DE LA RECHERCHE À L'INDUSTRIE

27TH INTERNATIONAL CONFERENCE ON MAGNET TECHNOLOGY
NOV 15 – 19, 2021, FUKUOKA/JAPAN

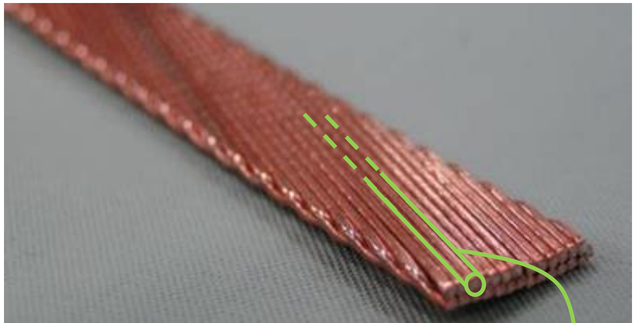
Dimensional changes measurement of Nb_3Sn Rutherford cables during heat-treatment using Digital Image Correlation

11/18/2021

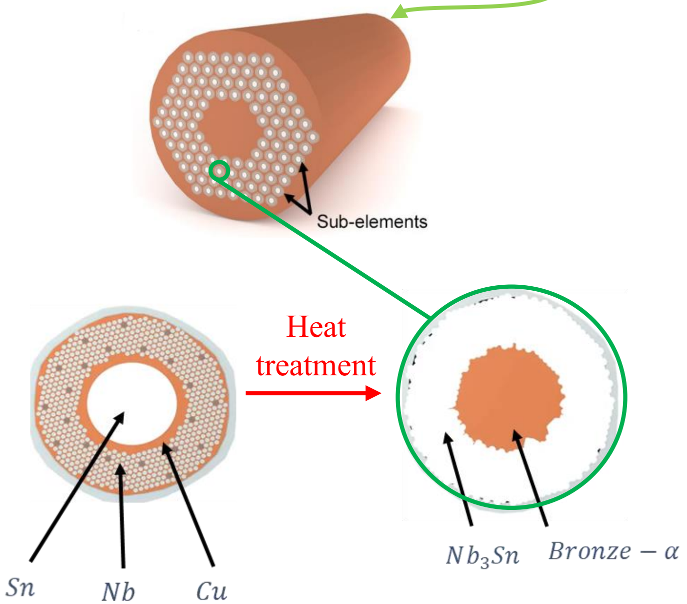
M. Abdel Hafiz[1,2], E. Rochepault[1], H. Felice[3], C. Lorin[1]
K. Lavernhe[2], O. Hubert[2]

[1]CEA Paris-Saclay/LEAS
[2]ENS Paris-Saclay/LMT
[3]CERN

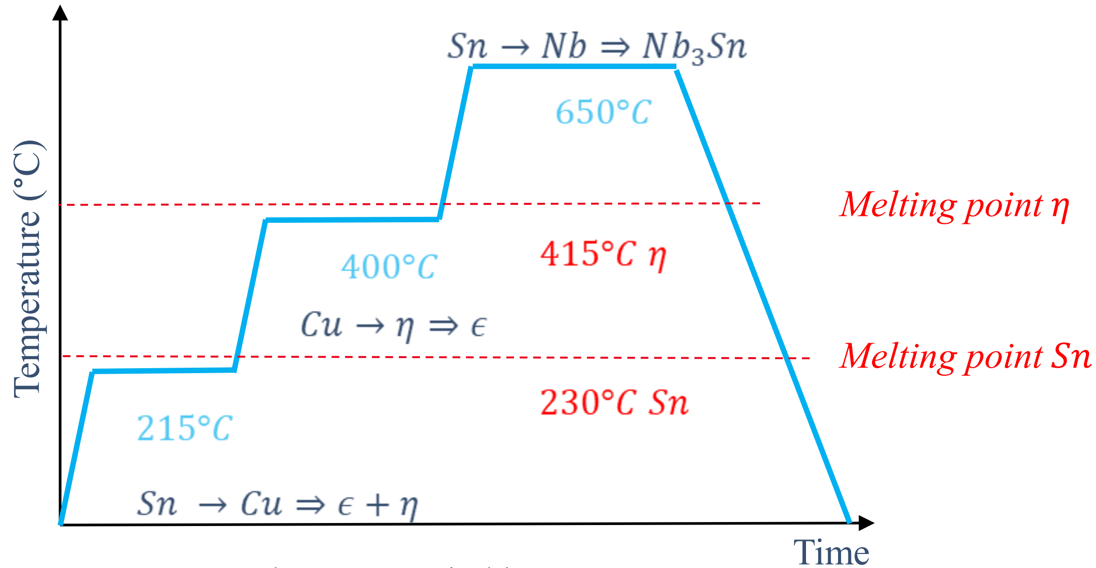
Nb_3Sn Heat Treatment *RRP* Wires



Nb_3Sn Rutherford cable
[credits : Fermilab]



