Ecole Nationale Supérieure des Mines
SAINT-ETIENNE

Centre for Health Engineering

Centre Ingénierie et Santé

LCG CNRS UMR 5146

www.emse.fr

Pierre Badel + colleagues

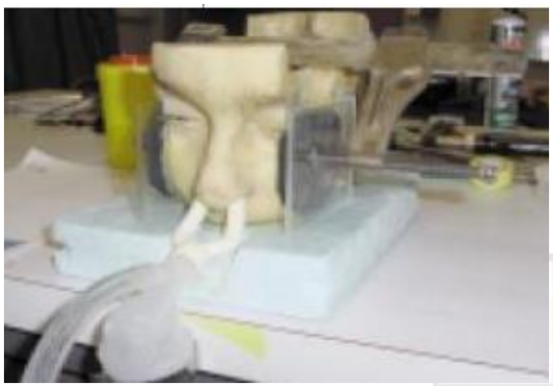
Identification of vascular soft tissue mechanical properties

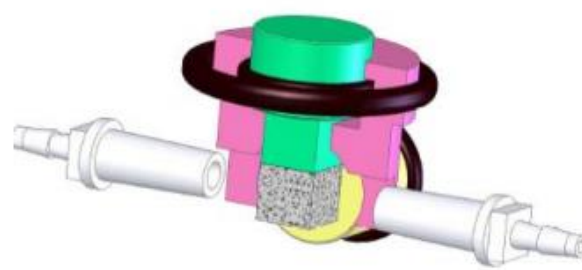
MINISTÈRE DE L'ÉCONOMIE
DES FINANCES ET DE L'INDUSTRIE

➲ Center for Biomedical and Healthcare Engineering

Multi-disciplinary
➔ Translational research

Close collaboration with clinical and industrial partners





➲ Soft Tissue Biomechanics group

Diagnosis

Healthcare & MD optimization

Translational research

Soft tissue / structure relationship

Multi-modality imaging
+
Mechanical modeling

Pathological (large) arteries

Osteo-articular system

Skin and sub-cutaneous tissue

Understanding the mechanical behavior of these tissues

Study of the mechanical action of medical devices

- Introduction
- **A few words on inverse identification methods applied to soft tissue biomechanics**
- **Ascending thoracic aortic aneurysm**
  - Hyper-elastic model identification
  - Rupture characterization
- Perspectives

Inverse identification

- Introduction
- **A few words on inverse identification methods applied to soft tissue biomechanics**
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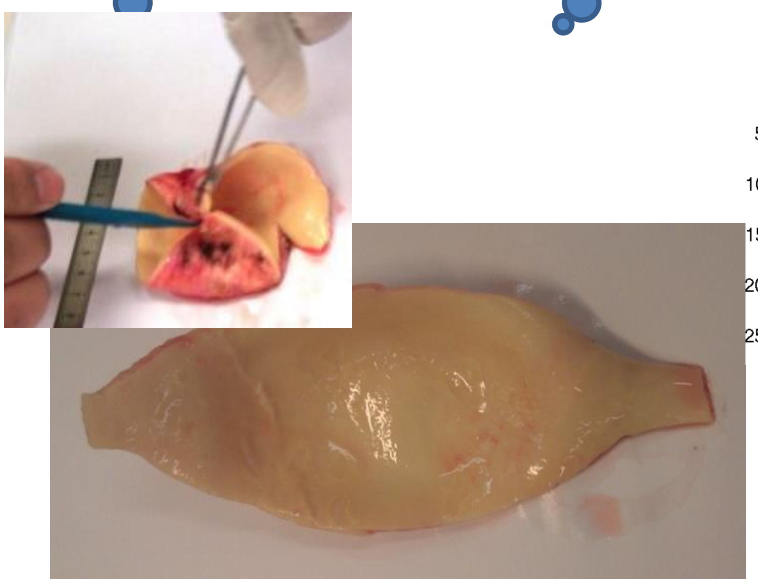
➲ Why inverse identification in soft tissue biomechanics?

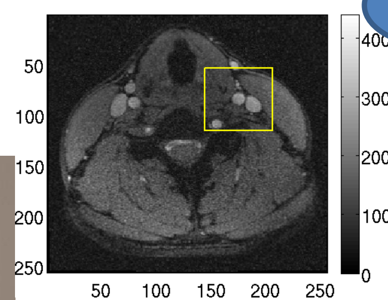
What kind of specimen?

What kind of test?

In vitro?
Access to tissue ?
Destructive?
Representatitve of what we are looking for?

In vivo?
What is the loading?
What is the geometry?





[sigvaris.fr]

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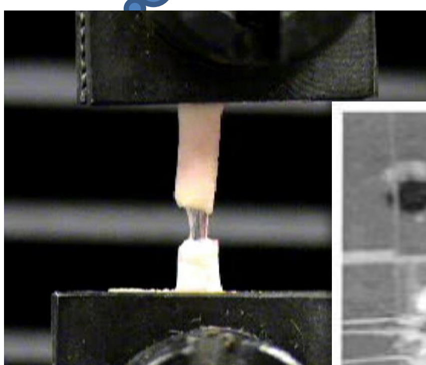
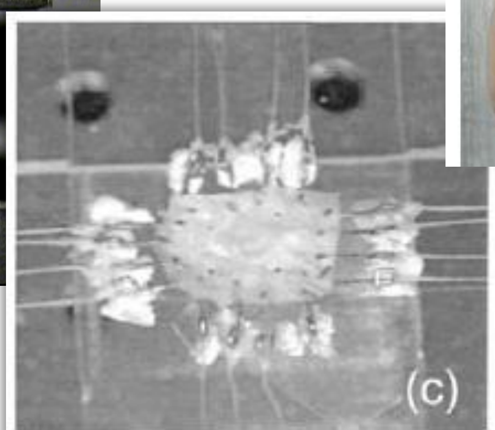
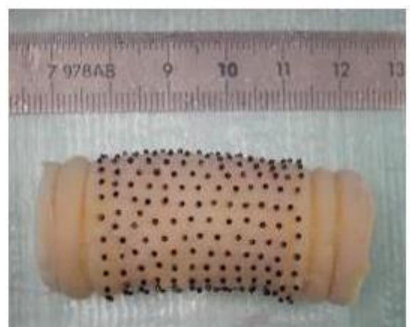
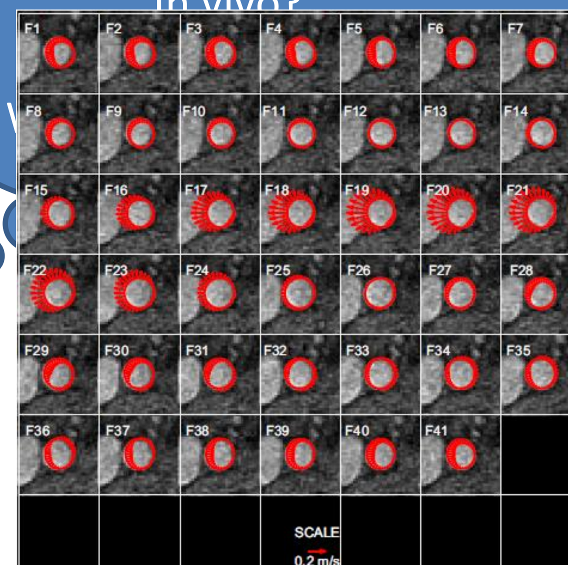
In vivo?


[Duprey, 2010]



[Sacks, 2000]


[Genovese, 2009]



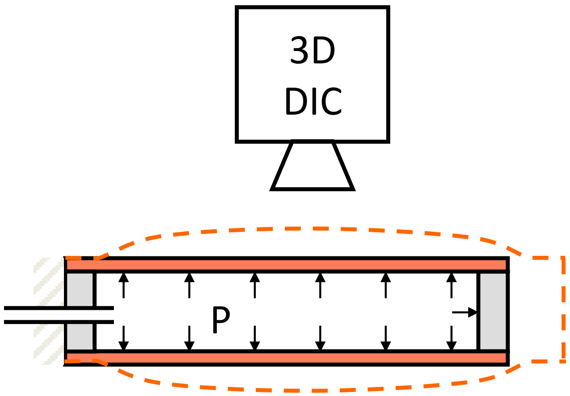
[Avril, 2011]

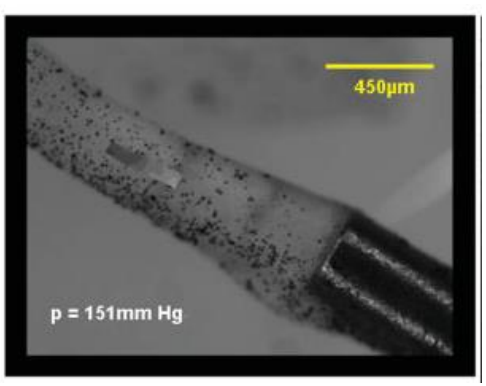
➲ Why inverse identification in soft tissue biomechanics?

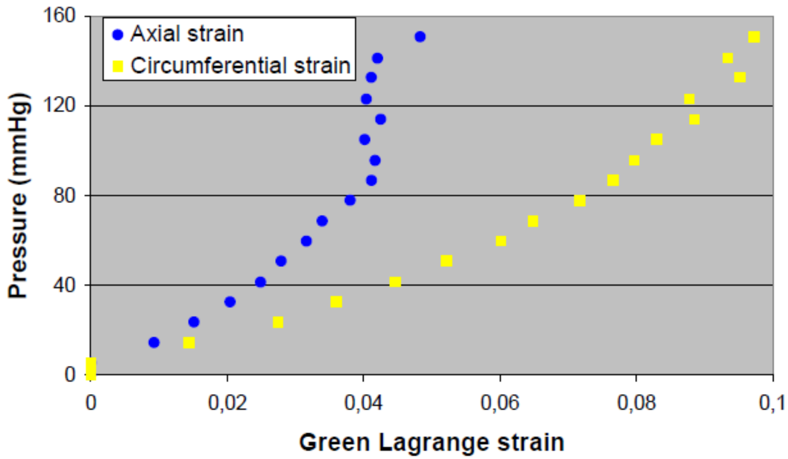
- ➲ **Relevant experimental data is complex (geometry, boundary conditions…)**
- ➲ **Complex tissues (non-linearity, heterogeneity…)**
- ➲ **Models are often complex**

➲ In vitro ex.: Inflation/extension, mouse carotid artery

(coll. M. Sutton, U South Carolina, USA)



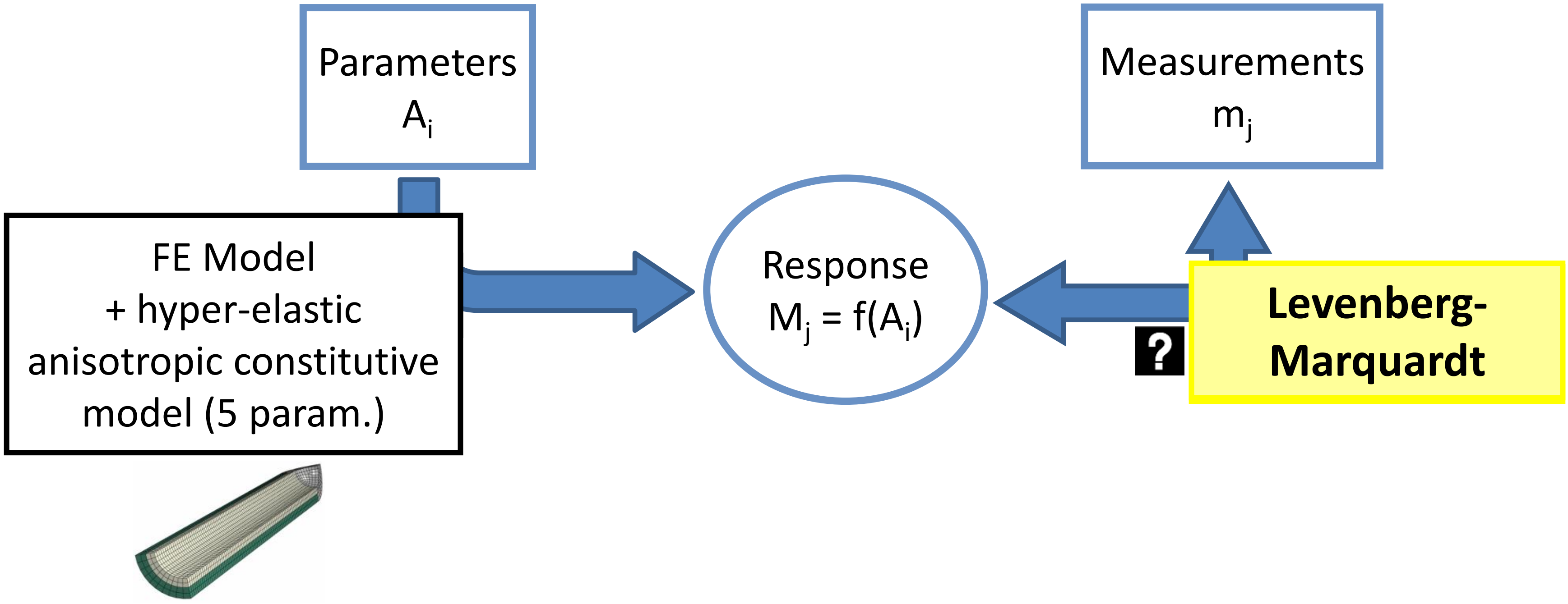




Mechanical properties of the artery?

