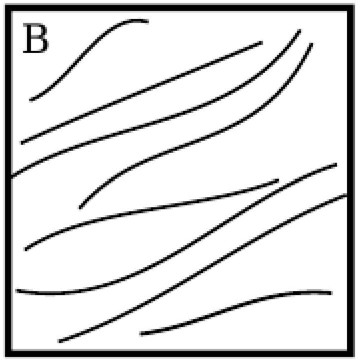


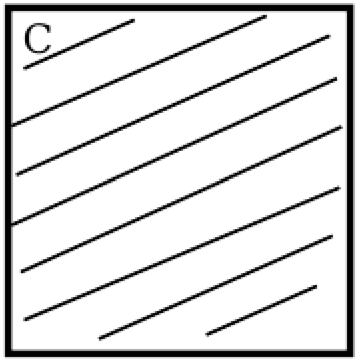


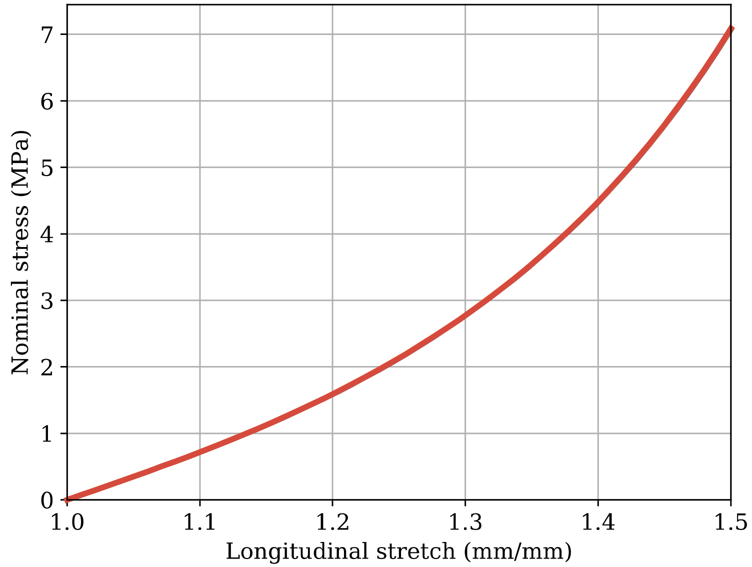


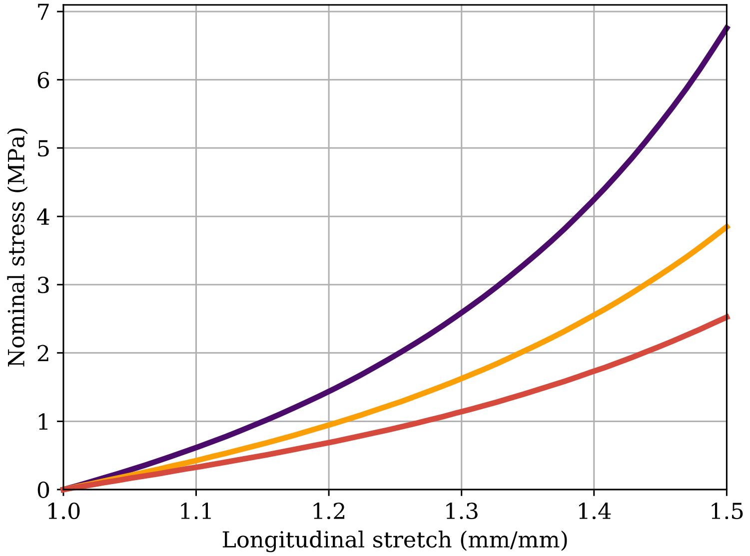


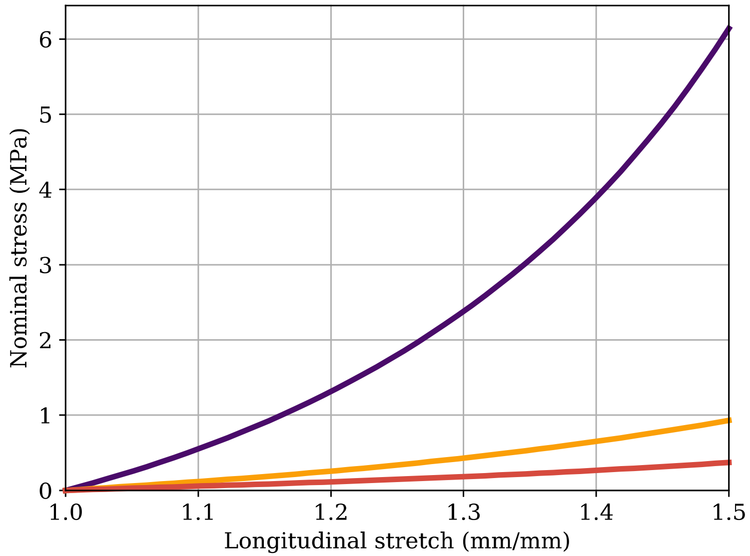


