CONTRIBUTION OF A MULTI-SCALE APPROACH TO MODEL AND CHARACTERIZE SUPRACONDUCTING COMPOSITES

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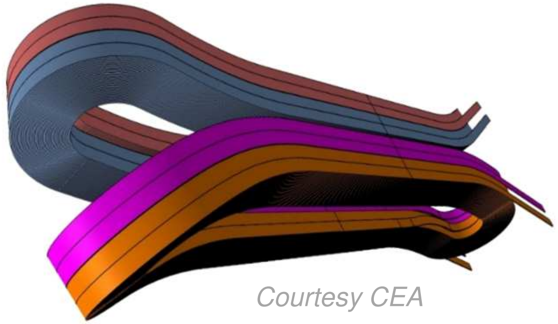
PROBLEM DESCRIPTION

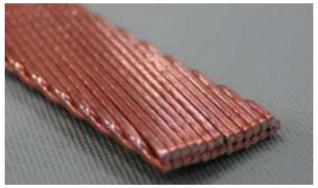
Various scales

coil



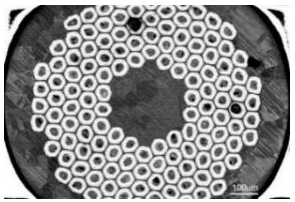
Courtesy CEA

cable



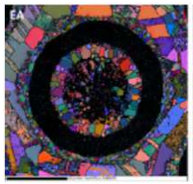
[Fermilab 17]

wire



[Lenoir 2017]

filament, grains



[Scheuerlein 2014]

Complex history

Cable forming process

[CERN]

Non-reacted wires
Room temperature
Complex process

High temperature reaction
Cooling

In service performances

Reacted wires.
Resin impregnated
Low temperature
Lorentz forces

SOME QUESTIONS TO BEGIN…

Which step of the life cycle do we want to predict/characterize?

State of the material

Loadings (mechanical, thermal, cyclic/monotonous…)

A model for what?

To predict the answer of the material

To understand the behavior of the material

To validate an object

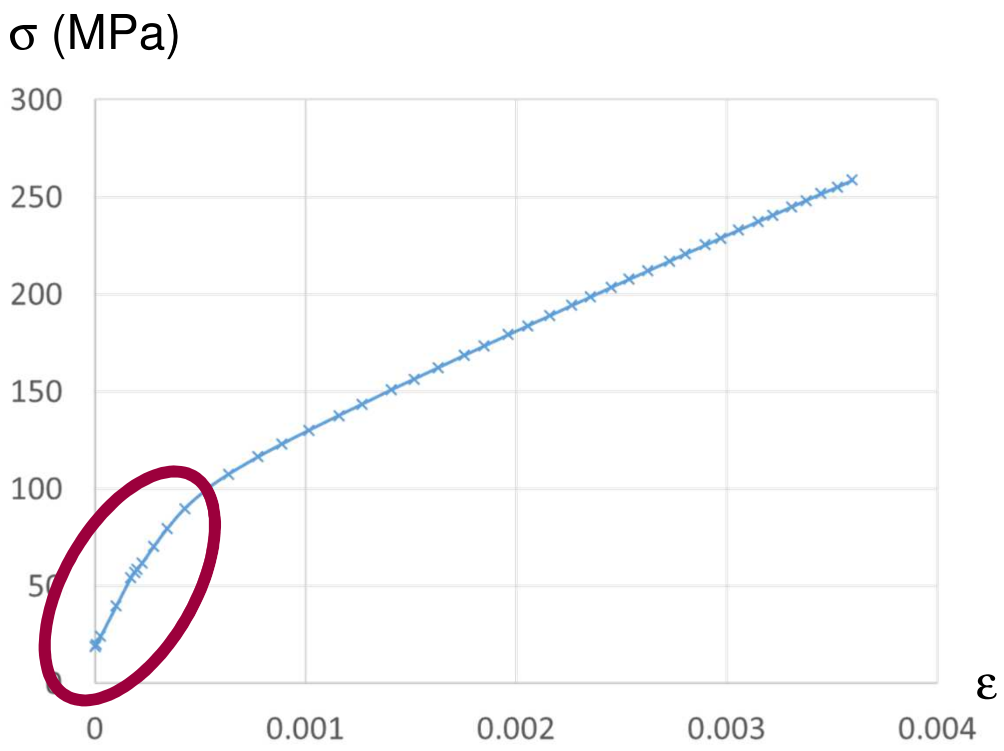
Which experimental characteristics do we need?

EXPERIMENTAL CHARACTERIZATION OF THE MECHANICAL BEHAVIOUR

- Measurement of Young's modulus
- Non-linear mechanical behaviour
- Test on heterogeneous media
- Local mechanical behaviour