Nb_3Sn strand and sub-element (*RRP*)
[Sanabria, C. 2017]



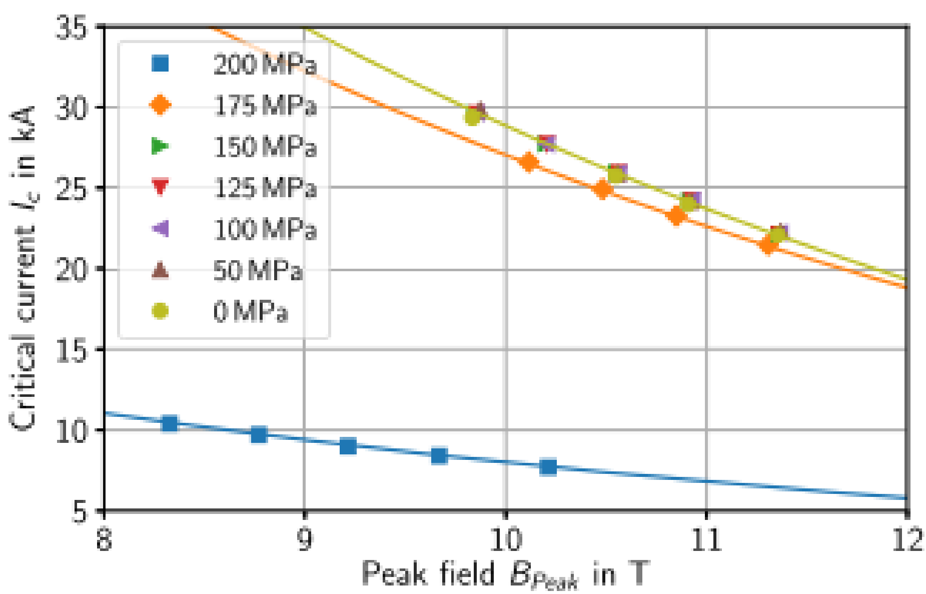
Nb_3Sn *RRP* typical heat treatment

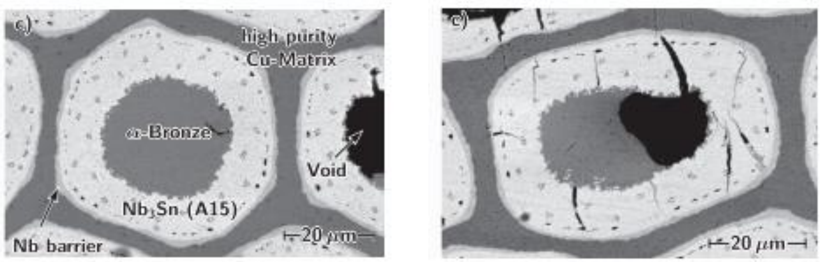
- Nb_3Sn superconducting phase created at 650°C
- Heat treatment steps allow diffusion of Sn particles to diffuse into Nb through Cu

➔ These chemical phenomena induce deformations

Nb_3Sn Brittleness

- Nb_3Sn phase is brittle
- Coils are wound then reacted
- Differential strains between coil and tooling create non-negligible stresses
- Superconducting properties are stress sensitive





$\sigma = 0\ MPa$ $\sigma = 200\ MPa$

Stress influence on superconducting properties
[Ebermann P. and al. 2018]

What are the deformations occurring during heat treatment in Nb_3Sn conductors?