Same number of integration points = STABILITY

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# MFront implementation



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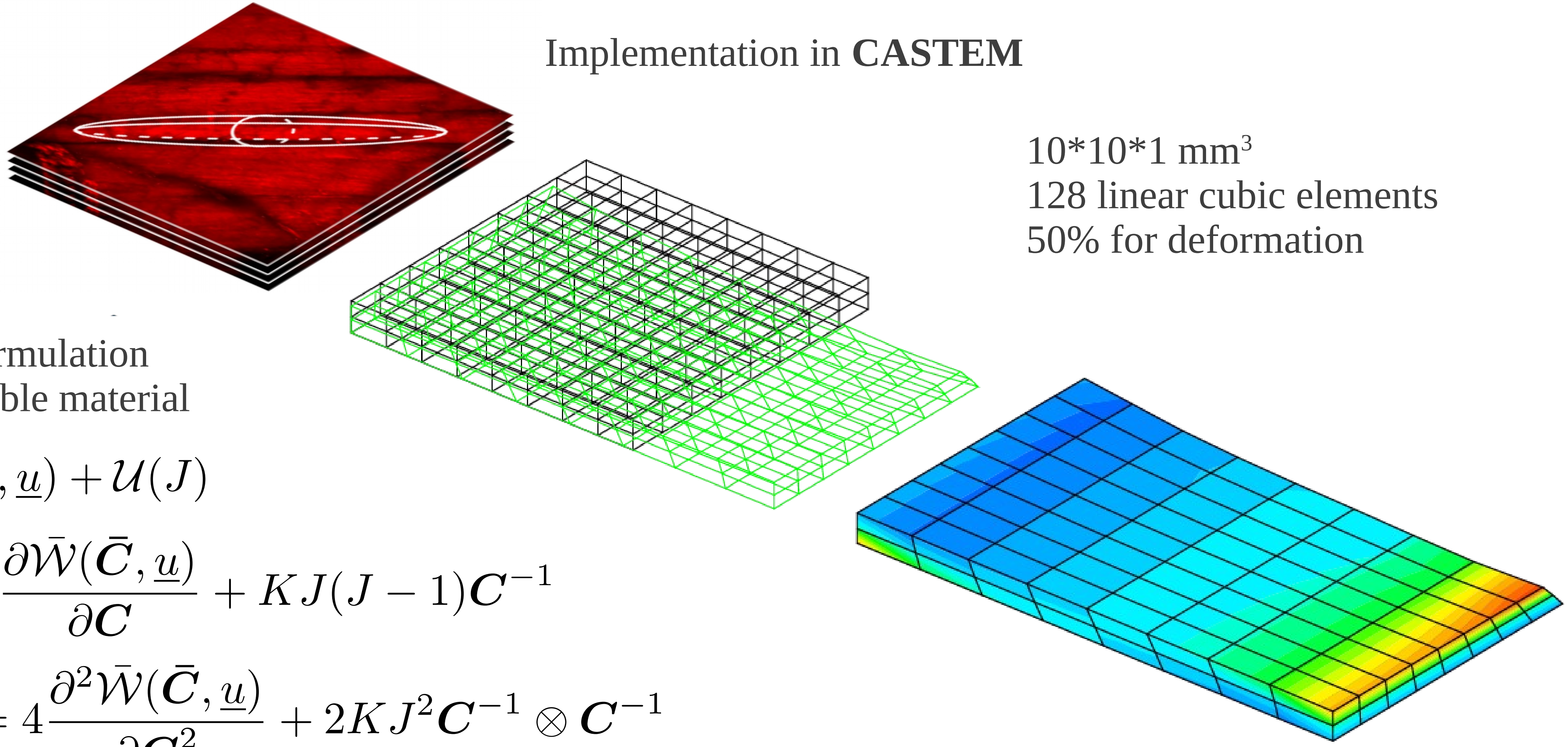
Implementation in **CASTEM**