MEASUREMENT OF YOUNG'S MODULUS

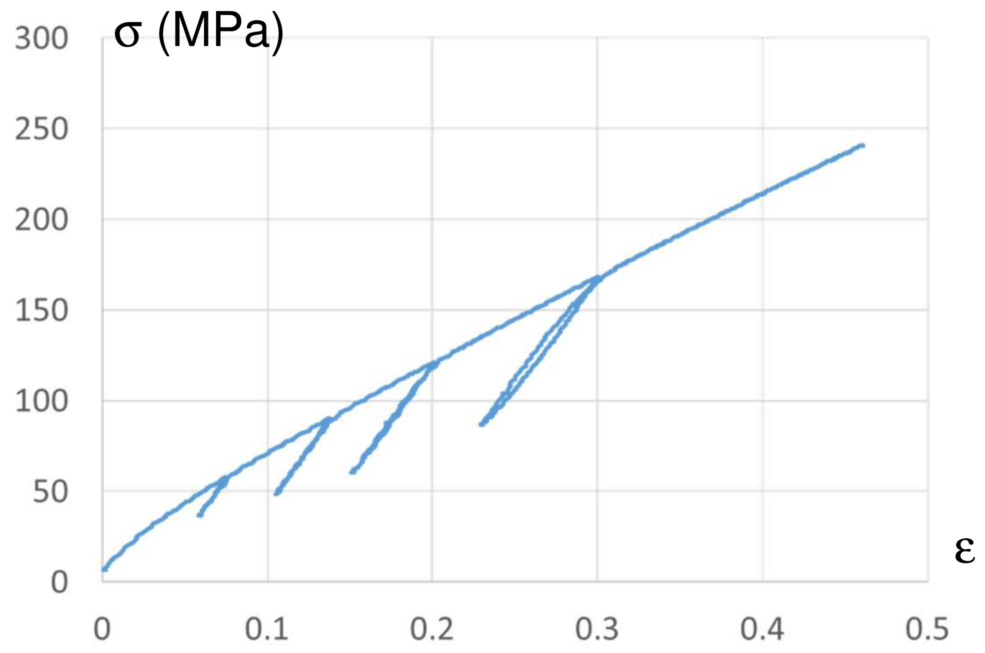
Tensile test on Nb_3Sn wire



Where is the elastic part?
Slope intrinsic or due to tightening of the grips?
Nb of points necessary to determine the slope of the curve?

MEASUREMENT OF YOUNG'S MODULUS

Tensile test on Nb_3Sn wire



Possible to measure E on the unloading parts

⇨ Linear regression

1rst loading	1rst unloading	2nd unloading	3rd unloading	4th unloading
81 GPa	127 GPa	124 GPa	127	126 (linear part) 116 (total unloading)

E measured on the loading part is underestimated
It is necessary to calculate E only on elastic parts

MEASUREMENT OF YOUNG'S MODULUS

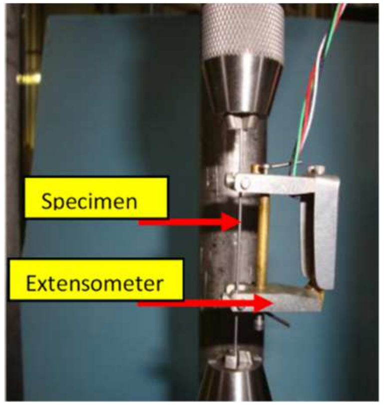
Errors may be due to

- Control of the loading. Is is pure tension?
- The wire may be initially bended
- Damage of the material (during handling?)
- Calculation of strain from the displacement measured by the tensile machine

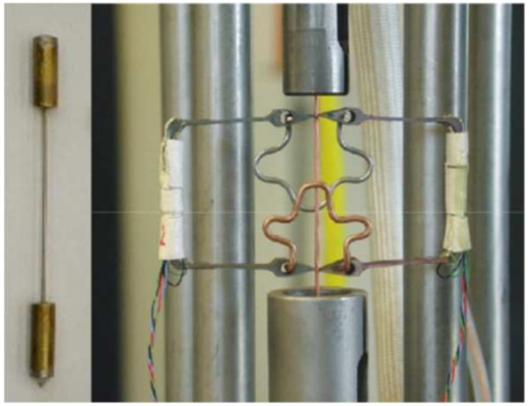
How can we improve the results?

SOME TENSILE TESTS OF THE LITERATURE (NOT EXHAUSTIVE)

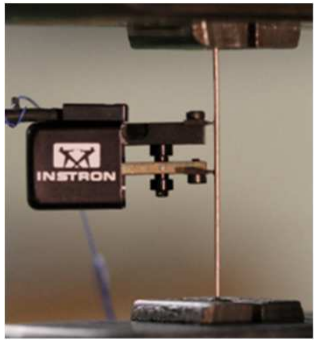
[Bajas 11]



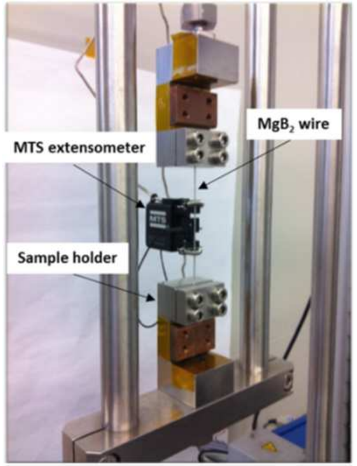
[Seth 12]



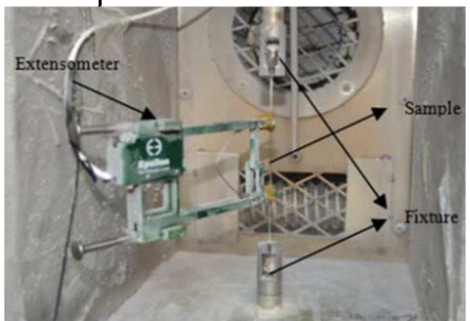
[van den Eijnden 05]



[Lenoir 17]



[Konstantopoulou 16]



[Xin 16]

Various systems used for the grips: keyless clamp, 3 jaws mandrell, soldering in a tube, soldering in a ball.

Most of them don't prevent damage to occur in the wire during handling.
The handling of the specimen, installation of the extensometer are generally not described, whereas researchers are dealing with fragile specimens, which require careful procedures.