➲ In vitro ex.: Inflation/extension, mouse carotid artery

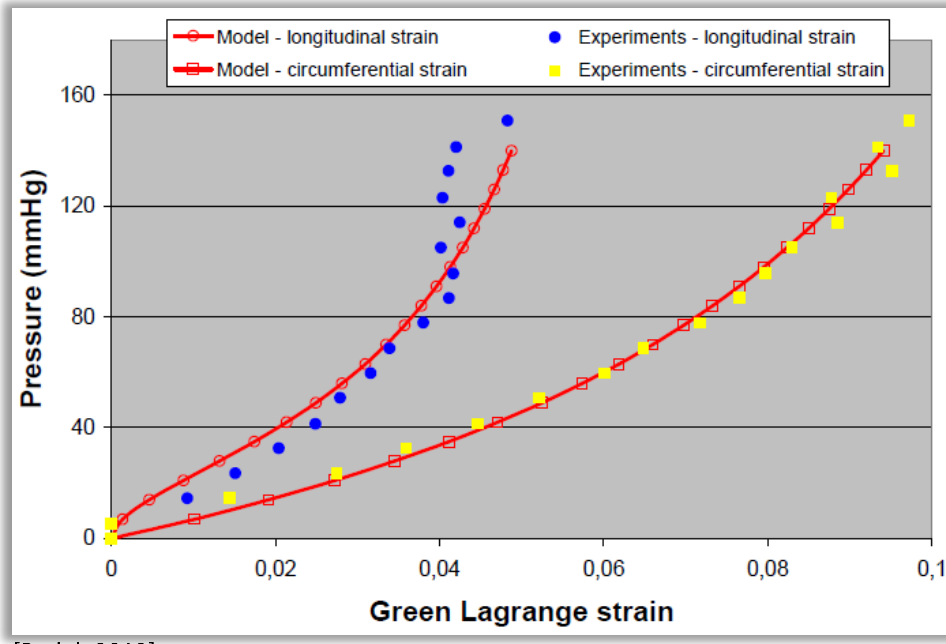
(coll. M. Sutton, U South Carolina, USA)



Finite Element Updating

➲ In vitro ex.: Inflation/extension, mouse carotid artery

(coll. M. Sutton, U South Carolina, USA)

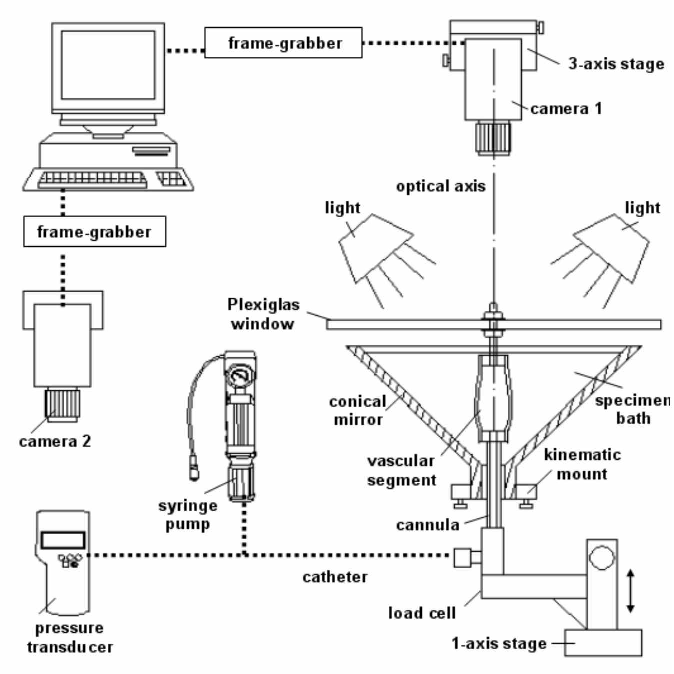


[Badel, 2012]

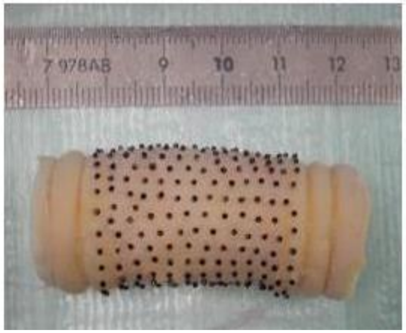
Finite Element Updating

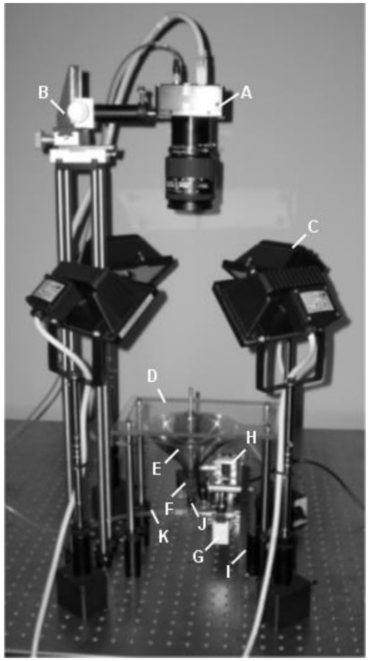
➲ In vitro ex.: Inflation of a pig aorta

(coll. K. Genovese, U della Basilicata, Italy)



[Genovese, 2009]

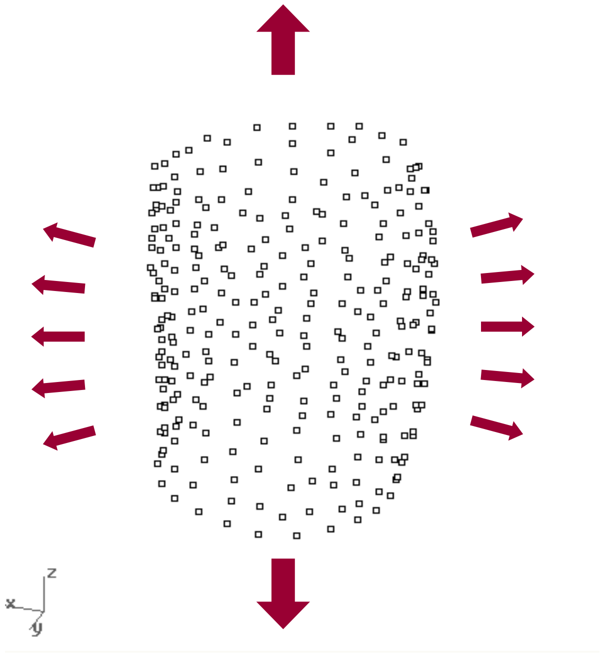




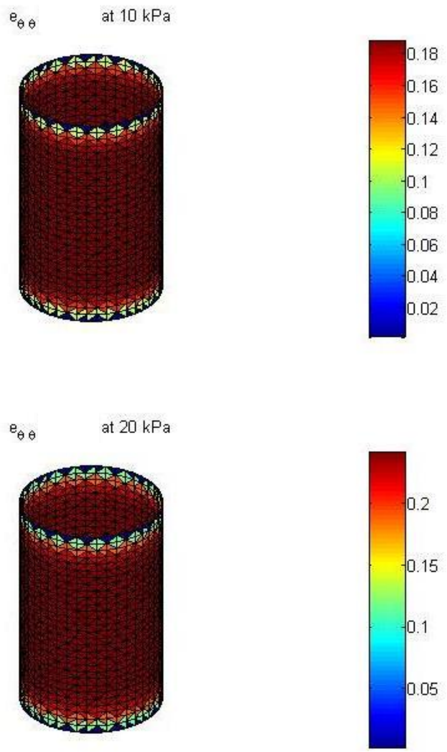
initial length	$L_0 \approx 35$ mm
initial outer radius	$r_0 \approx 10$ mm
initial thickness	$e_0 \approx 1.3$ mm

➲ In vitro ex.: Inflation of a pig aorta

(coll. K. Genovese, U della Basilicata, Italy)



Green Lagrange strain reconstruction



➲ In vitro ex.: Inflation of a pig aorta

Principle of virtual work with given test functions

$$-\int_V \sigma_{ij}:\varepsilon_{ij}^* \, dV + \int_{\partial V} T_i u_i^* \, dS = 0$$

Constitutive model (unknown parameters)

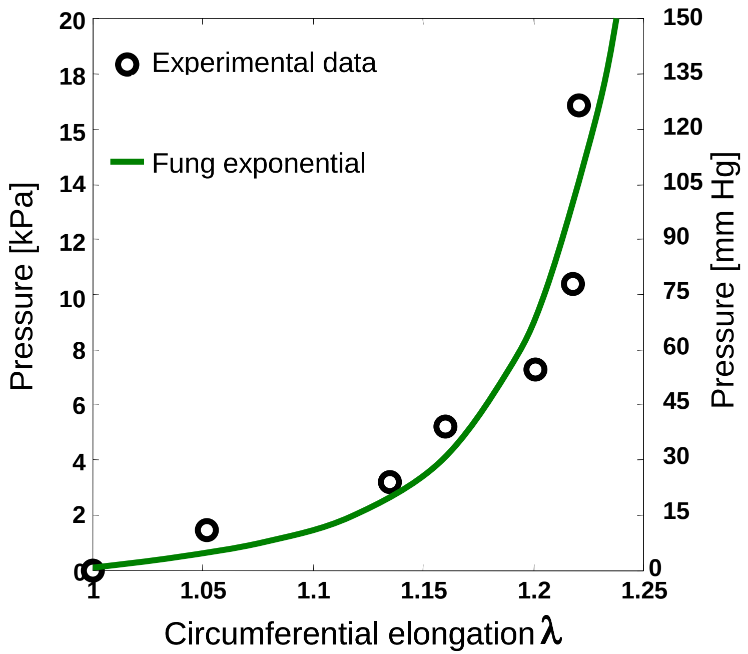
$$-\int_V \sigma_{ij}\left(\underline{\underline{E}}, A\right):\varepsilon_{ij}^* \, dV + \int_{\partial V} T_i u_i^* \, dS \overset{?}{\Leftrightarrow} 0$$

Equilibrium ⇔ Actual properties

Virtual Fields Method

➲ In vitro ex.: Inflation of a pig aorta

(coll. K. Genovese, U della Basilicata, Italy)



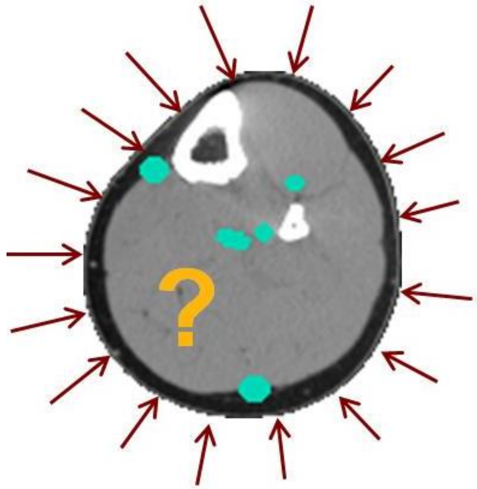
[Avril S, Badel P, Duprey A, 2010]

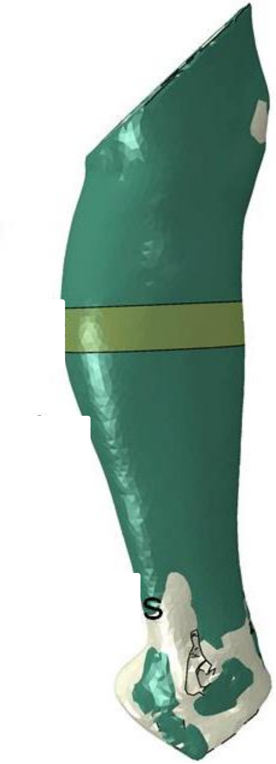
Virtual Fields Method

➲ In vivo ex.: Soft tissues of the leg

Pressure transmission mechanisms?? … FE modeling of the action of compression socks

http://www.Sigvaris.fr



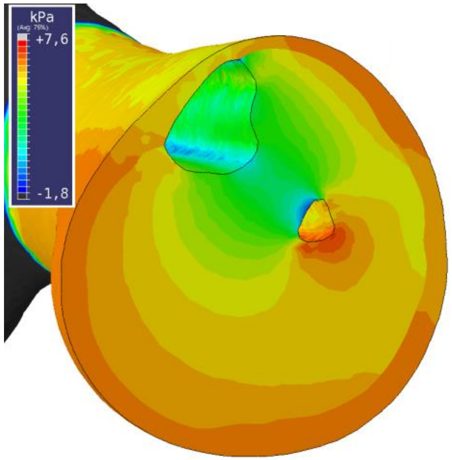


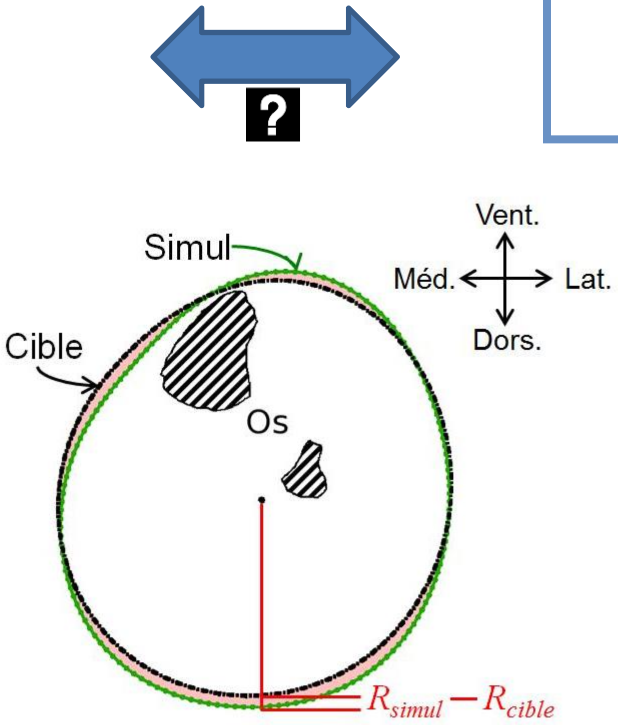
Properties of the leg's soft tissues?

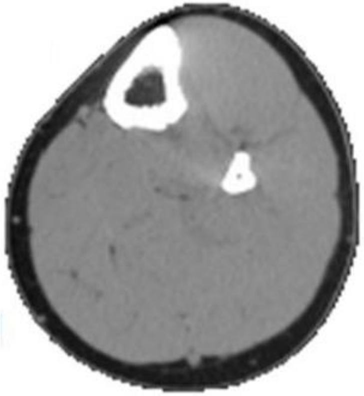
➲ In vivo ex.: Soft tissues of the leg

FE model
Compressed leg

CT-scan image
leg + compression sock



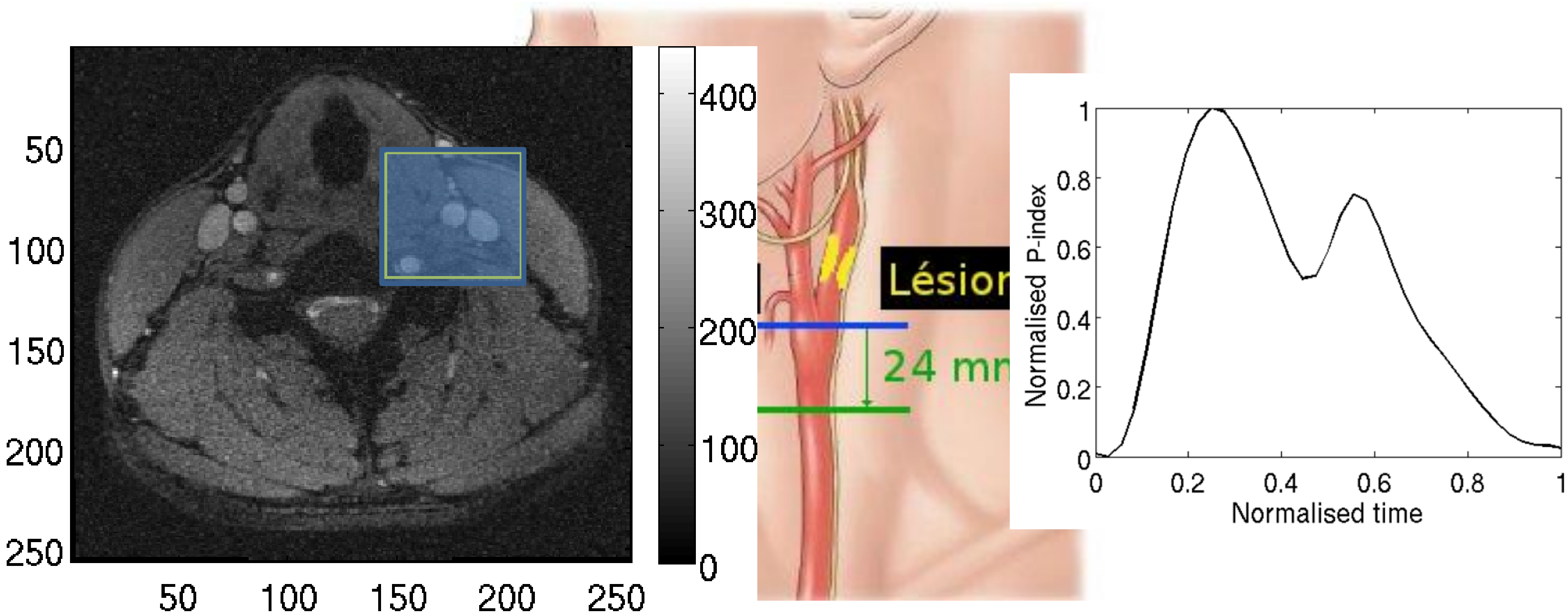




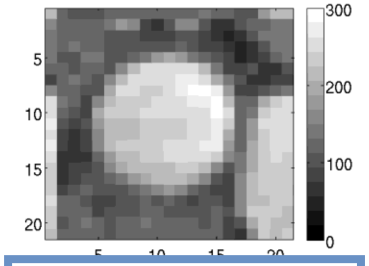
FE Updating + specific cost function

➲ In vivo ex.: elastic properties of human carotid arteries

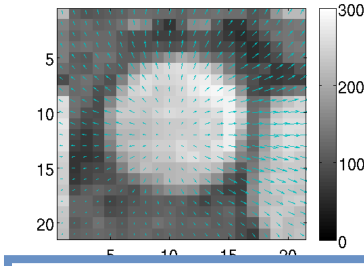
The data we can access



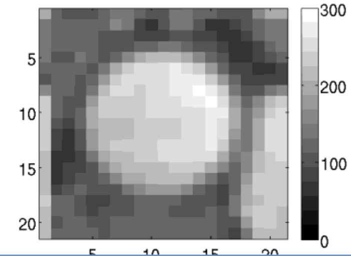
➲ In vivo ex.: elastic properties of human carotid arteries