10*10*1 mm$^3$
128 linear cubic elements
50% for deformation

Deviatoric formulation
for compressible material

$$\mathcal{W} = \bar{\mathcal{W}}(\bar{\boldsymbol{C}}, \underline{u}) + \mathcal{U}(J)$$

$$\hookrightarrow \boldsymbol{S} = 2\frac{\partial \bar{\mathcal{W}}(\bar{\boldsymbol{C}}, \underline{u})}{\partial \boldsymbol{C}} + KJ(J-1)\boldsymbol{C}^{-1}$$

$$\hookrightarrow \mathbb{C} = 4\frac{\partial^2 \bar{\mathcal{W}}(\bar{\boldsymbol{C}}, \underline{u})}{\partial \boldsymbol{C}^2} + 2KJ^2\boldsymbol{C}^{-1} \otimes \boldsymbol{C}^{-1}$$



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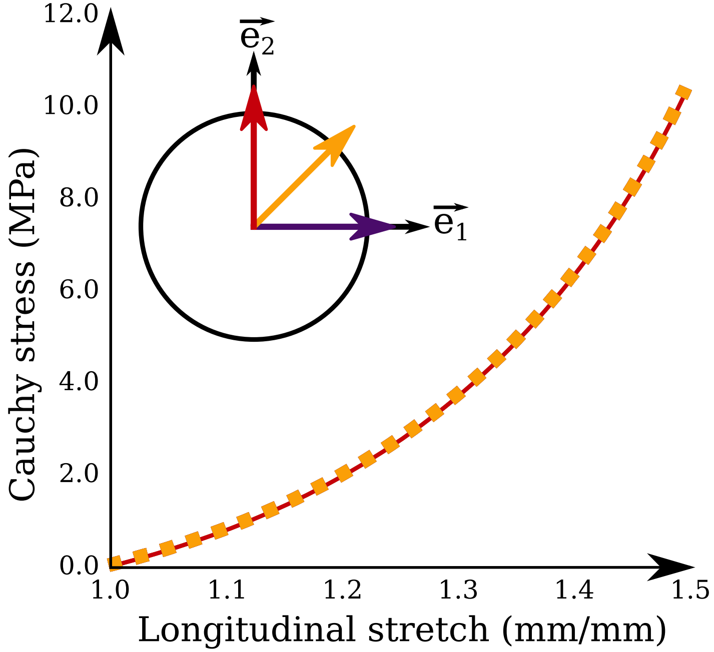
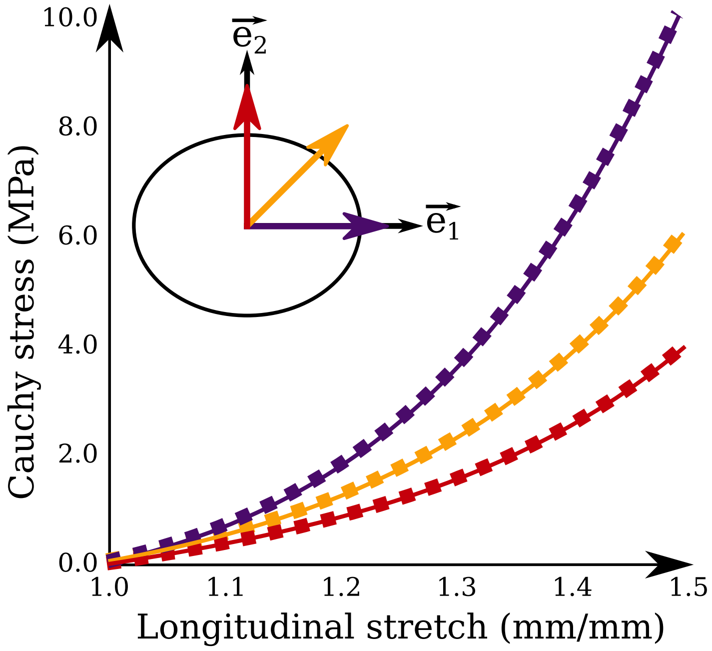
# Castem results