Digital Image Correlation Method: Correli 3.0 Principle

- Correli 3.0 software developed at LMT
- Allows a 2D *in situ* displacement measurement between 2 ≠ images → use of speckle
- 2 hypotheses:
  > Grey level is conserved
  > Displacement is the only difference between the images

Residual: $\eta^2 = \int \left|f\left(\vec{x} + \vec{u}(\vec{x})\right) - g(\vec{x})\right|^2 d\vec{x}$

f reference image
g deformed image

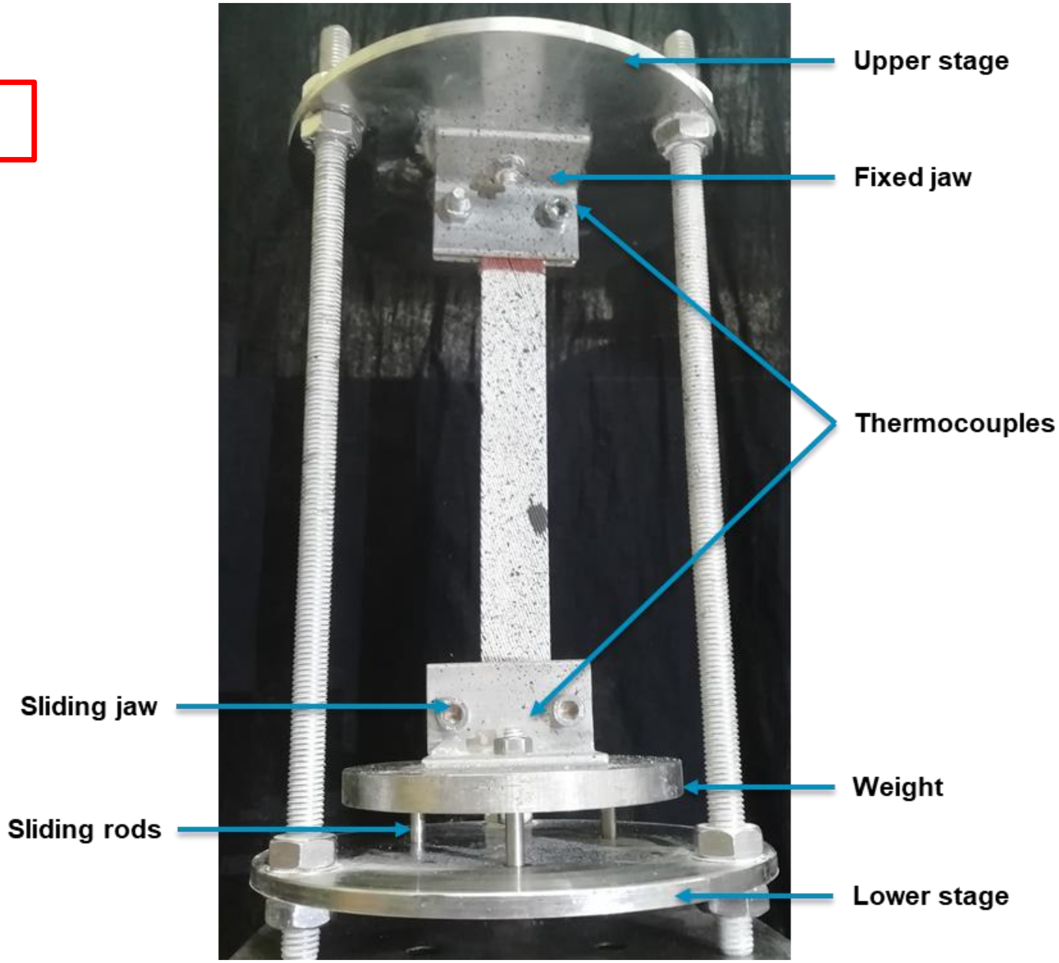
Solution displacement : $\vec{u}(\vec{x}) = argmin_{|\vec{u}}(\eta)$

DIC speckle on Rutherford cable

Sample Holder

Experimental setup: sample holder

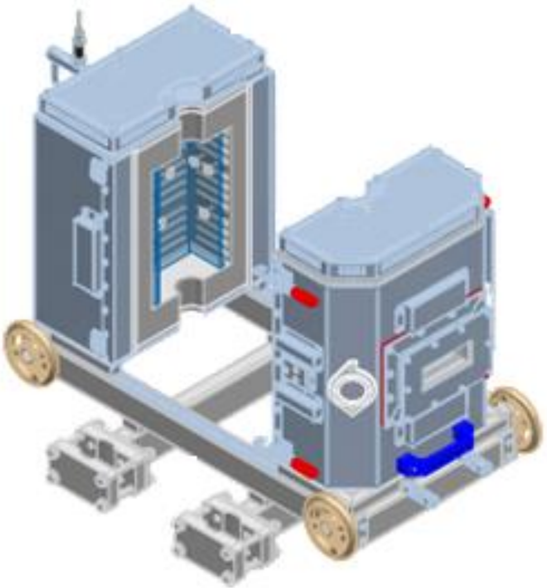
- Sample holder vertically adjustable
- Jaws maintaining upper and down side of the cable and thermocouples
- Weight preventing the cable to collapse [Michels M., 2017]
- Sliding rods restraining cable from twisting and bending