Presentation of G. Lenoir

OTHER WAYS TO ACCESS YOUNG'S MODULUS

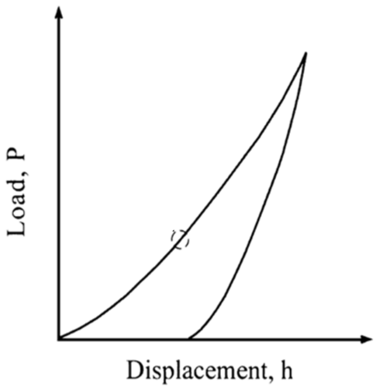
Compression tests

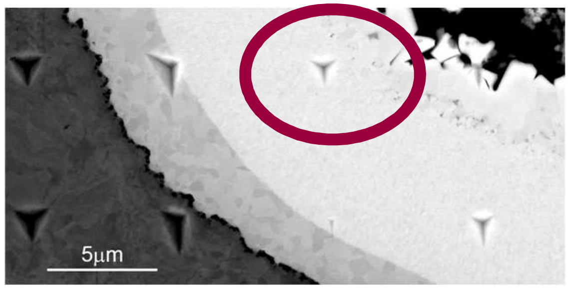
- E generally under-estimated
- Problems of contact on the loading surfaces

3 or 4 point bending tests

- Very efficient to measure E

Nanoindentation

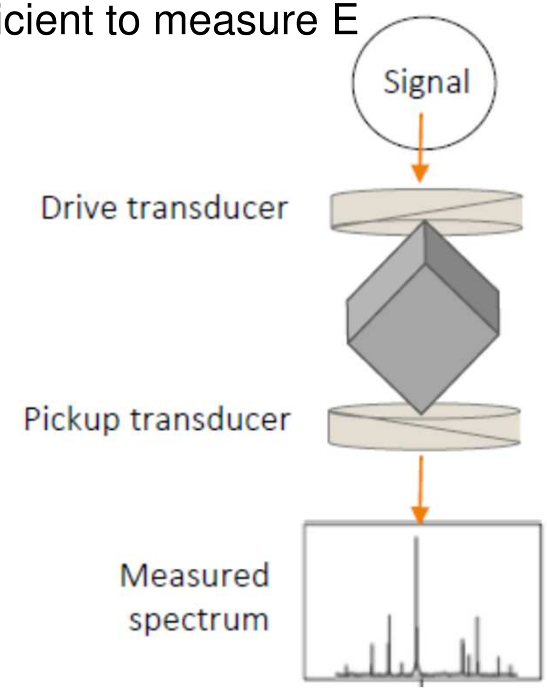




Possible to access to local values

Resonance ultrasound spectroscopy

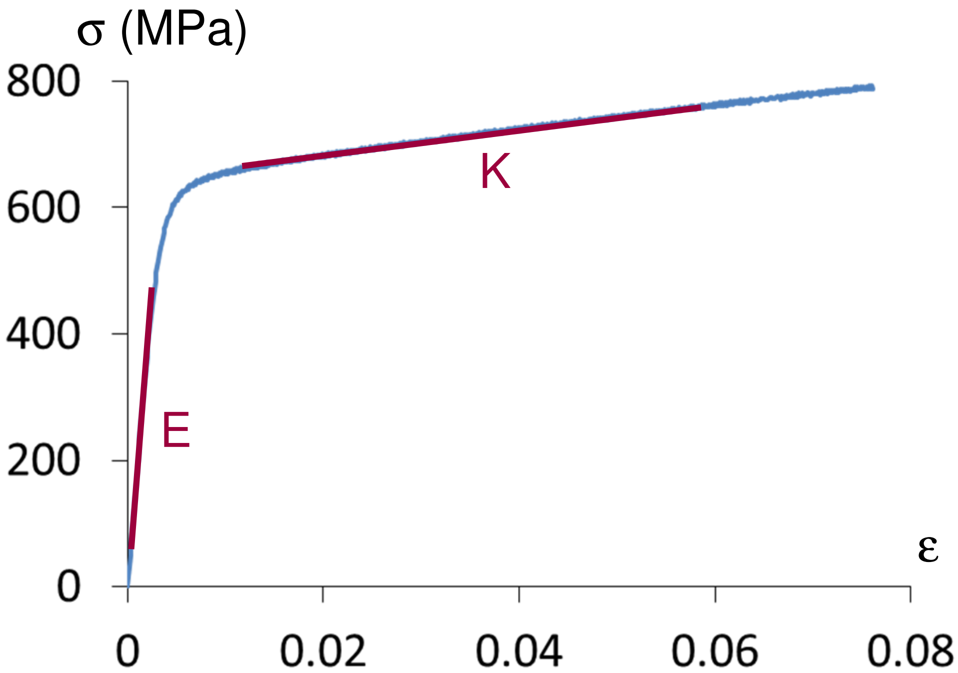
- Very efficient to measure E



[Ciria 2017]

WHAT ABOUT THE NON-LINEAR BEHAVIOUR

We obtain typical non-linear curves, whatever the sample loaded (wire, 10 stack, …)

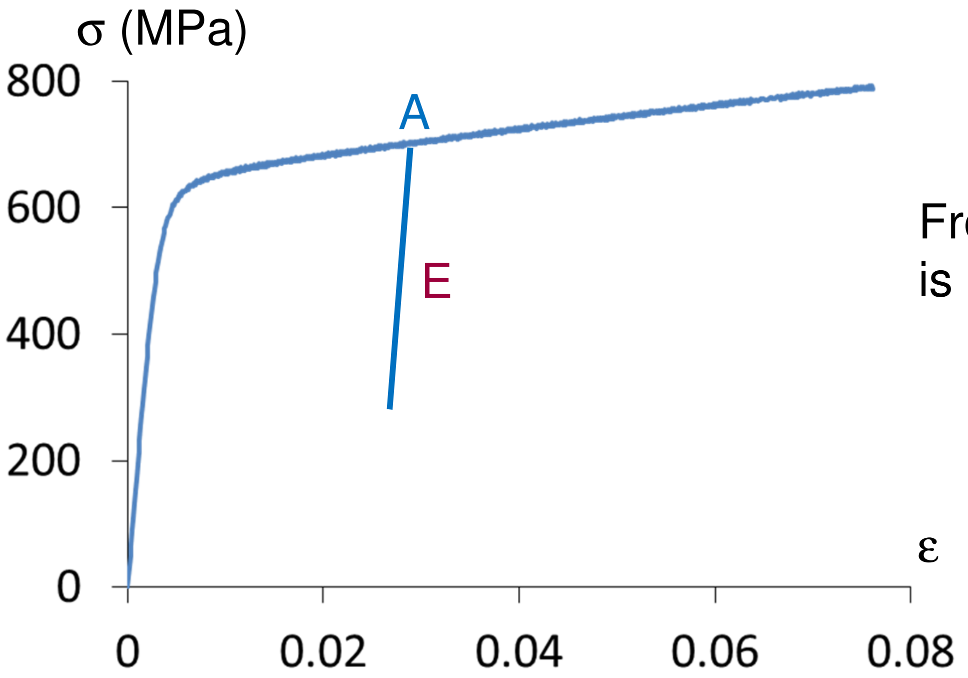


[Aubin 2001]