Low pressure
MRI image



Reconstruction of a high pressure image



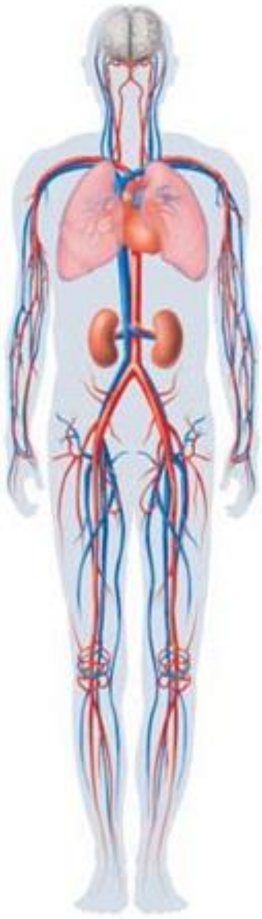
High pressure
MRI image

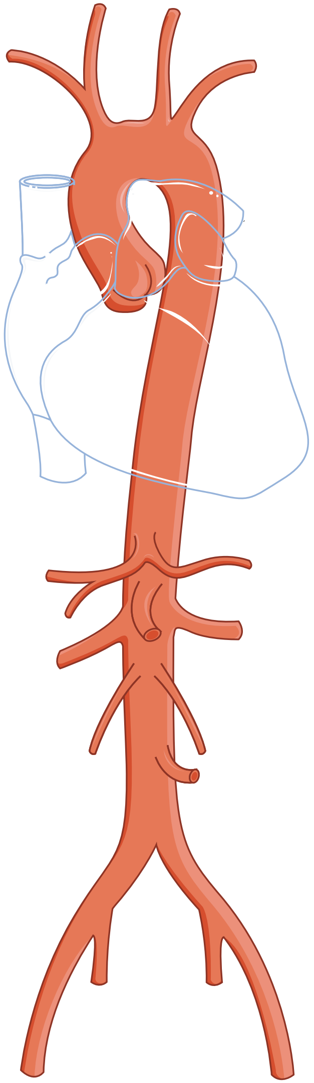
FE model

FE Updating + specific cost function

Application to ATAA

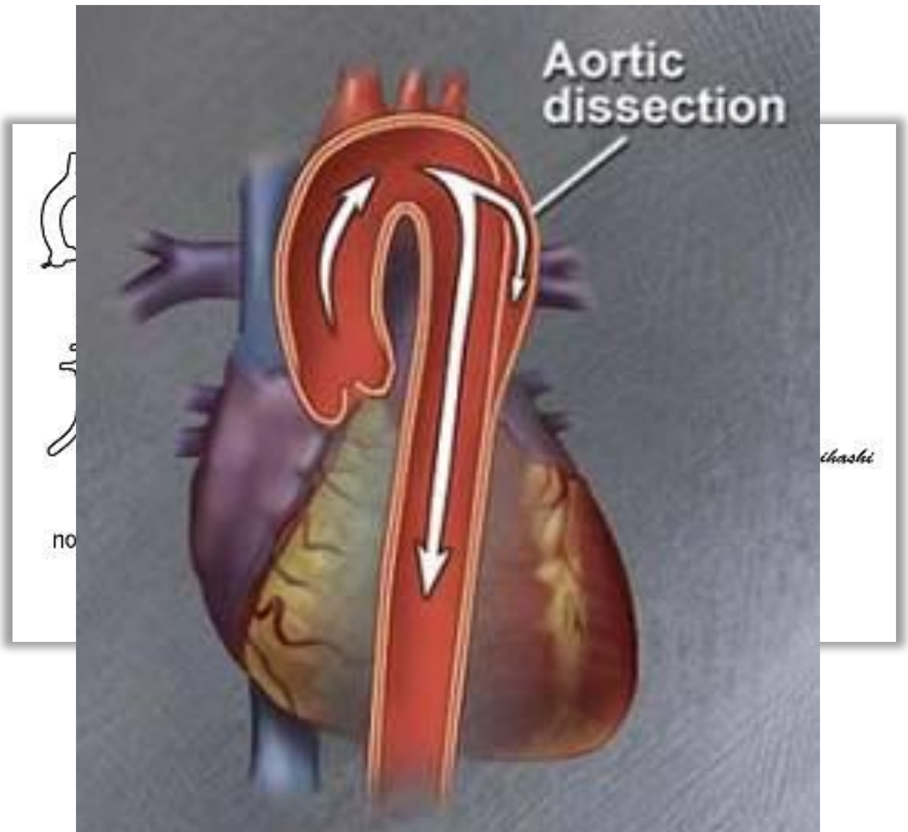
- Introduction
- **A few words on identification methods applied to soft tissue biomechanics**
- **Ascending thoracic aortic aneurysm (PhD A. Romo)**
  - Hyper-elastic model identification
  - Rupture characterization
- Perspectives

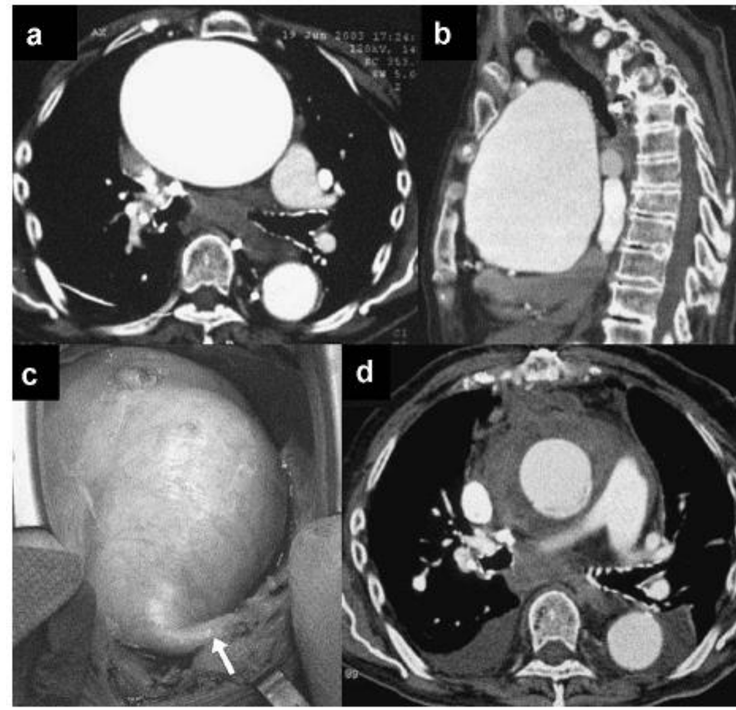




Motivation

➲ … examples of diseases…



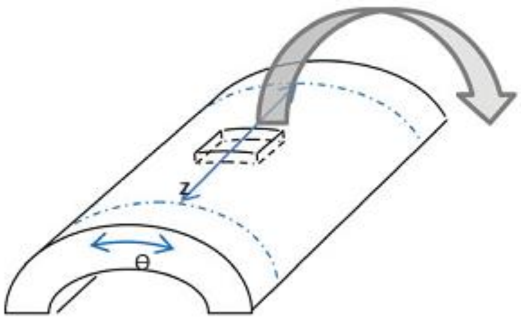


[Chavanon, 2006]

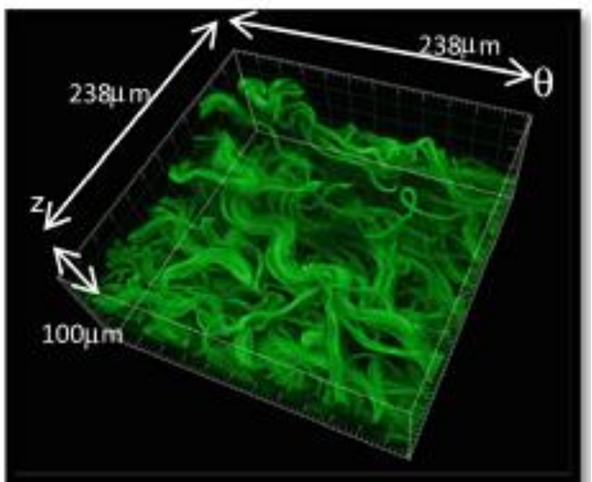
Ascending aorta

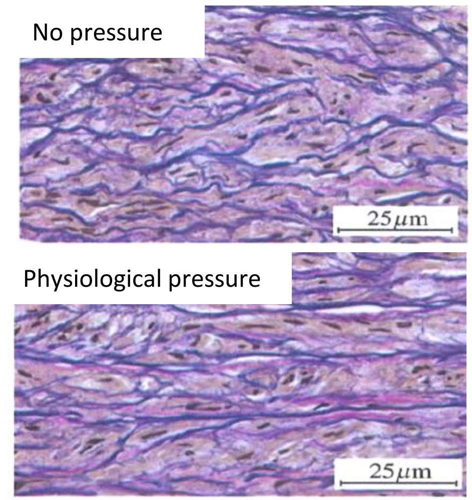
… which motivate research!

Structure

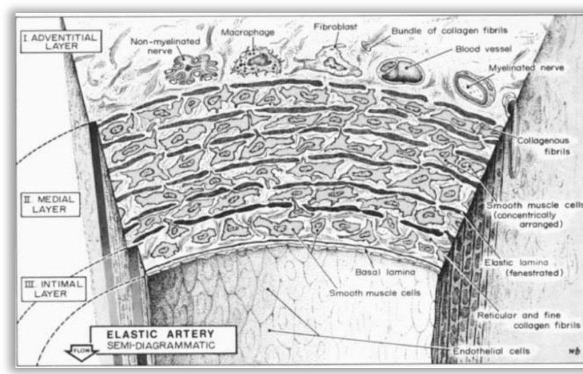


[Rezakhaniha et. al., 2011]





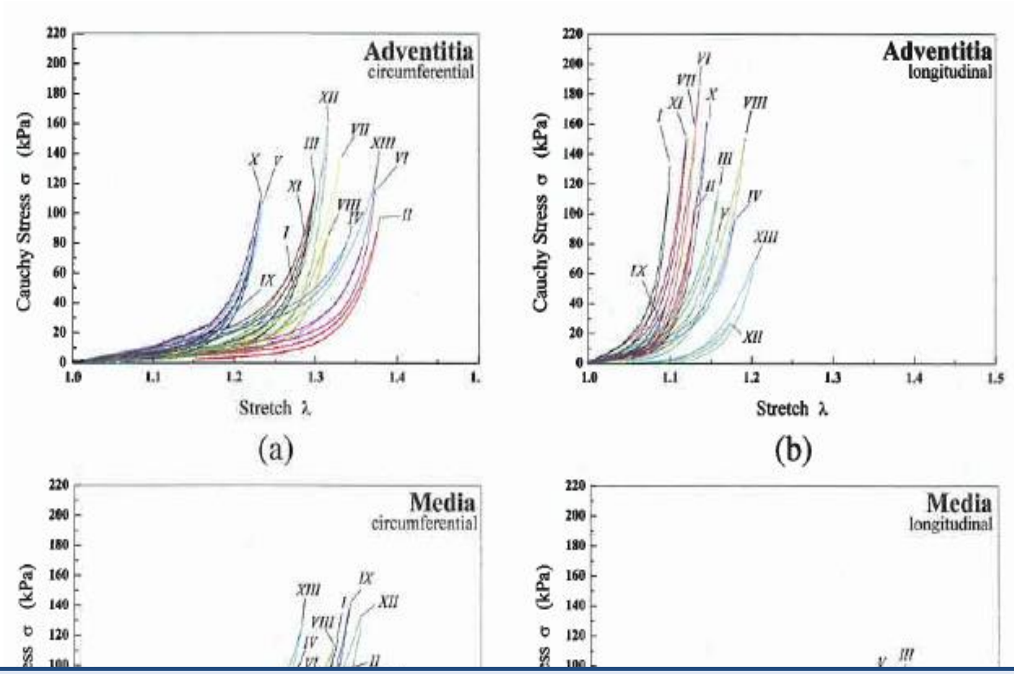
[Sommer et. al. 08]



[Rhodin, 1979]

Motivation

➲ Mechanical behavior well known, qualitatively



➲ **Patient-specific properties?**

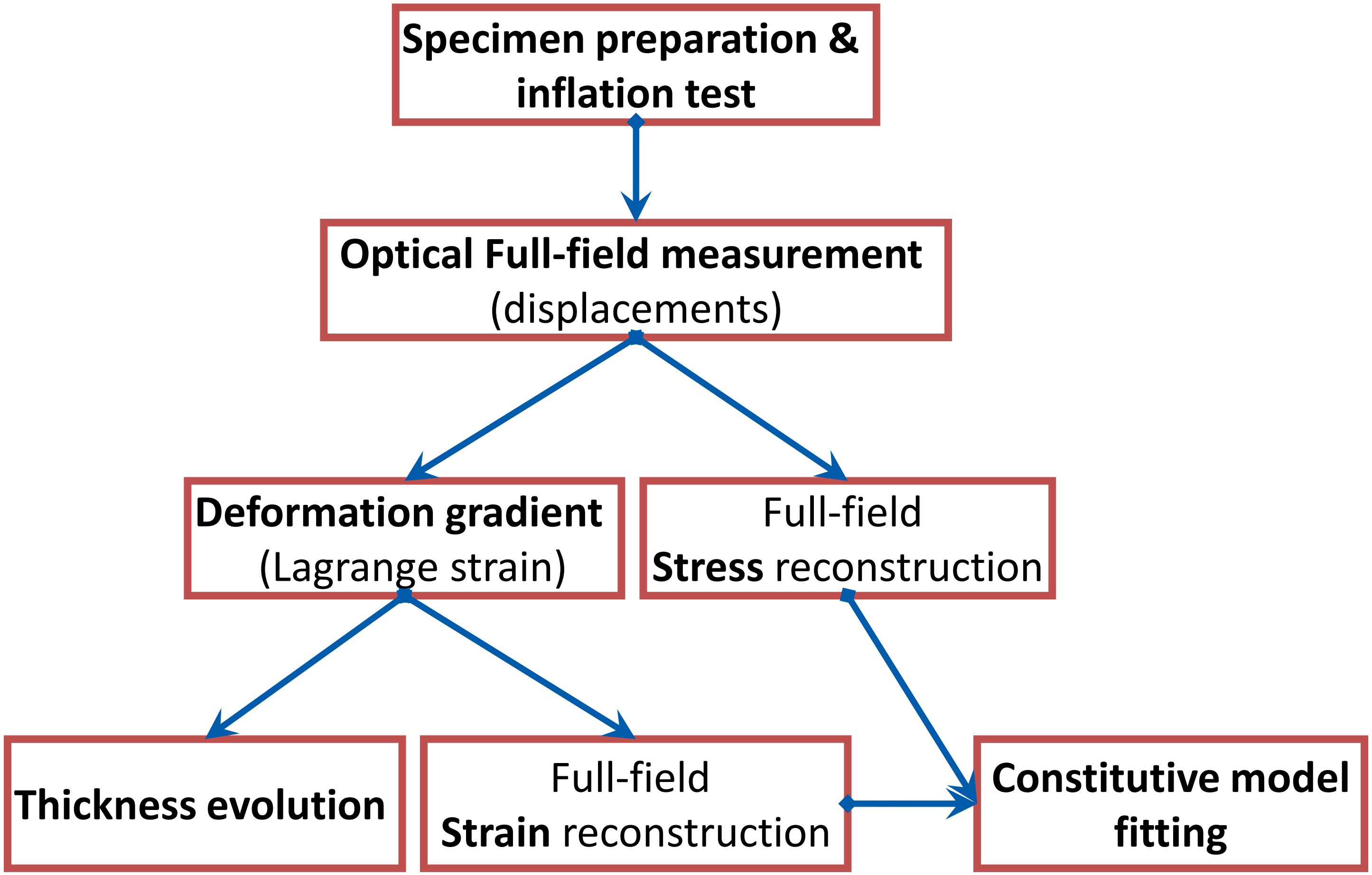
➲ **Aneurysm rupture strength/characterization?**