Experimental Setup

- 5 windows allowing to take *in situ* pictures
- Compatible with tensile torsion compression machine (not used)
- Argon supply, O_2% maintained under 1 – 2%
- Vertical gradient of temperature from 1 to 0.5 K/cm

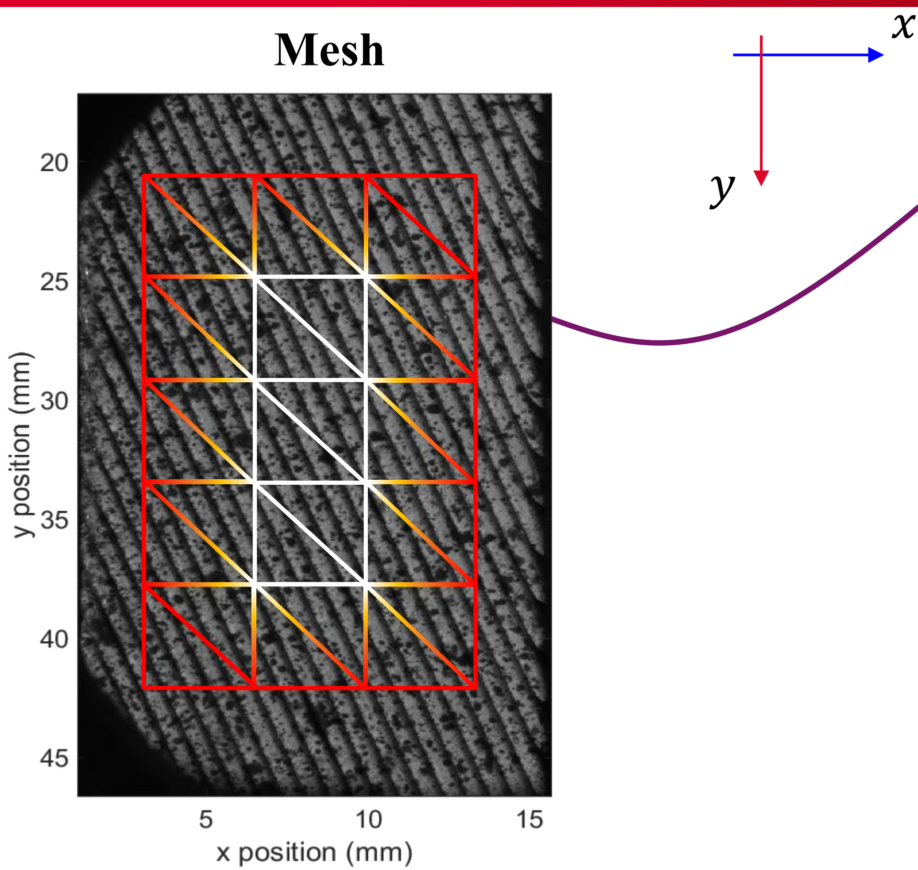