Mostly bilinear

Is it true to describe this curve with two modulus and to write $\sigma = E\,\varepsilon$ or $\sigma = K\,\varepsilon + k_1$ depending on the level of strain?

WHAT ABOUT THE NON-LINEAR BEHAVIOUR



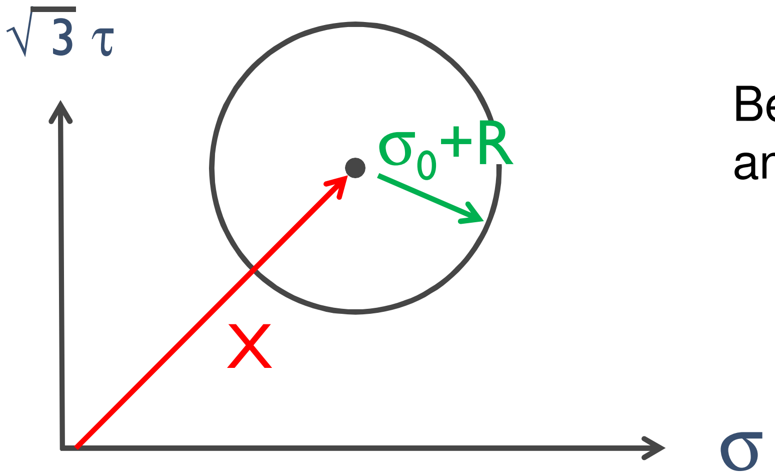
[Aubin 2001]

From point A, the unloading is elastic, with slope E

If the model has to be used under **non-monotonous loading** (cyclic loading, change of loading direction),
it is **necessary to use an elasto-plastic model**.

FOCUS ON ELASTO-PLASTIC BEHAVIOUR

Assumption of an elastic domain



Behaviour elastic inside the domain, and elasto-plastic at the boundary

X = kinematic hardening (Displacement of the elastic domain)

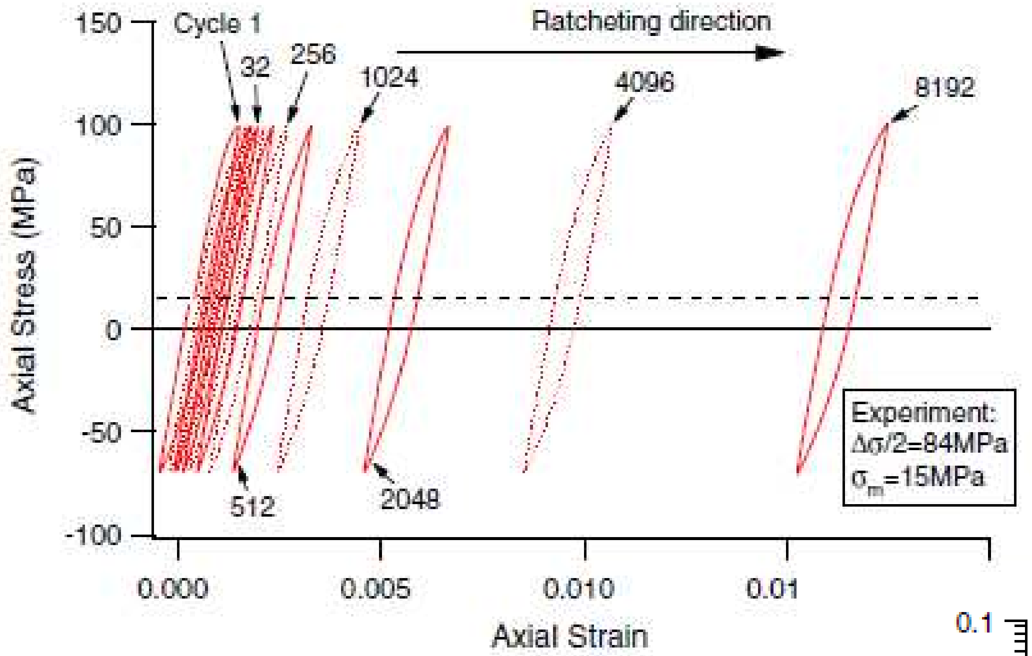
R = isotropic hardening (Change in the size of the elastic domain)