➲ **Damage/rupture mechanisms?**

Methodology

➲ Our methodology

[Romo A, Badel P, Duprey A, Favre J-P, Avril S. In vitro Analysis of Localized Aneurysm Rupture. *J Biomech*. 2014]



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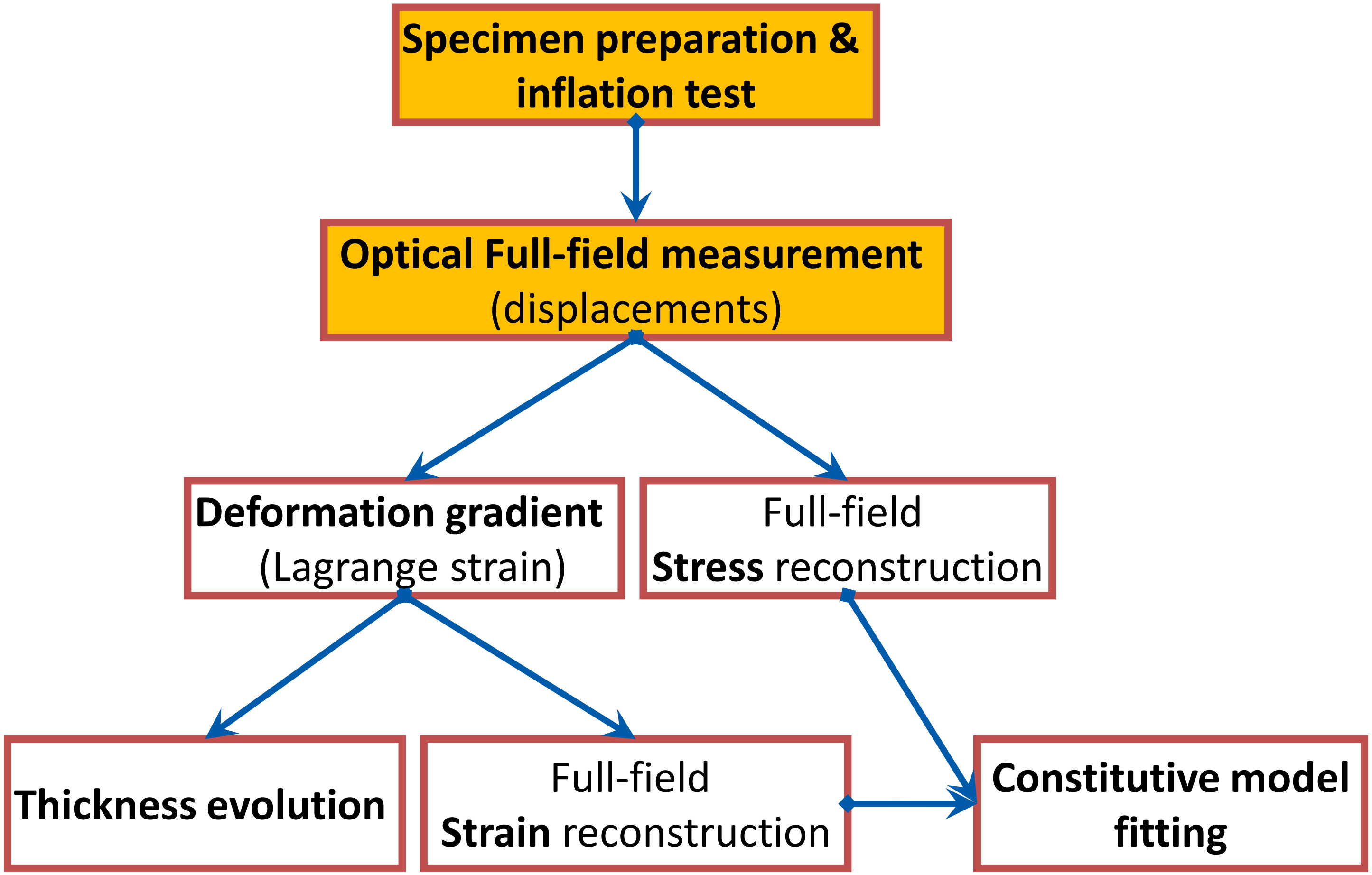
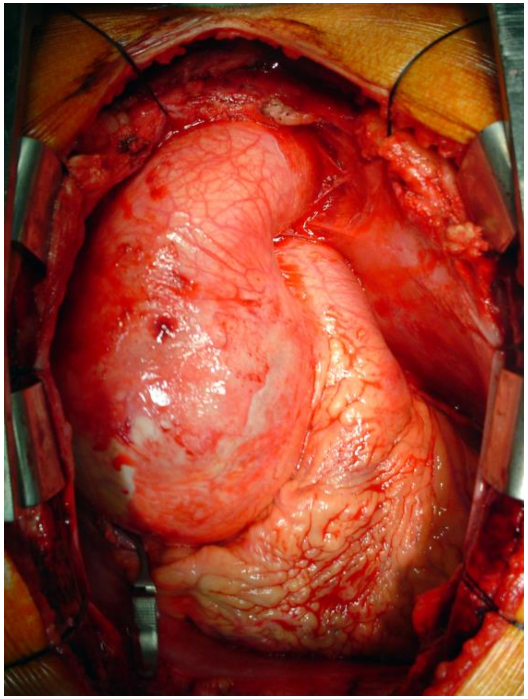
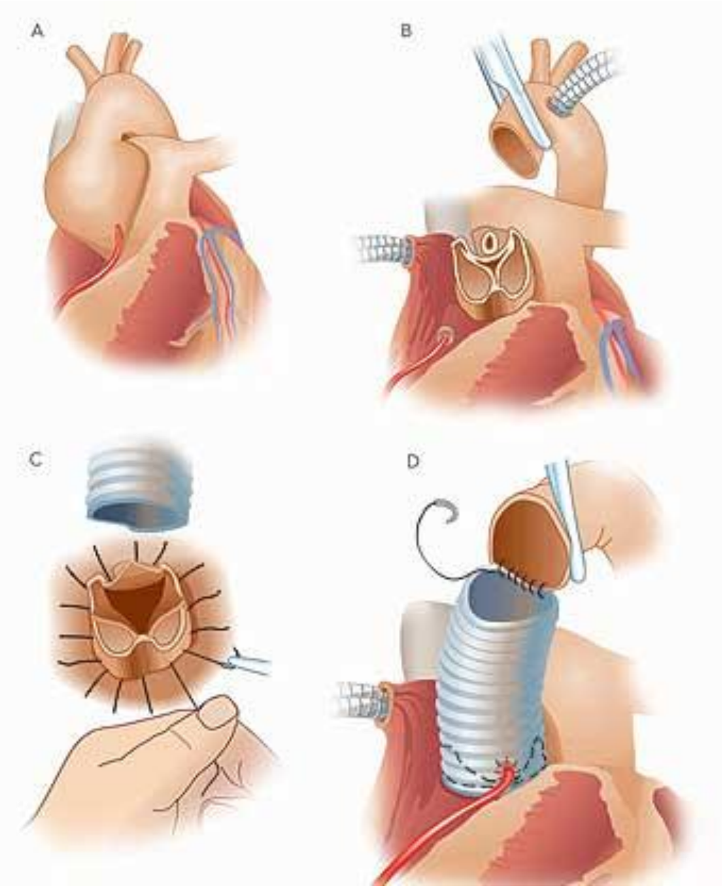


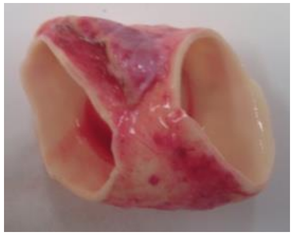
➲ Ascending Thoracic Aortic Aneurysm: Surgery

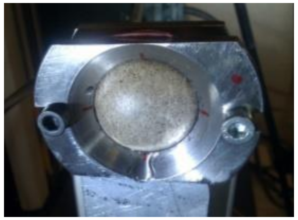




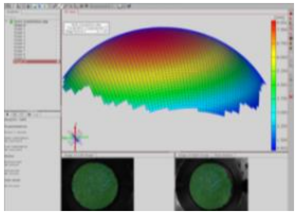
Experiment

➲ Exp: bulging test + full-field measurements





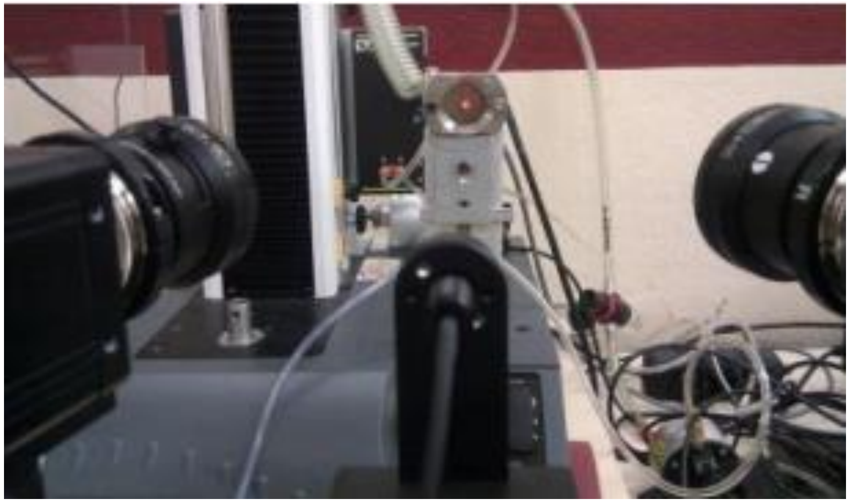
30 mm



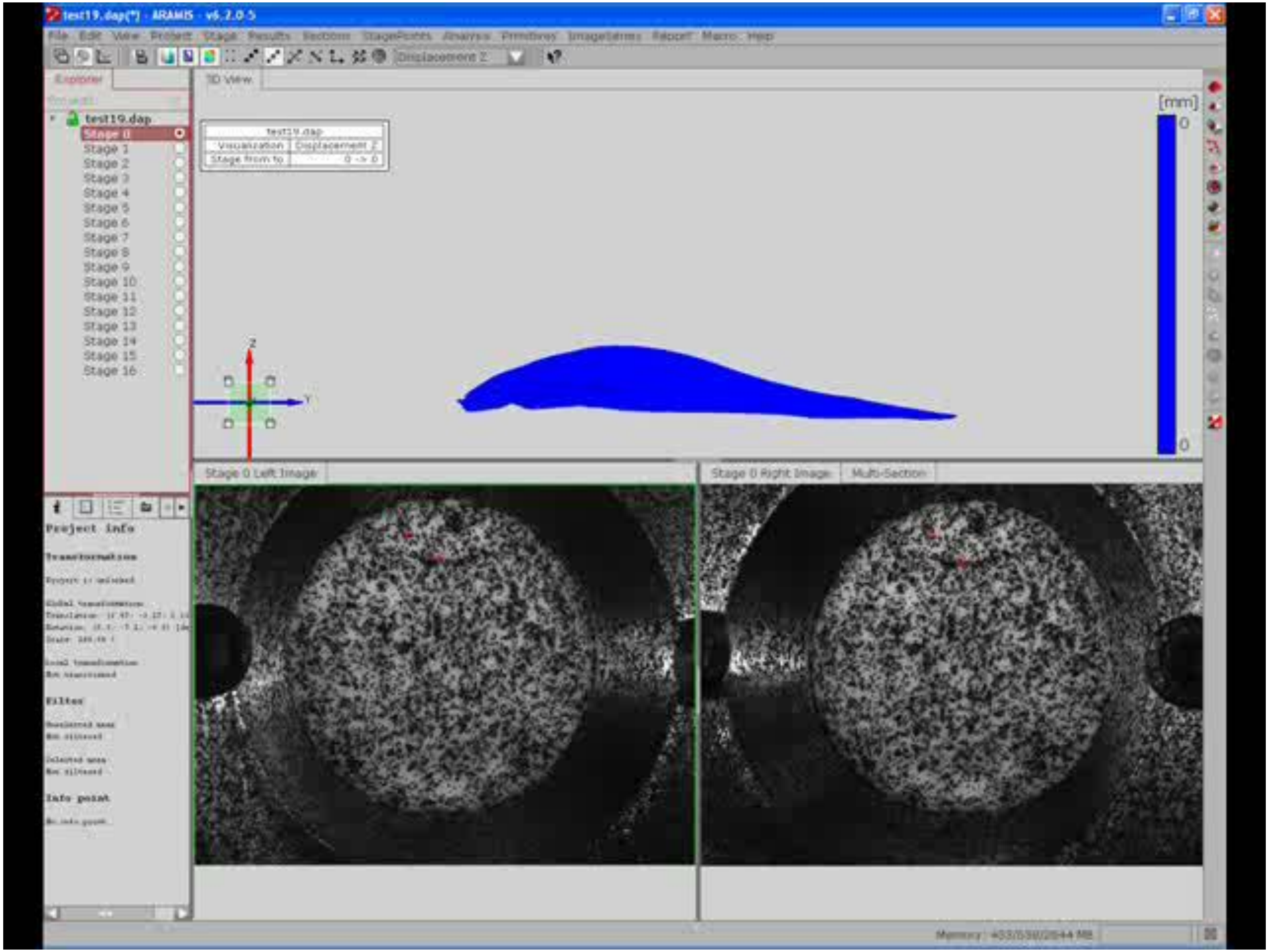
Reconstruction of a **3D surface**

\+

Rupture stress calculation



Experiment


test19.dap(*) - ARAMIS - v6.2.0-5
File Edit View Project Stage Results Sections StagePoints Analysis Primitives ImageSeries Report Macro Help
Explorer
3D View
test19.dap
Stage 0
Stage 1
Stage 2
Stage 3
Stage 4
Stage 5
Stage 6
Stage 7
Stage 8
Stage 9
Stage 10
Stage 11
Stage 12
Stage 13
Stage 14
Stage 15
Stage 16
[mm]
Project info
Stage 0 Left Image
Stage 0 Right Image
Multi-Section