Experimental setup: oven



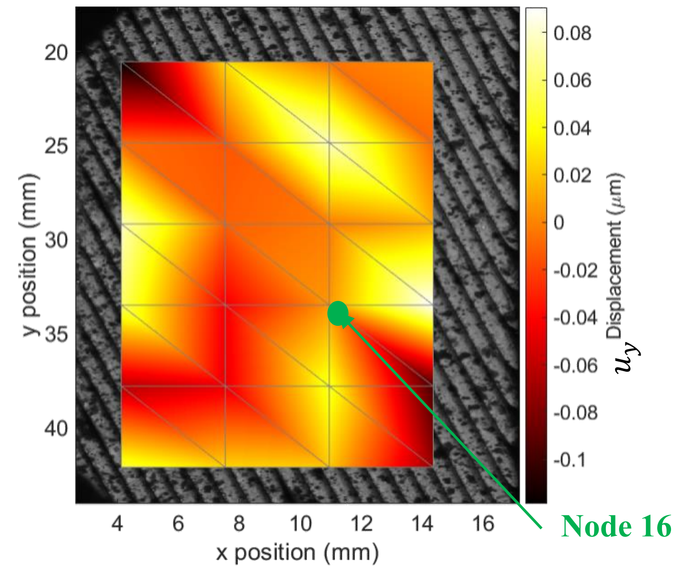
Oven scheme

General Method: Noise Measurement on Copper Cable

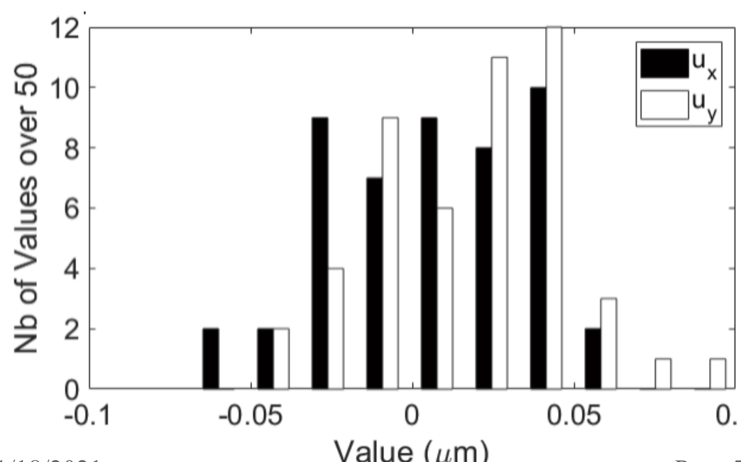
Mesh



Displacement interpolation in ZoI



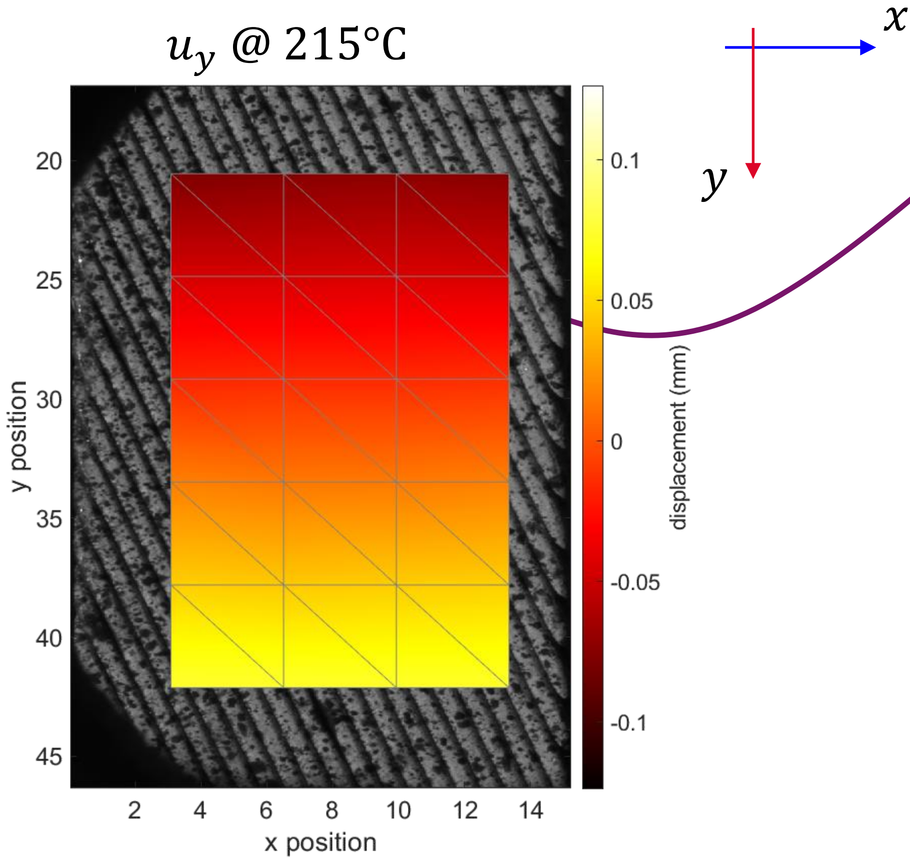
Noise measurement : Node 16 Displ.