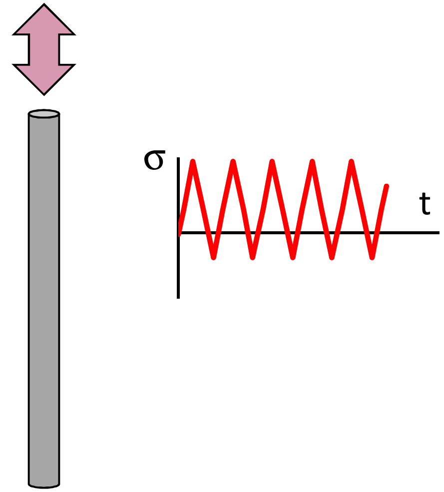
Classical formulations

$$\dot{X} = C * \dot{\varepsilon}^p - \gamma * X * \dot{p}$$

$$\dot{R} = b * (Q - R) * \dot{p}$$

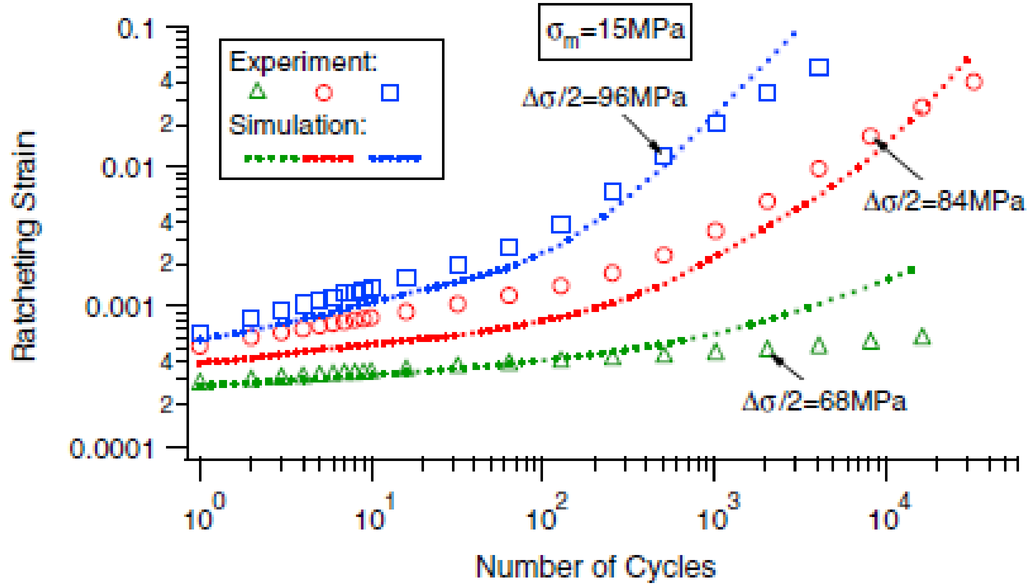
RATCHETTING EFFECT



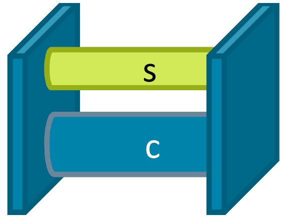


OFHC copper
Room temperature

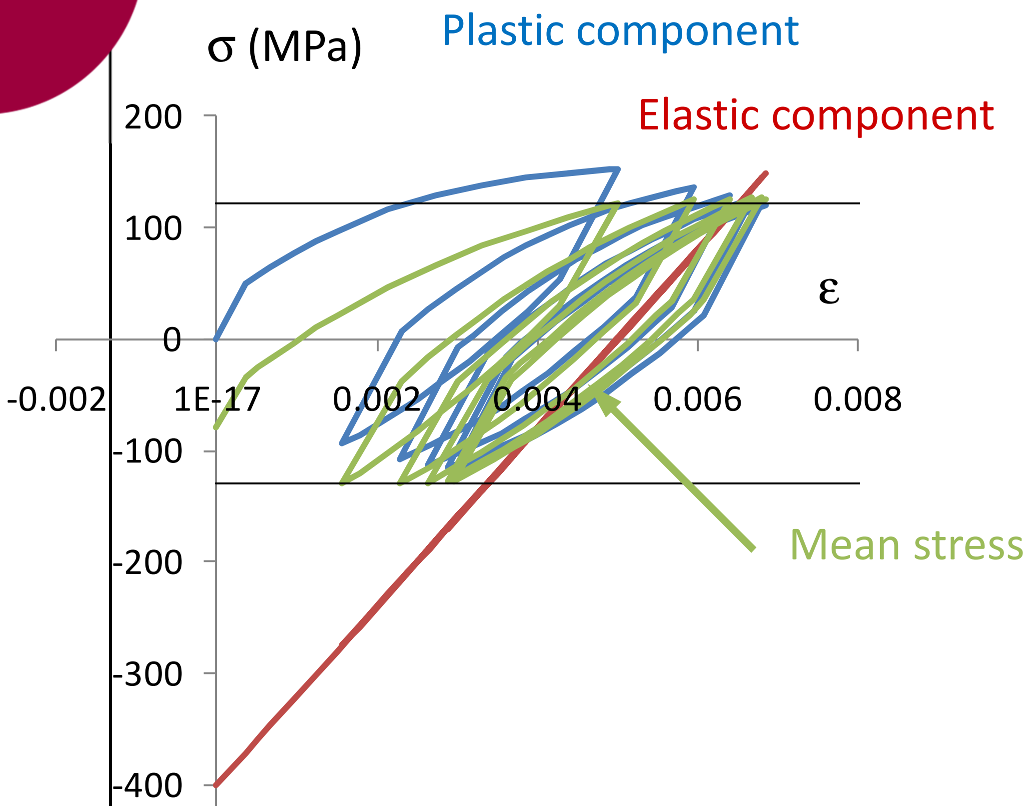
[Zhang 2008]