Methodology

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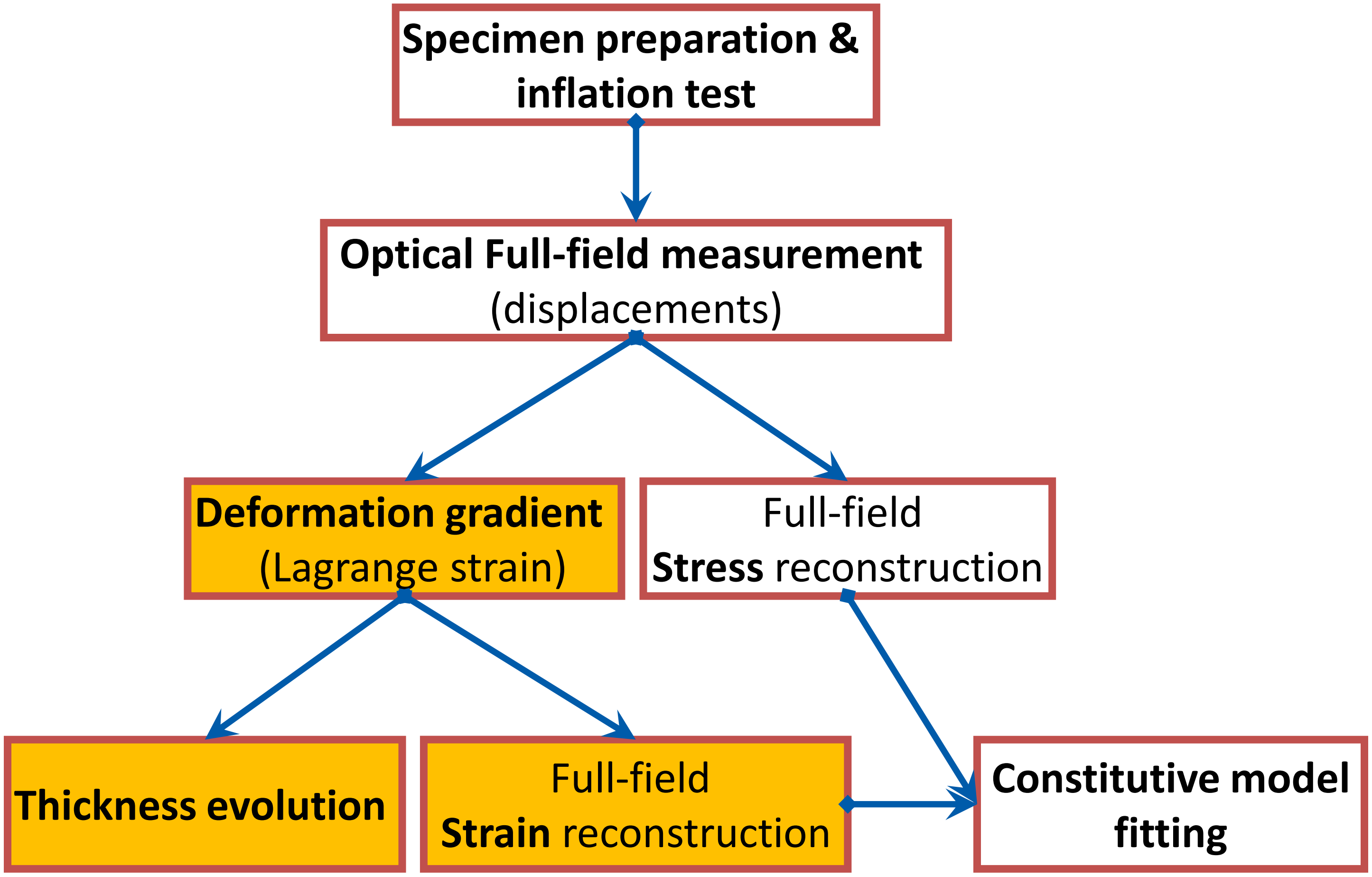
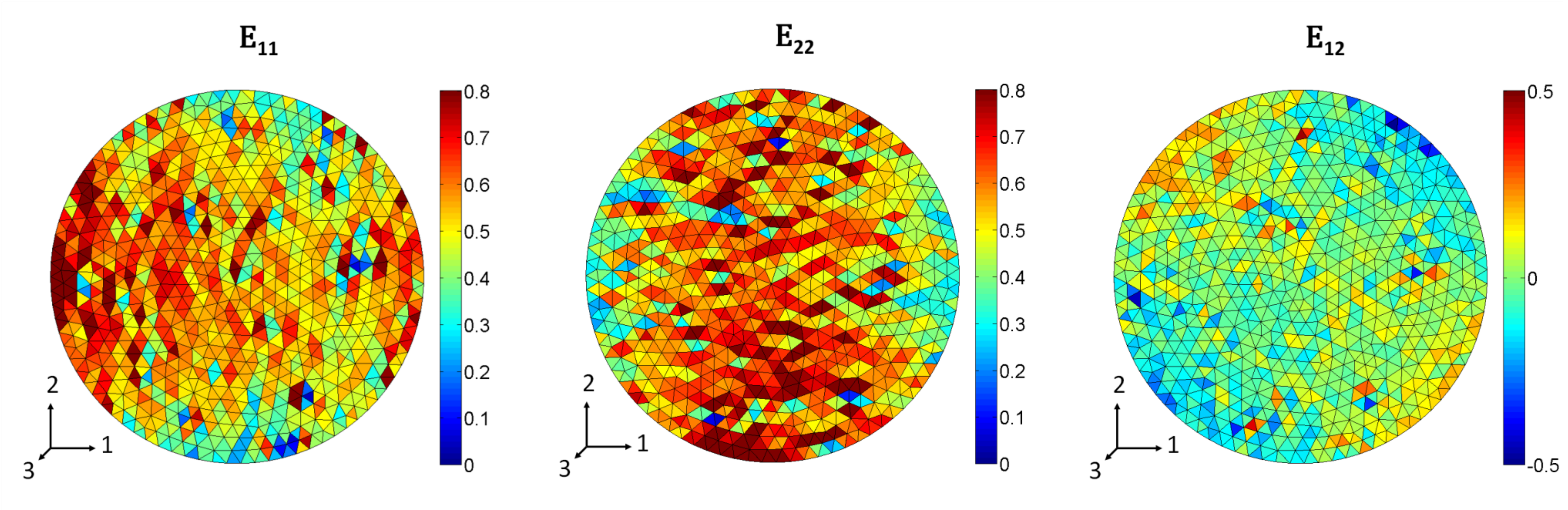


➲ Local strain field

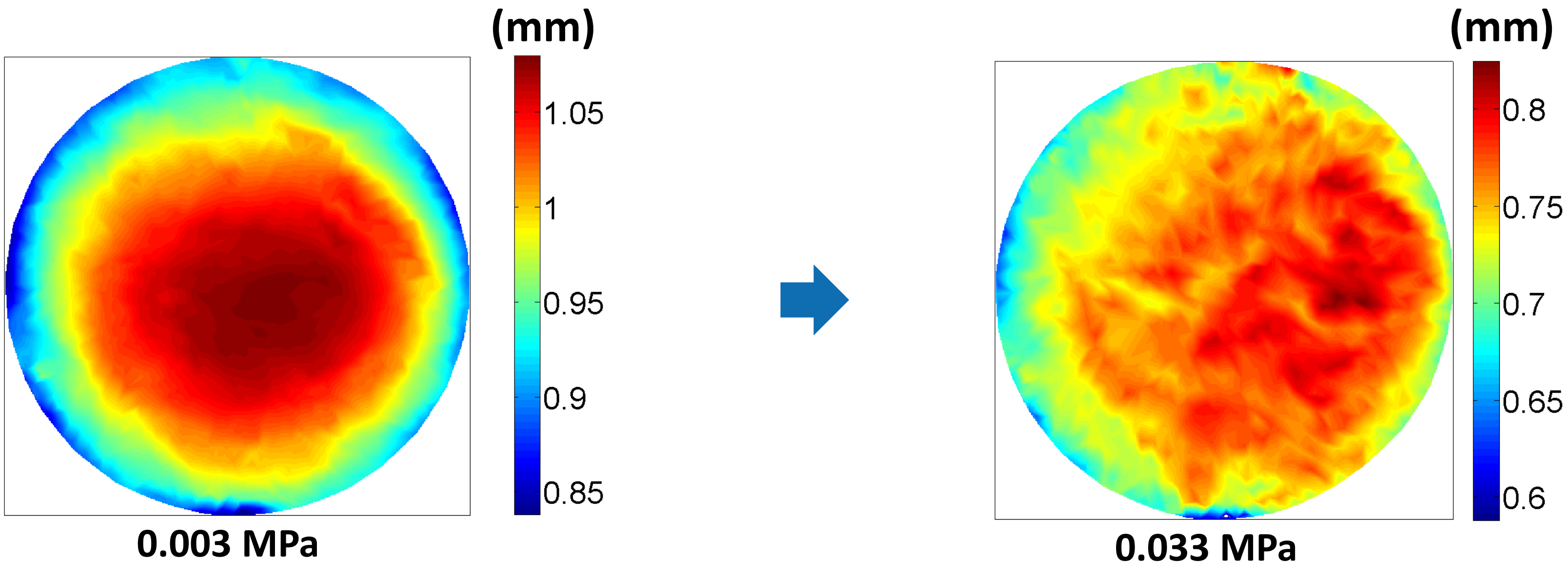


Green-Lagrange strain tensor

$$E = \frac{1}{2}(F^T F - I) = \begin{bmatrix} E_{11} & E_{12} \\ E_{21} & E_{22} \end{bmatrix}$$

➲ Thickness evolution

h_0 is the **homogeneous initial thickness**
+ assumption: **incompressibility**



$$h = \frac{h_0}{F_{11}F_{22} - F_{21}F_{12}}$$

Methodology

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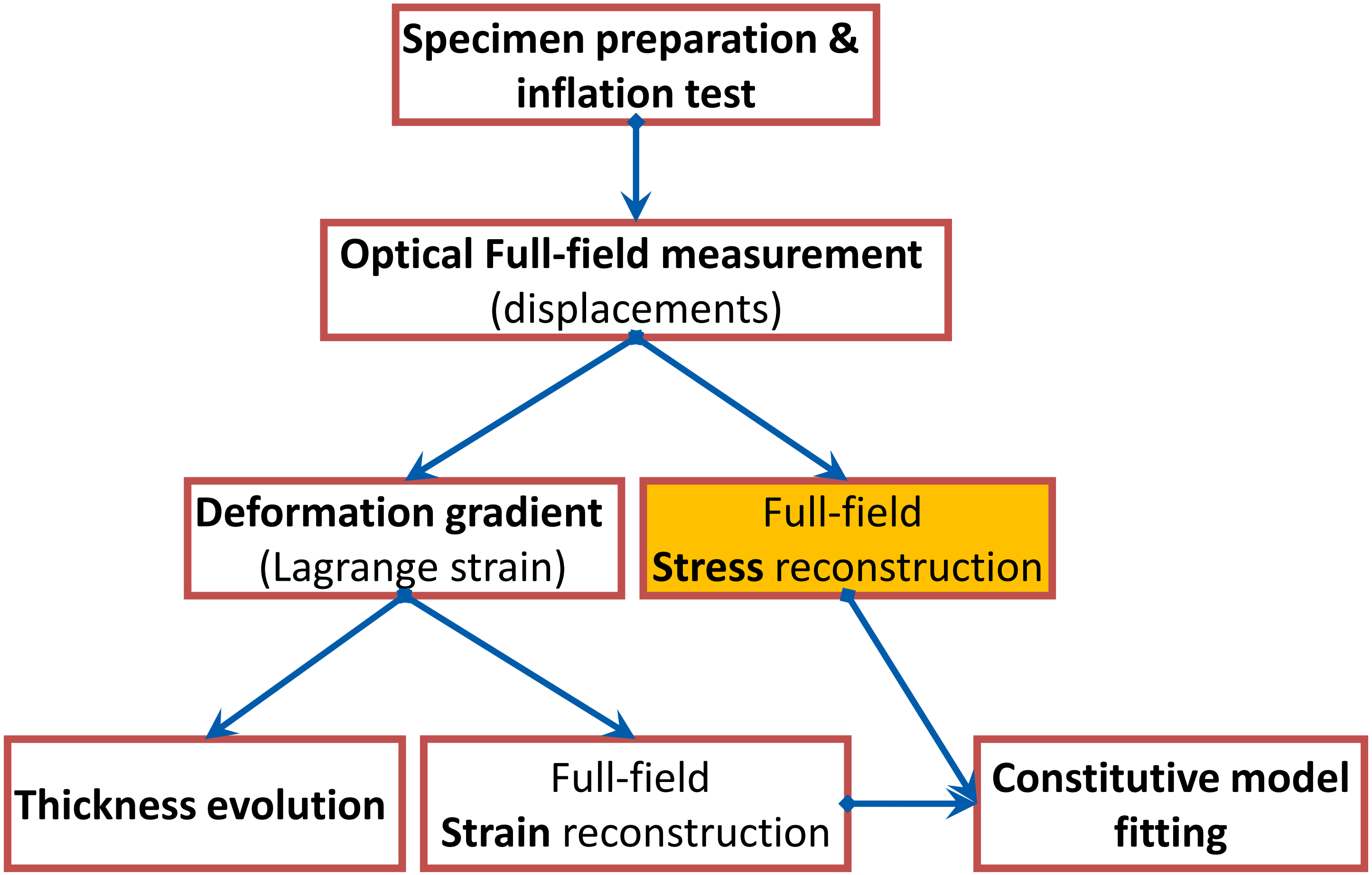
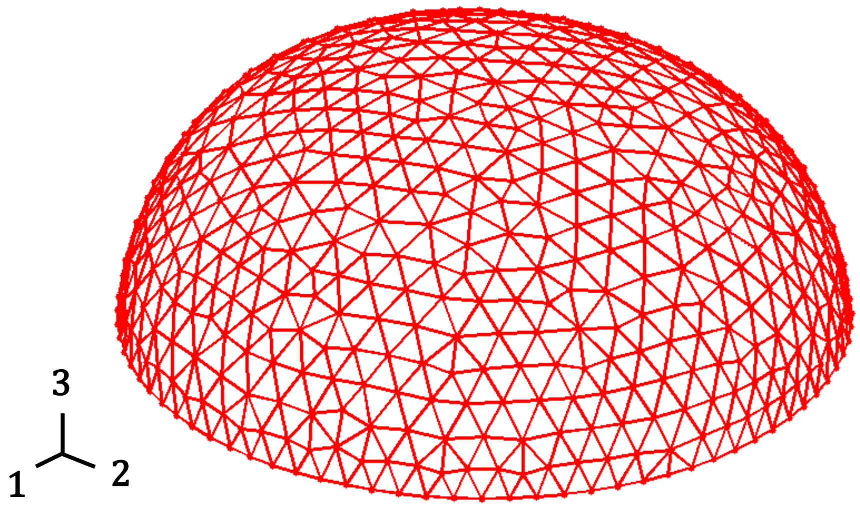