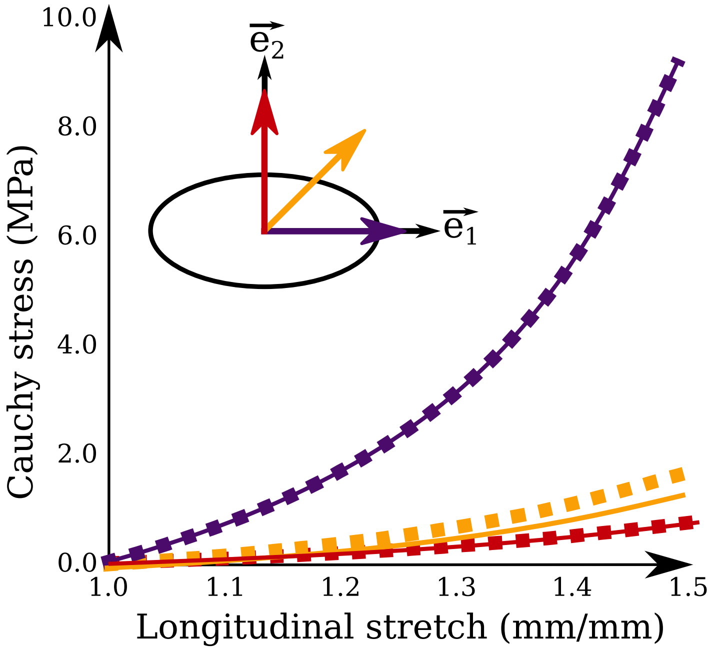
## Isotropy

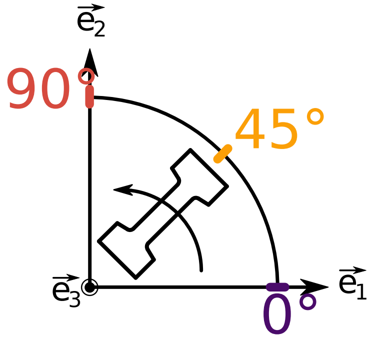



## Moderate anisotropy




## Huge anisotropy




■ ■ ■ ■ Numerical

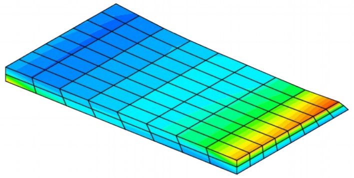
—— Theoretical

Each Gauss point → Σ/400
Very long

# Conclusion & outlooks

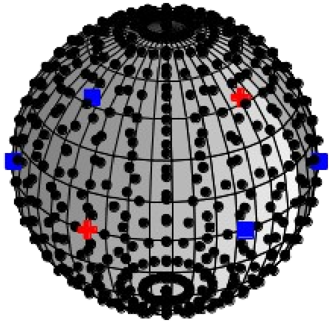
Penalization of the **deformations** instead of the stresses
→ Non-affinity of the fibers displacement