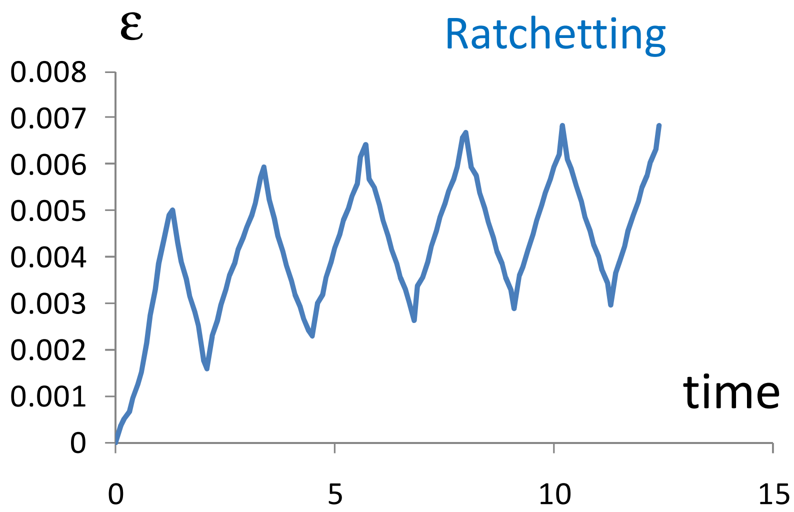


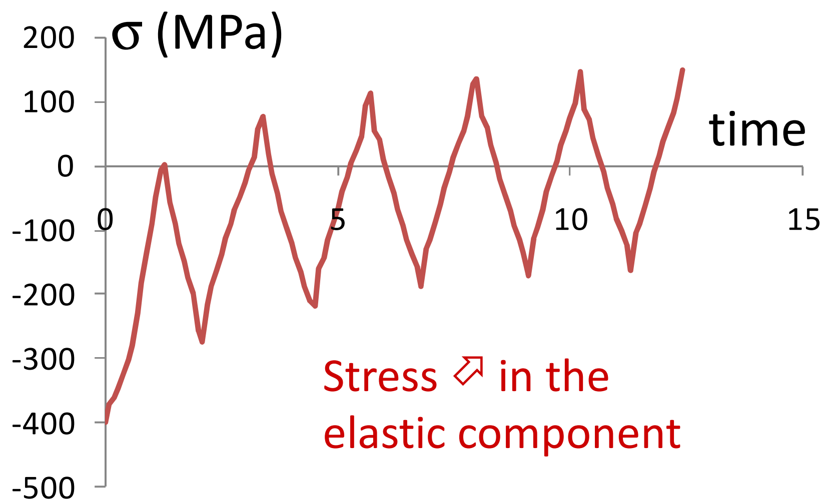
WHICH EFFECT IN A COMPOSITE?



In the elastic component $\sigma_s = E_s\,\varepsilon_s$







The plastic component may ratchet, inducing higher stress in the elastic component

⇩

Cyclic damage, failure

TESTS ON HETEROGENEOUS COMPOSITES

10 stack sample

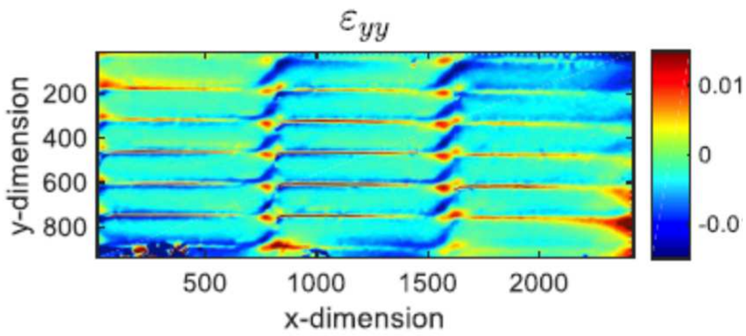
Presentation of F. Wolf

Experimental characterization difficult to carry out

- Only some loadings can be applied (compression, bending, shear)
- Sample heterogeneous
  - Measuring what?

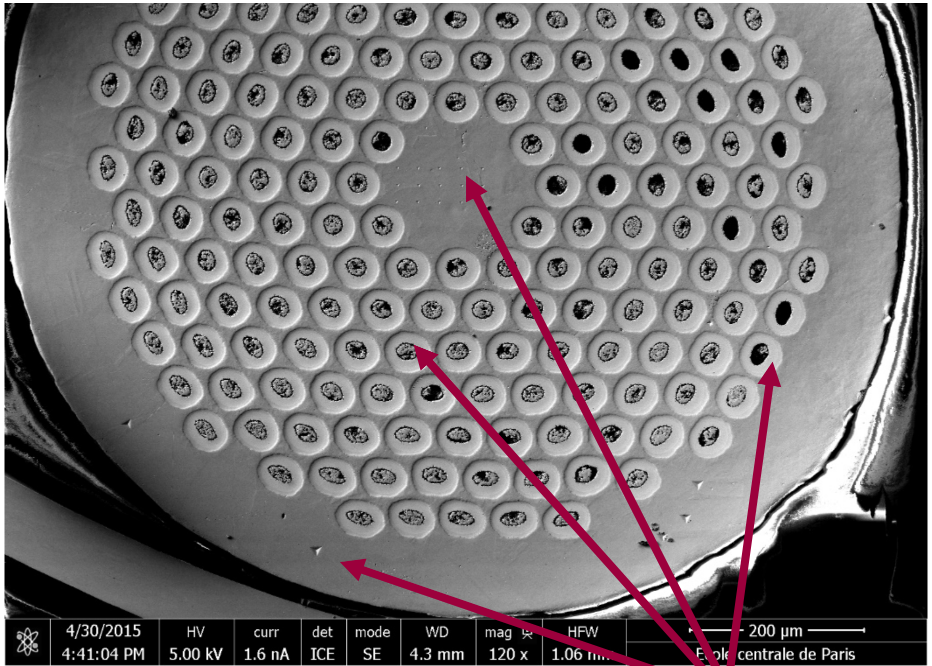
Interest of kinematic field measurements

- To verify the boundary conditions
- To provide average strain measurement if not available
- To product displacement/strain fields related to heterogeneities



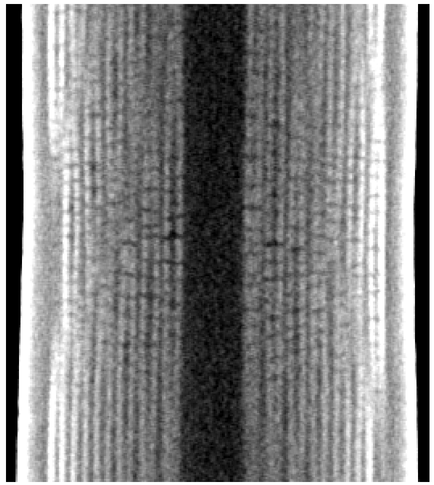
Presentation of M. Grédiac

MECHANICAL CHARACTERIZATION AT THE LOCAL SCALE



Which behaviour do these various zones have?