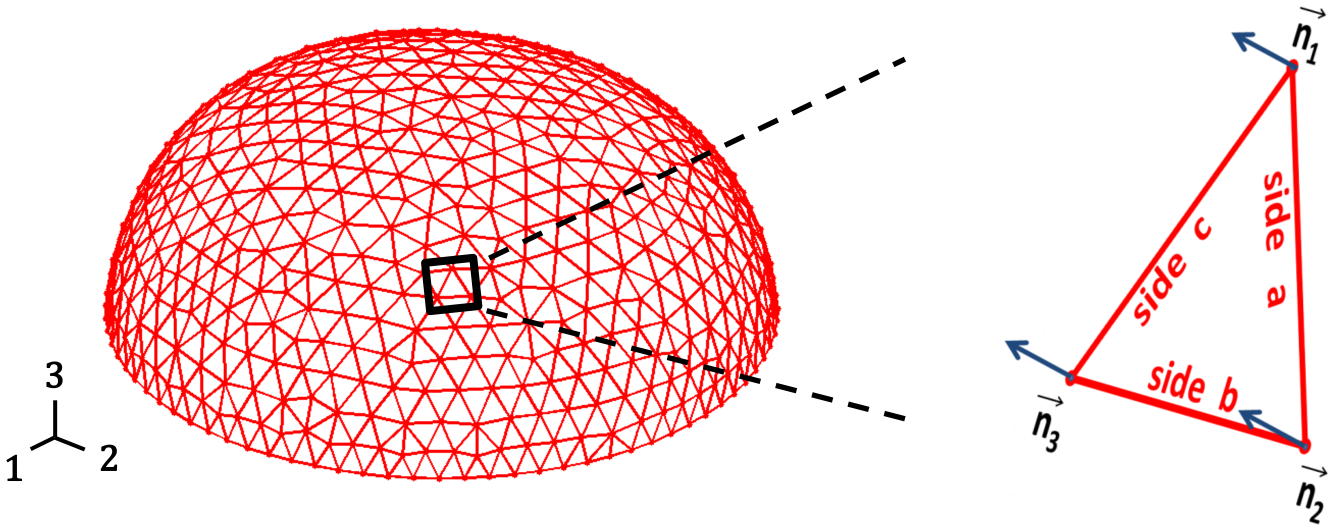
➲ Membrane elastostatics

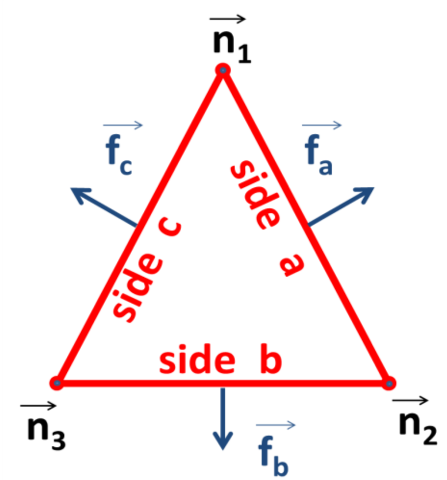


$$div(\boldsymbol{\sigma}) + f = 0$$

$$[A] \cdot [\boldsymbol{\sigma}] = [B]$$

➲ Membrane elastostatics





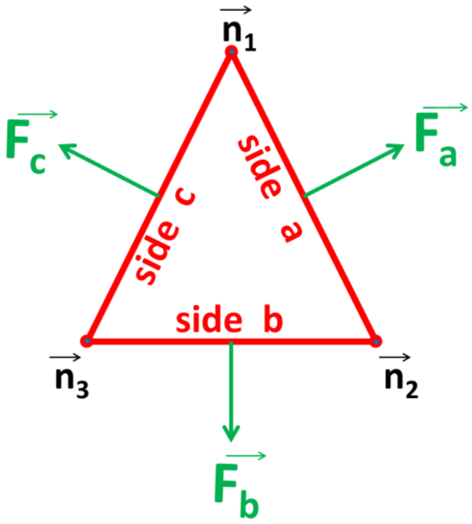
Define **normal** (at nodes) and **facet vectors**

➲ Membrane elastostatics

Compute facet forces

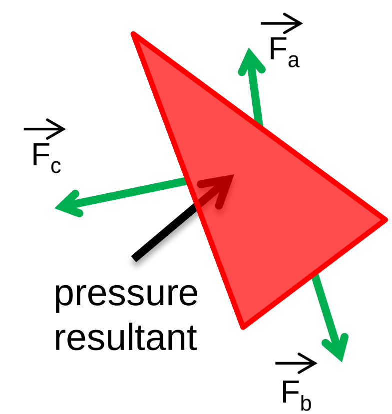
$$\overrightarrow{F_b} = \frac{\boldsymbol{\sigma}_{n_2} + \boldsymbol{\sigma}_{n_3}}{2} \cdot \overrightarrow{f_b} \cdot l_b \cdot h$$

$$\boldsymbol{\sigma} = \begin{bmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{12} & \sigma_{22} \end{bmatrix}$$



LOCAL EQUILIBRIUM

$$\overrightarrow{F_a} + \overrightarrow{F_b} + \overrightarrow{F_c} = p \cdot s \cdot \frac{\overrightarrow{n_1} + \overrightarrow{n_2} + \overrightarrow{n_3}}{3}$$

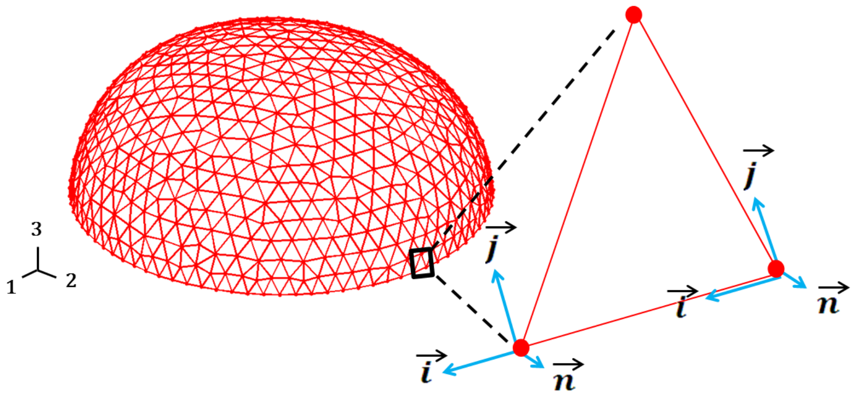


Membrane elastostatics

Add boundary conditions

$$(\sigma \cdot \vec{j}) \cdot \vec{n} = 0$$ → In-plane traction

$$(\sigma \cdot \vec{j}) \cdot \vec{i} = 0$$ → No shear

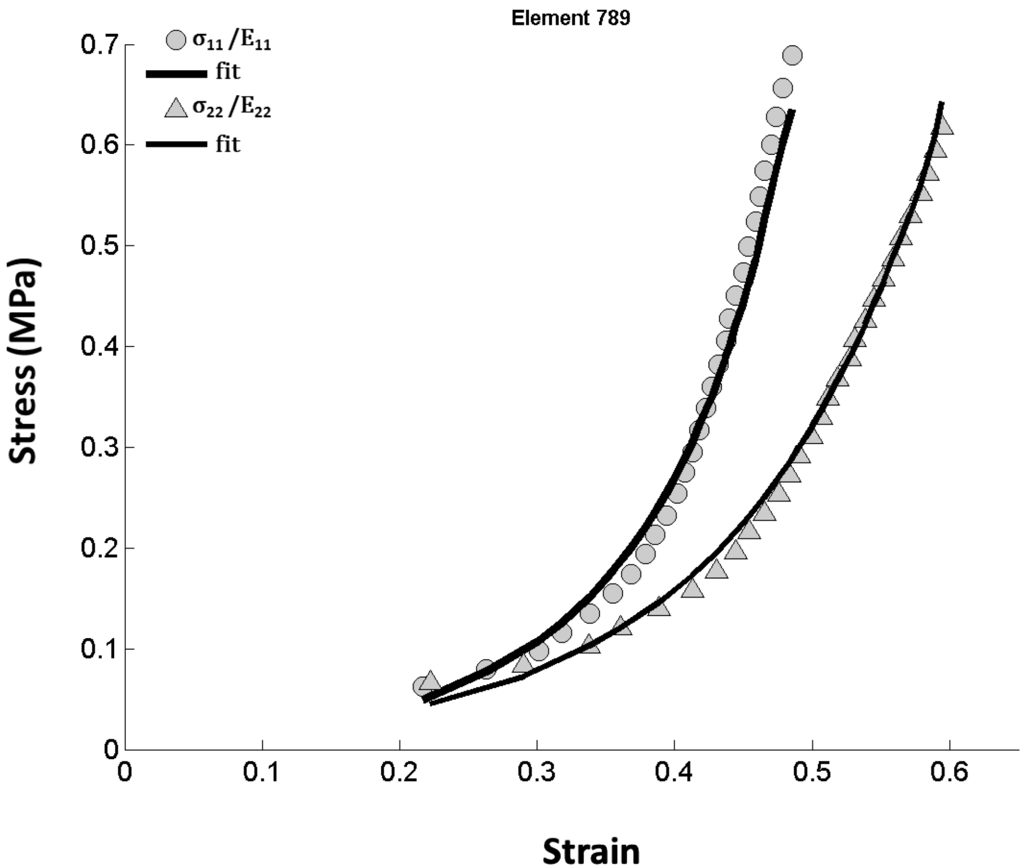


FINAL SYSTEM TO BE SOLVED

$$[A] \cdot [\boldsymbol{\sigma}] = [B]$$

<3609x1932> <1932x1> <3609x1>

3xElements 3xNodes Unknowns 3xElements

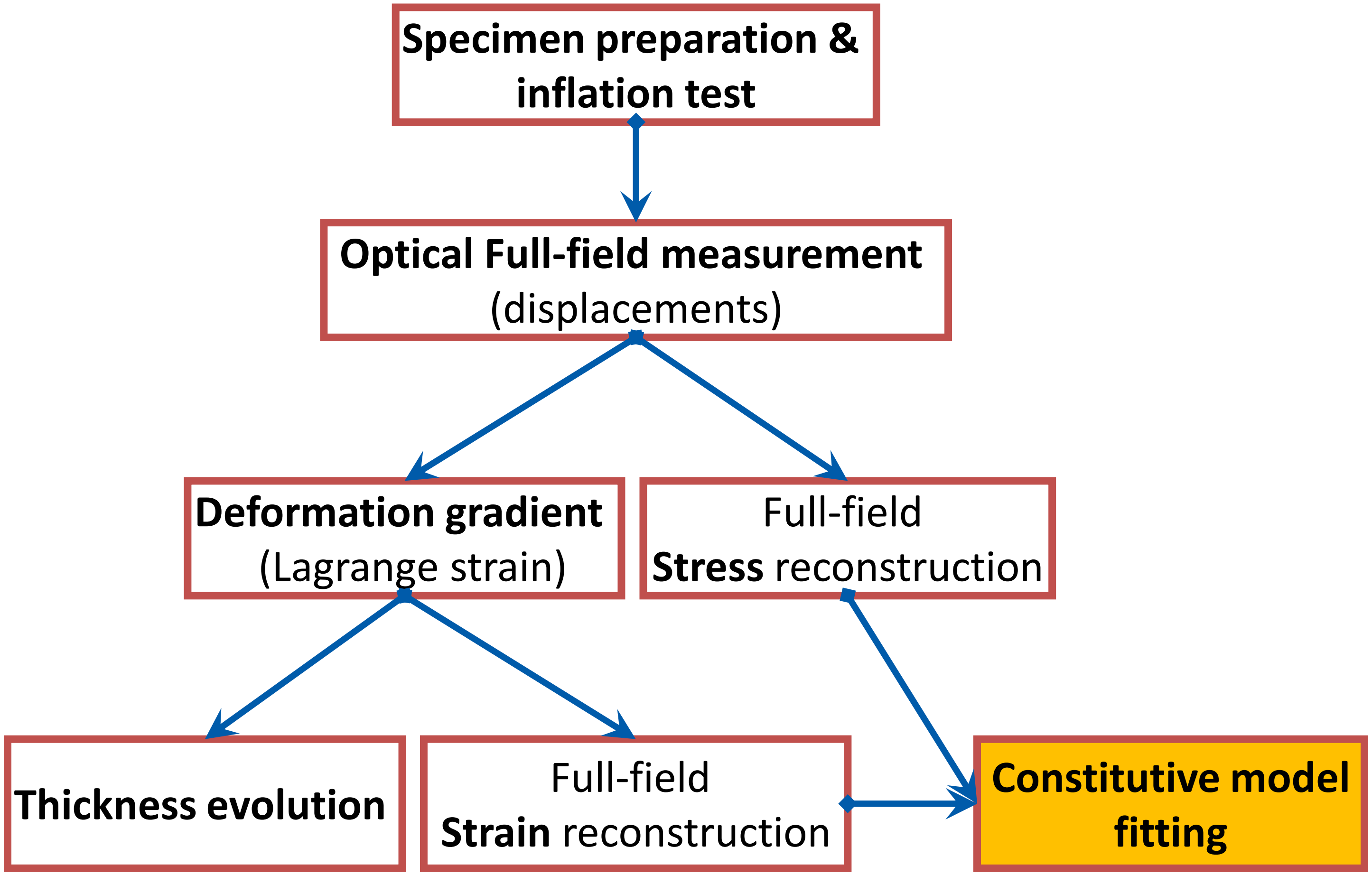


Stress field reconstructed without a constitutive model !!