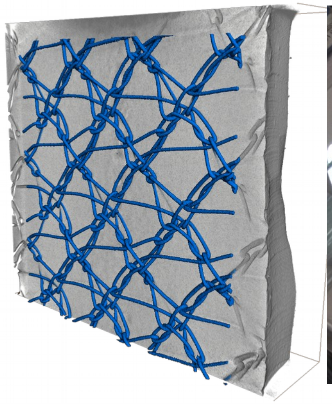
Successful implementation in a **FEM code**

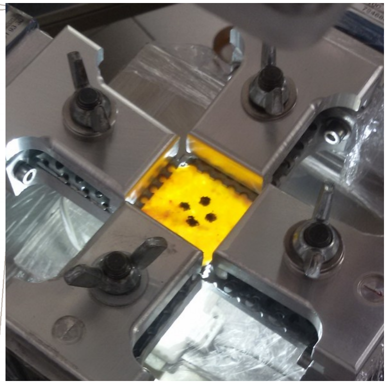


**FEM simulation**

**Multi-axial** modeling
Damaging process
Prosthetic mesh
Multi-scale anisotropy







Approach combining FEM and image analysis
→ reverse approach for **patient-specific care**

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# Merci pour votre attention


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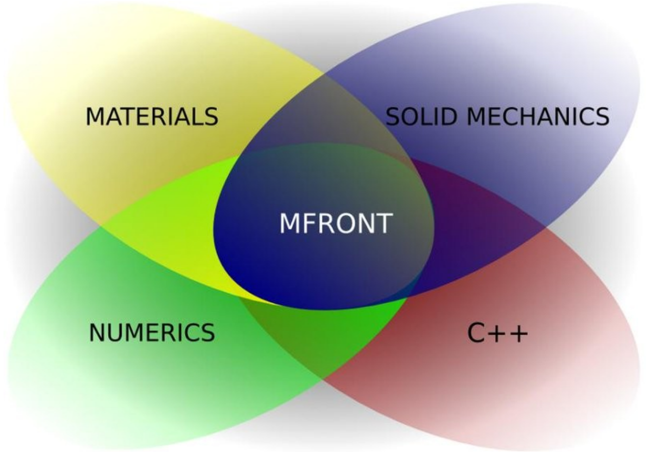


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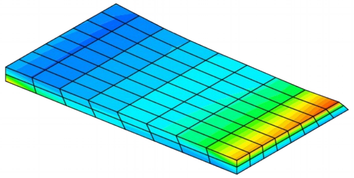
# Conclusion & outlooks

Penalization of the **deformations** instead of the stresses
→ Non-affinity of the fibers displacement

**Removal** of the integration needed for micro-sphere model
→ Significant acceleration and simplification



**FEM** simulation

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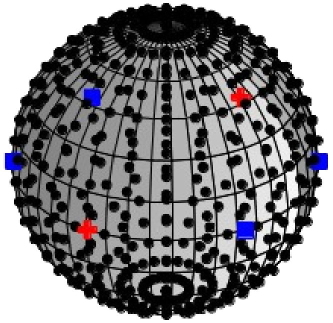

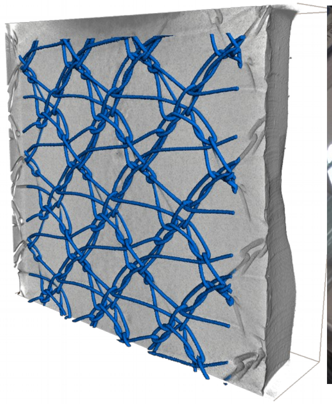

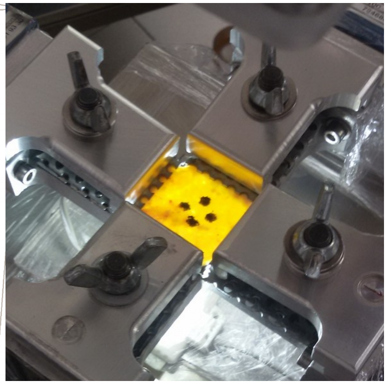

Approach combining FEM and image analysis
→ reverse approach for **patient-specific care**