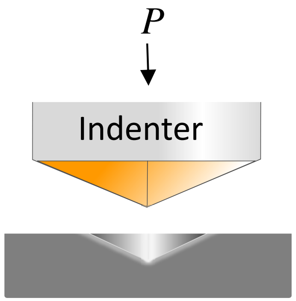
Nb_3Sn-PIT *[Lenoir 2017]*

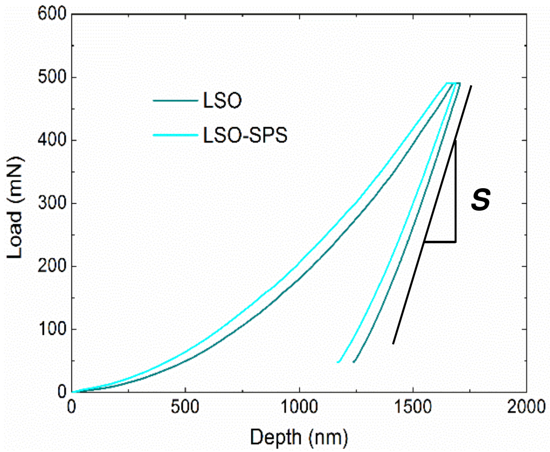


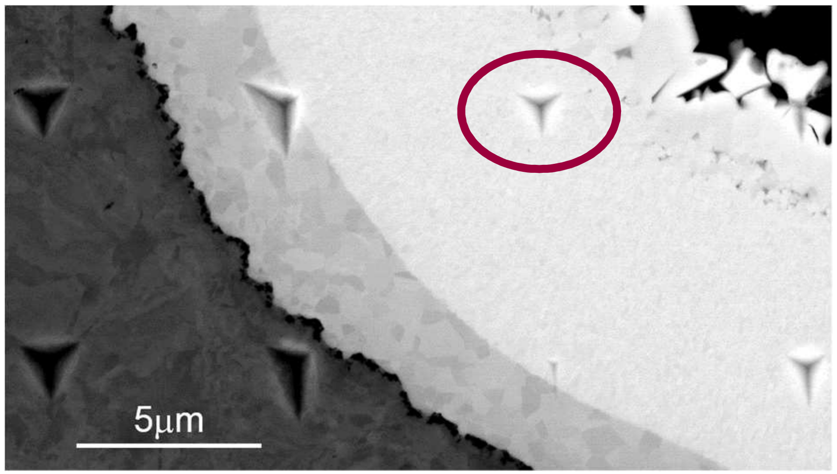
+ characterization of microstructure (phases, grain size, texture, chemical composition, porosities, cracks…)

CHARACTERIZATION AT THE LOCAL SCALE

Nano-indentation on Nb_3Sn PIT







Components		# indents	E (GPa)	SD E (GPa)	H (GPa)
Cu	Outside layer	18	133	5	1.25
	Core	15	125	4	1.14
	Matrix	92	132	6	1.33
Nb_3Sn		35	171	6	13.10
Nb		13	125	13	1.68

[Lenoir 2017]

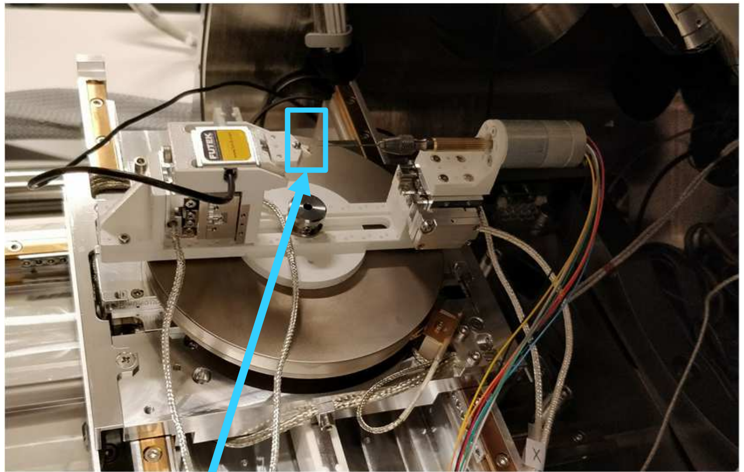
⇨ Shows homogeneity of copper
⇨ Measurement of E
⇨ Estimation of σ_y

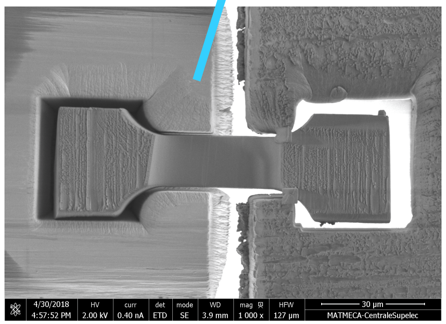
Large number of indentations needed
Sensitivity to surface roughness

CHARACTERIZATION AT THE LOCAL SCALE

Tensile test at micro-scale

[Ben Salem 2012]





Micro-specimen
(70x15x10µm)

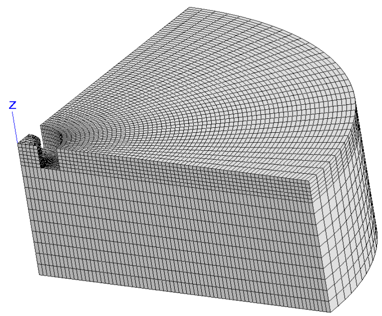
Grips machined at the end of rotating needle
Load measured by a specific load cell
Strain field measured by DIC