Methodology

➲ Our methodology

[Romo A, Badel P, Duprey A, Favre J-P, Avril S. In vitro Analysis of Localized Aneurysm Rupture. *J Biomech*. 2014]



➲ Hyper-elastic model identification

Strain energy function

$$\Psi = \Psi_g + \Psi_f$$

Ground substance + elastin

Isotropic

$$\Psi_g = C_{10}(\bar{I}_1 - 3)$$

C_{10} parameter fixed at **5 kPa**

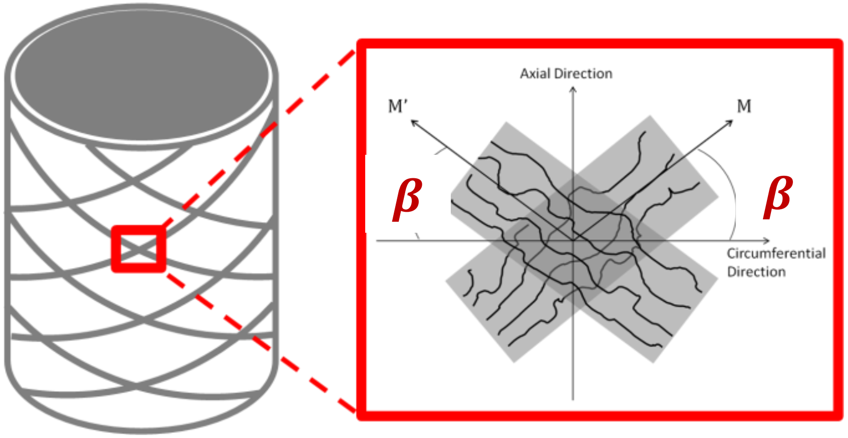
(Weisbecker et al. 2012)

Collagen fibers

Anisotropic

$$\Psi_f(I_4, I_6) = \frac{\mathbf{k_1}}{2\mathbf{k_2}} \sum_{i=M,M'} \left\{ exp\left[\mathbf{k_2}(\lambda_i^2 - 1)^2\right] - 1 \right\}$$

(Holzapfel et al., 2000)



+ incompressiblity

➲ Hyper-elastic model identification

Strain energy function

$$\Psi = \Psi_g + \Psi_f$$

↓

2nd Piola-Kirchhoff stress tensor:

$$S = S_g + S_f = \frac{\partial \Psi_g}{\partial E} + \frac{\partial \Psi_f}{\partial E}$$

↓

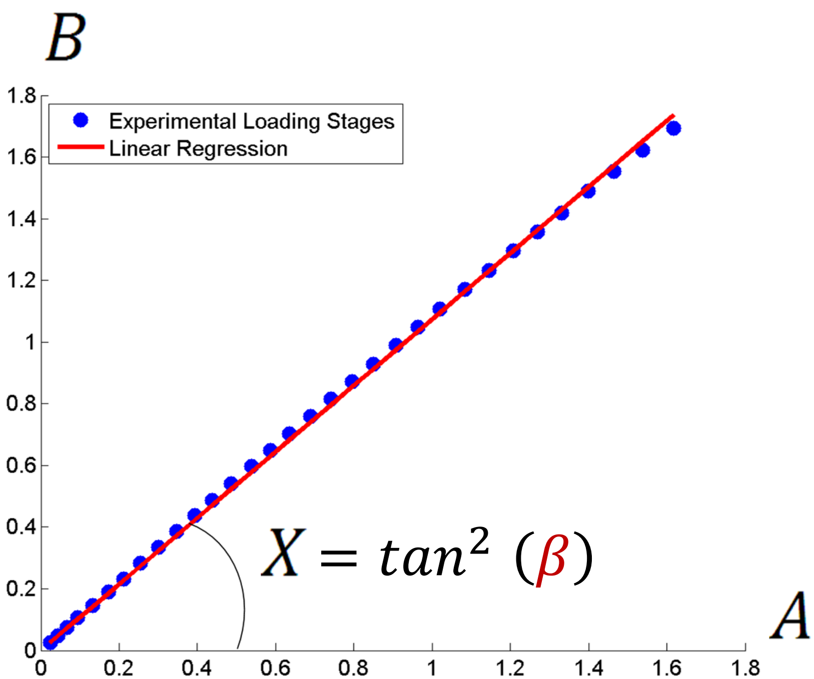
Cauchy stress tensor:

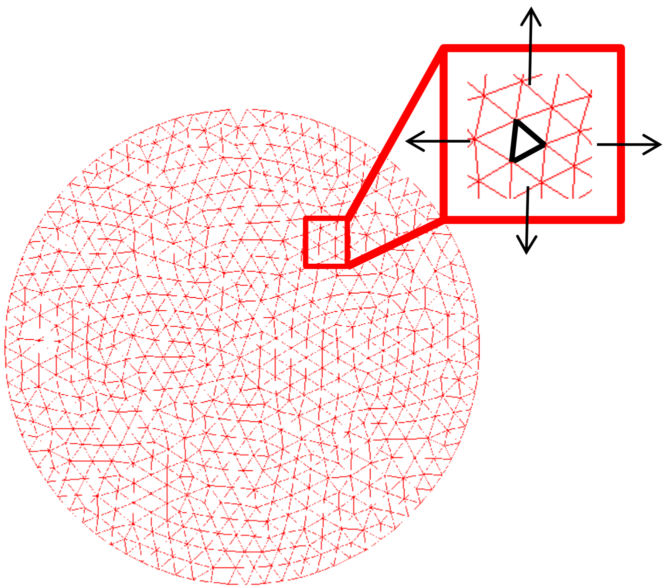
$$\sigma = F \cdot S_g \cdot F^T + F \cdot S_f \cdot F^T + cI$$

Local identification method

➲ Hyper-elastic model identification

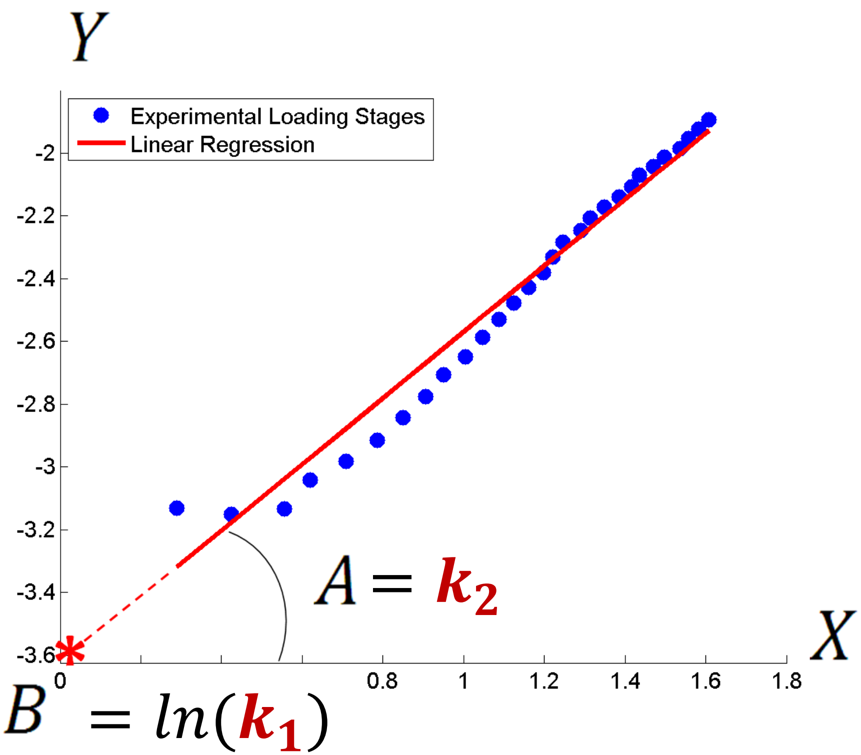
$$A(\sigma', F)tan^2\boldsymbol{\beta} + B(\sigma', F) = 0$$

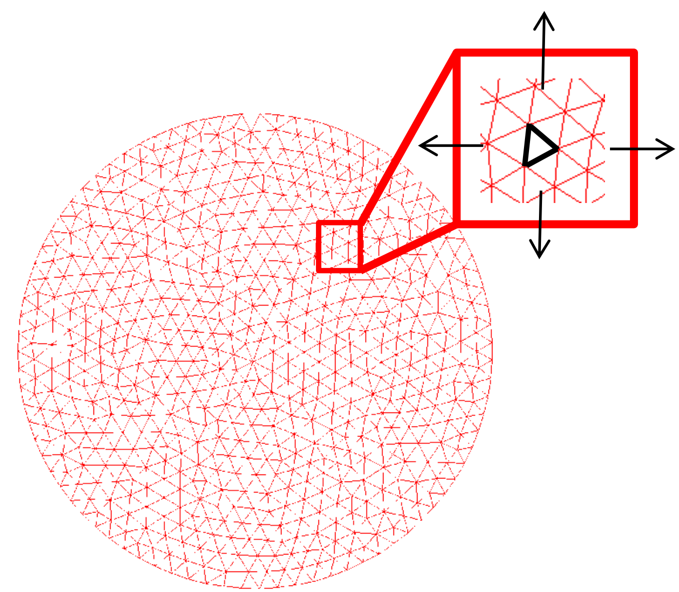




➲ Hyper-elastic model identification

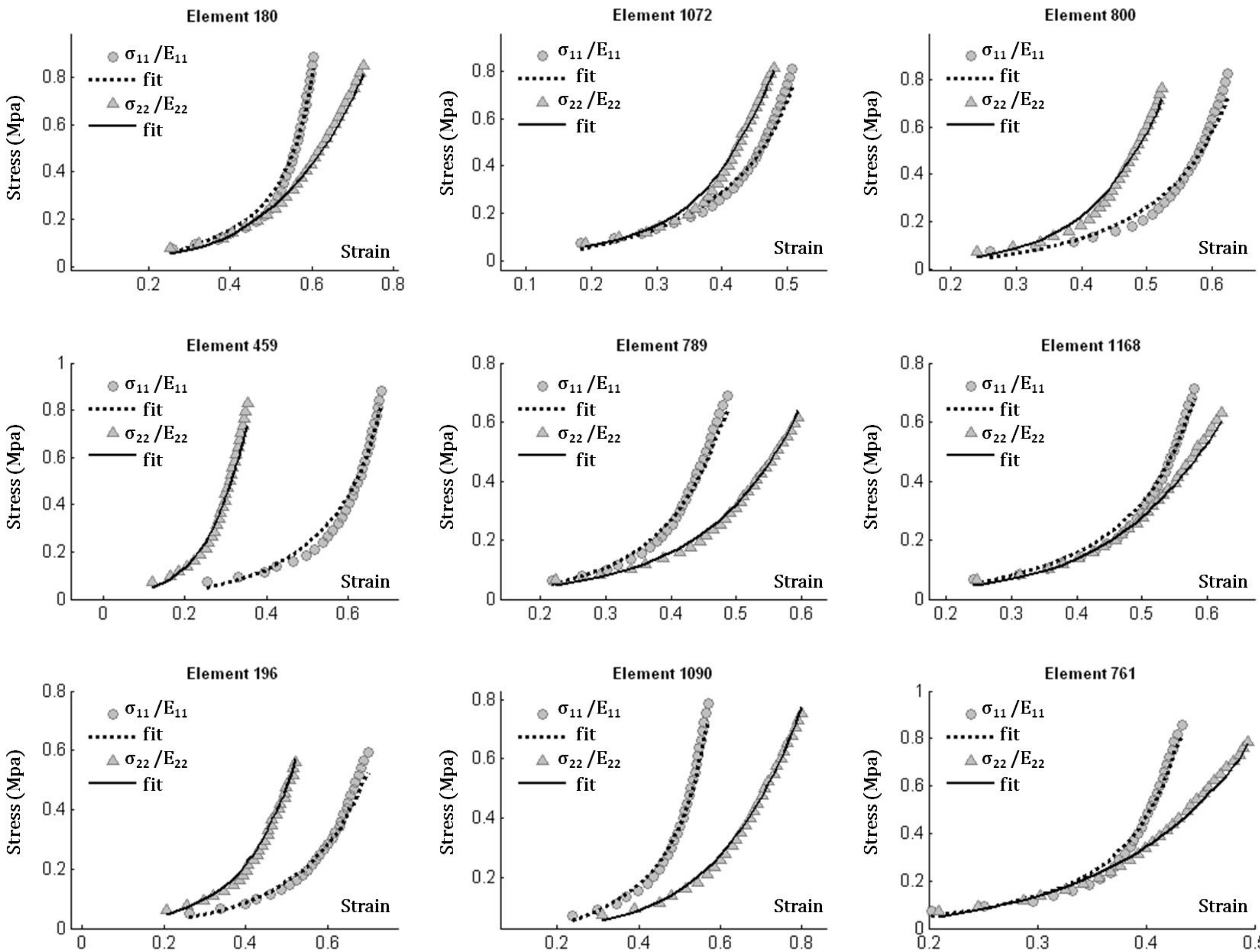
$$\sigma'_{11} = 4\mathbf{k_1}\lambda_1^{\,2}cos^2(\beta)\left(\lambda_f^{\,2} - 1\right)e^{\mathbf{k_2}\left(\lambda_f^{\,2}-1\right)^2}$$



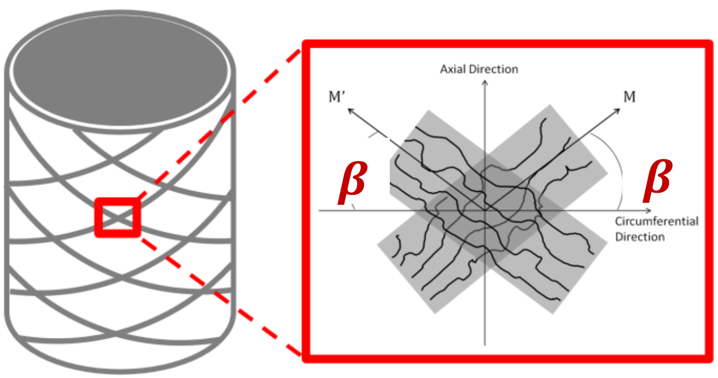


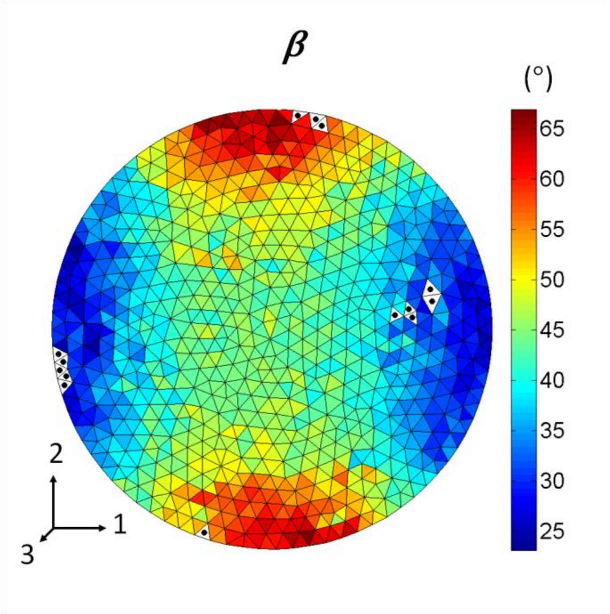
Results

➲ Results: bi-directional experimental fitting



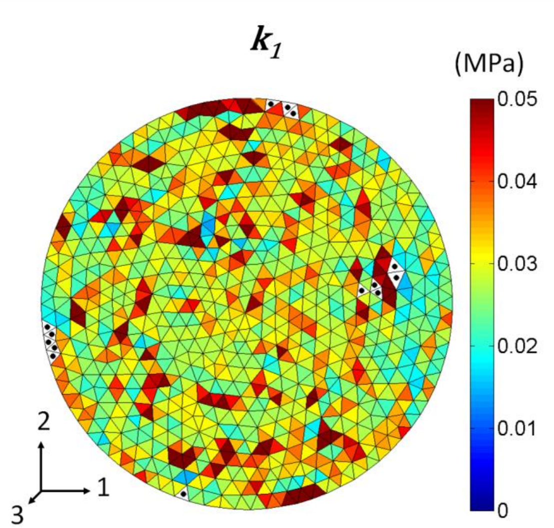
➲ Results: β identification (typical result)

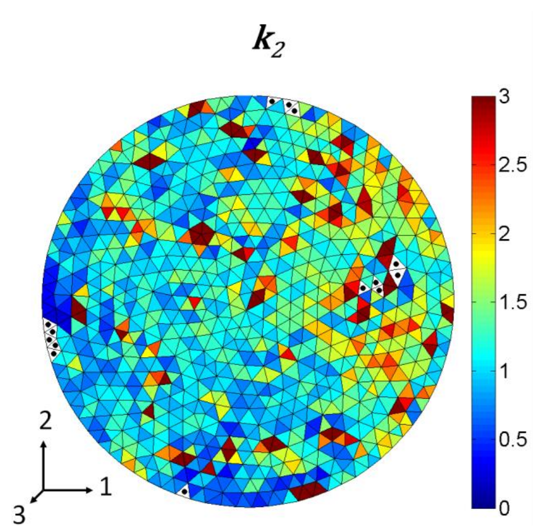




Results

➲ Results: k_1 and k_2 identification (typical result)





Very heterogeneous,

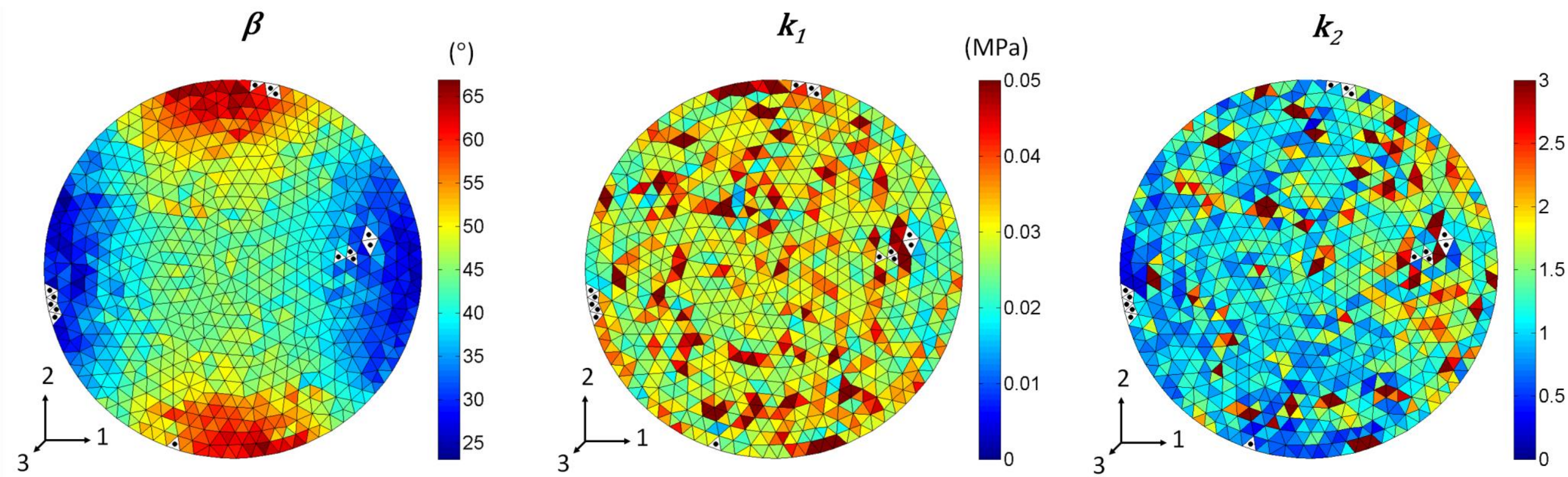
… choice of the model?