CHARACTERIZATION AT THE LOCAL SCALE

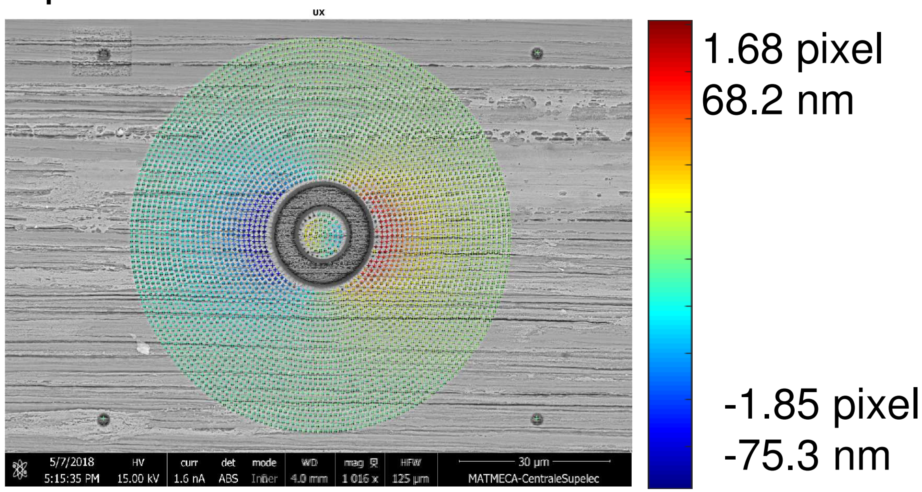
Measurement of residual stress

[Larippe 2012]

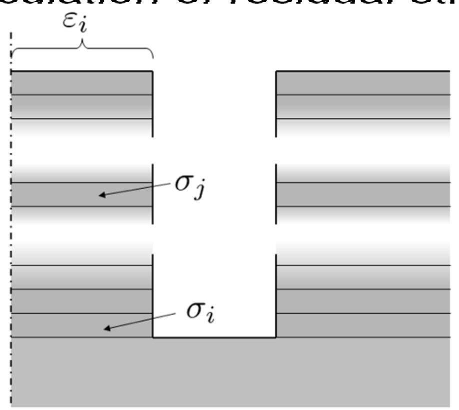
Machining of a hole in the surface



Displacement field due to stress relaxation



Calculation of residual stress field



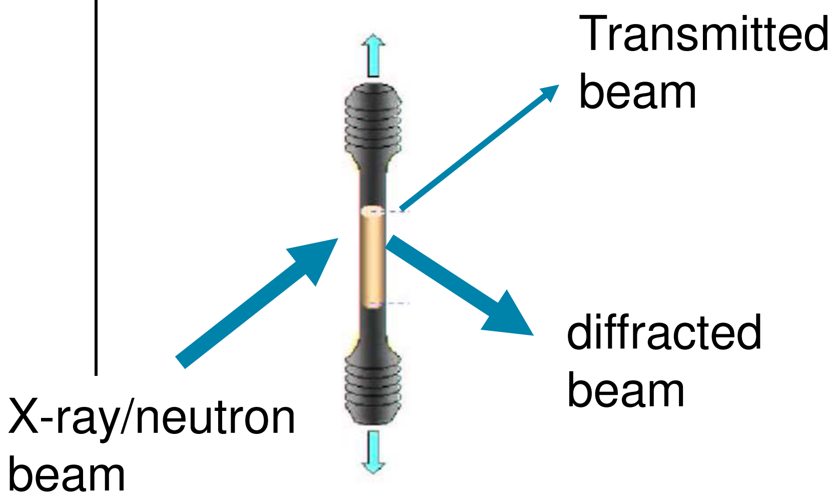
$$\underline{\varepsilon_i} = \boxed{\underline{\underline{\underline{A_{ij}}}}}\,\underline{\sigma_j}$$

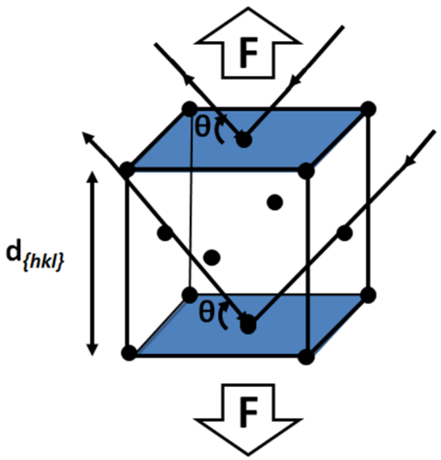
Influence matrix calculated by FE analysis

[Schajer, 2007]
[Glacet, 2015]
[Flores 2018]

CHARACTERIZATION AT THE LOCAL SCALE

Elastic strain measurement by diffraction

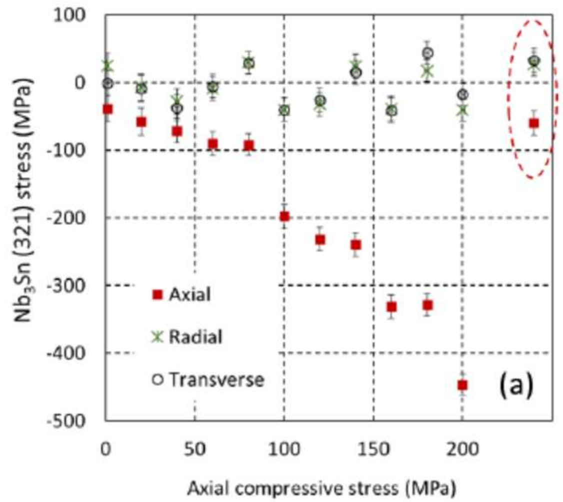




Crystalline lattice used as a gauge

$$\varepsilon_{hkl} = \frac{d_{hkl} - d_{0\ hkl}}{d_{0\ hkl}}$$

Presentation of C. Scheuerlein



Assumptions (texture, elastic parameters) → Average stress state in each component