Results

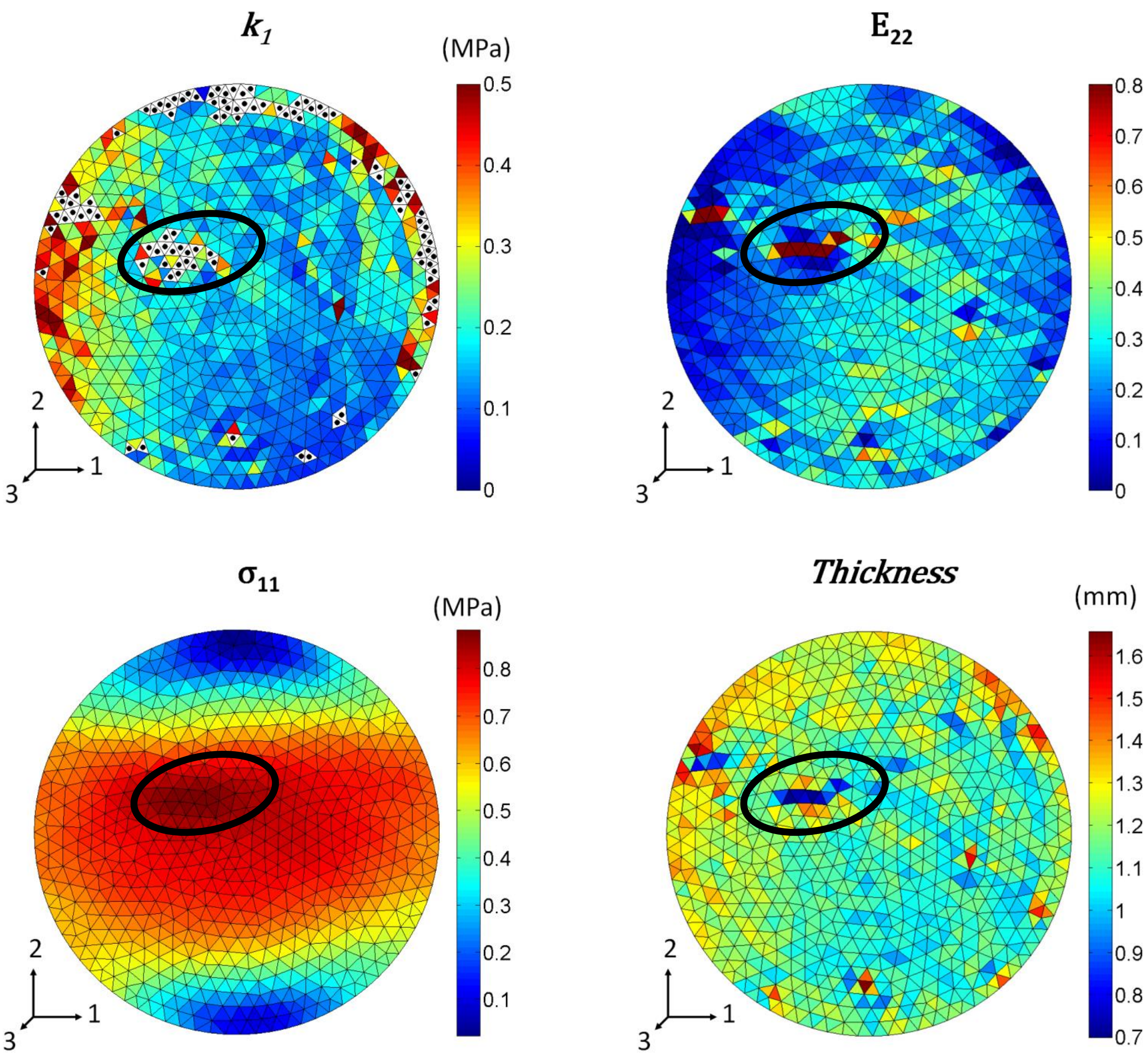
➲ Results: local identification: discarded elements

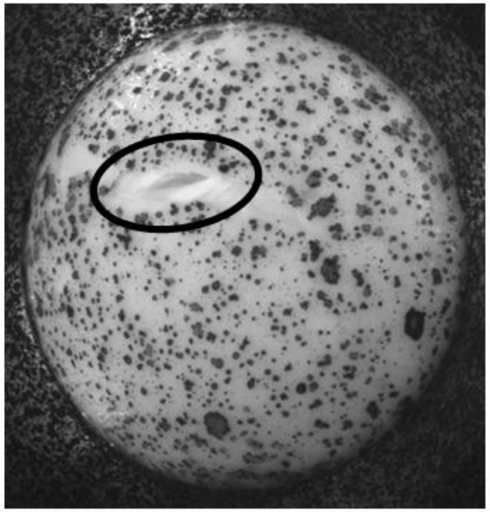
Quality of fit (classical criterion)

$$R^2 = 1 - \frac{SS_r}{SS_t}$$



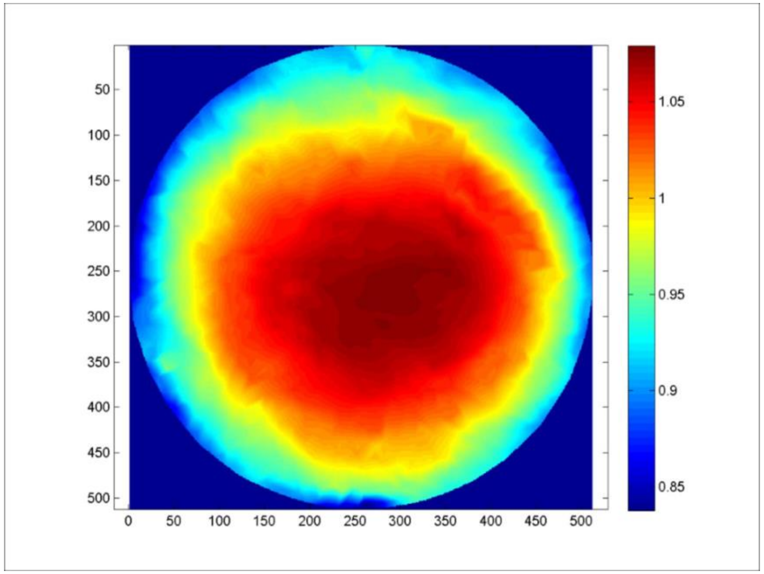
Results


k_1
(MPa)
0.5
0.4
0.3
0.2
0.1
0
2
1
3
E_{22}
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
2
1
3
σ_{11}
(MPa)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
2
1
3
Thickness
(mm)
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
2
1
3

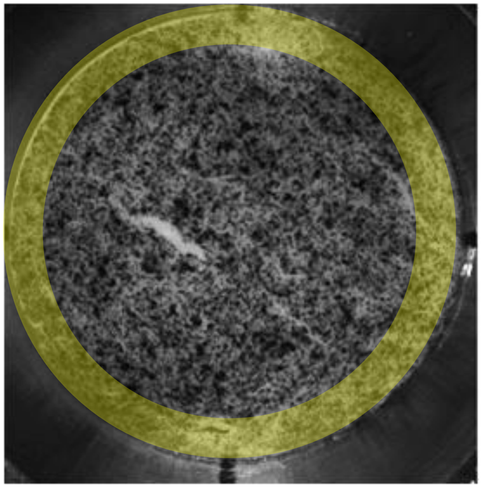


➲ Results: thickness evolution

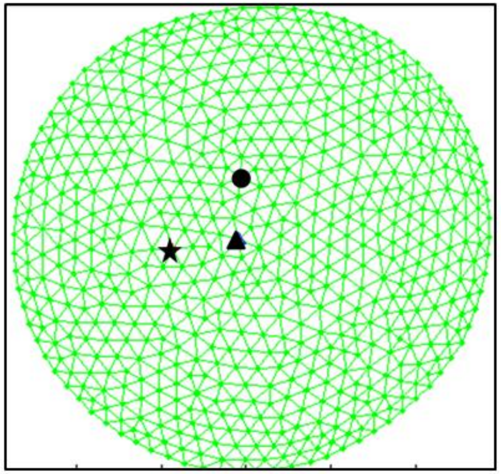
Local thickness evolution (mm)



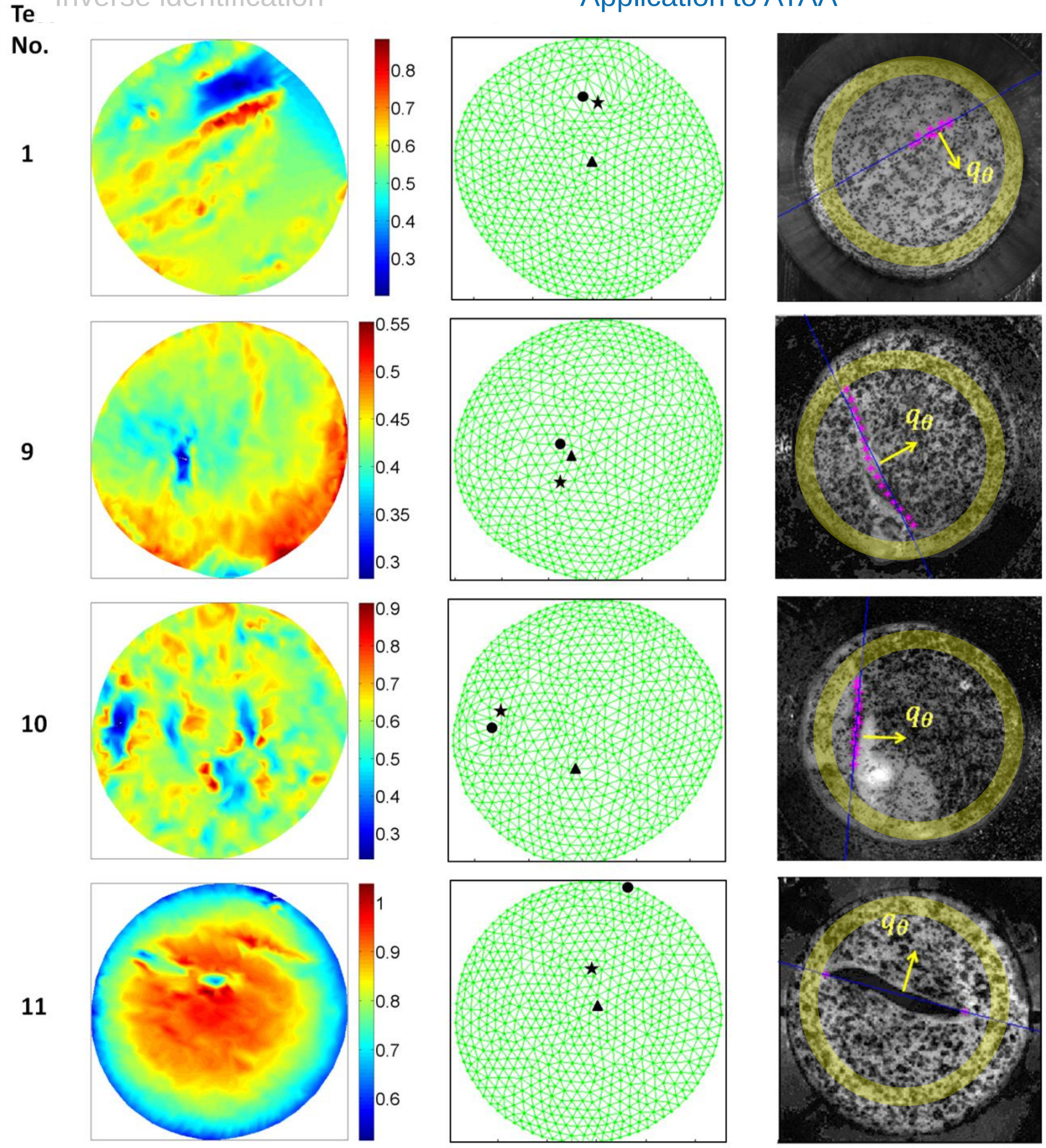
Rupture picture and area of interest (AOI)



Mesh



● = NodeMAX
▲= NodeTOP
★= NodeRUP



Four tests showing, a) the color map of the thickness measurement, b) the deformed mesh (● = NodeMAX, ▲= NodeTOP, ★= NodeRUP) and c) the rupture picture and the area of interest (yellow circle).

Conclusion/perspectives

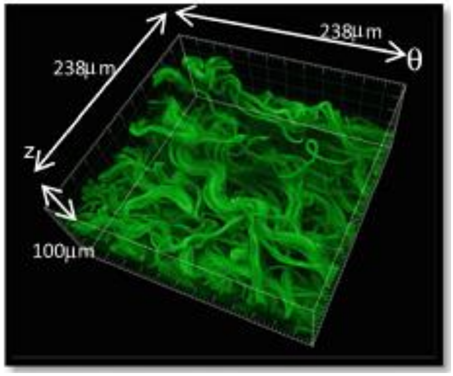
- Able to
  - detect weak zones prior to rupture. This questions the hypothesis of maximal stress at rupture!
  - identify local elastic properties and rupture strength

- Issues
  - Choice of the model (sensitivity to induced anisotropy, heteregeneities)
  - Choice of the hypotheses?

➲ Perspectives

– Local rupture criterion.

– Microstructural investigations: what are the **determinants of rupture**???



– Macroscopic modeling from such evidence to address **in vivo rupture risk assessment**

– This would require in vivo stress reconstruction… FSI?

Still much to do!

MERCI

➲ Special thanks

Stéphane Avril, Jérôme Molimard (colleagues)

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➲ Thank you!