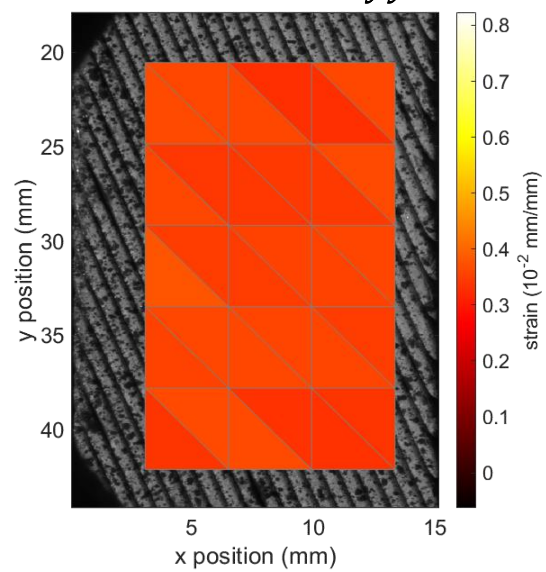
- Selecting Zone of Interest (ZoI) and mesh
- Displacement measurement at nodes
- Displacement interpolation in ZoI
- Noise estimation without loading

General Method: Strain Measurement on Copper Cable

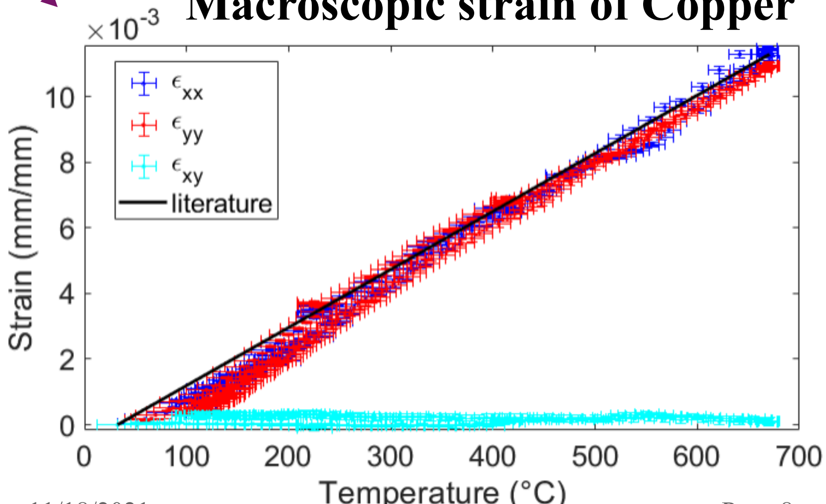
u_y @ 215°C



Strain calculation ε_{yy} @ 215°C



Macroscopic strain of Copper

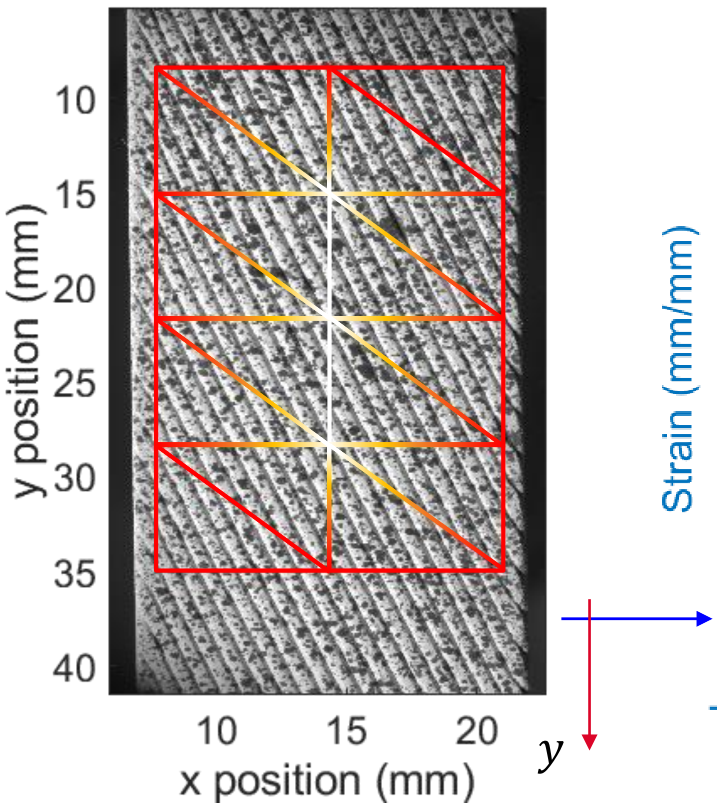


- Displacement measurement at nodes
- Displacement interpolation in ZoI
- Strain calculation, FEM
- Macroscopic strain determination

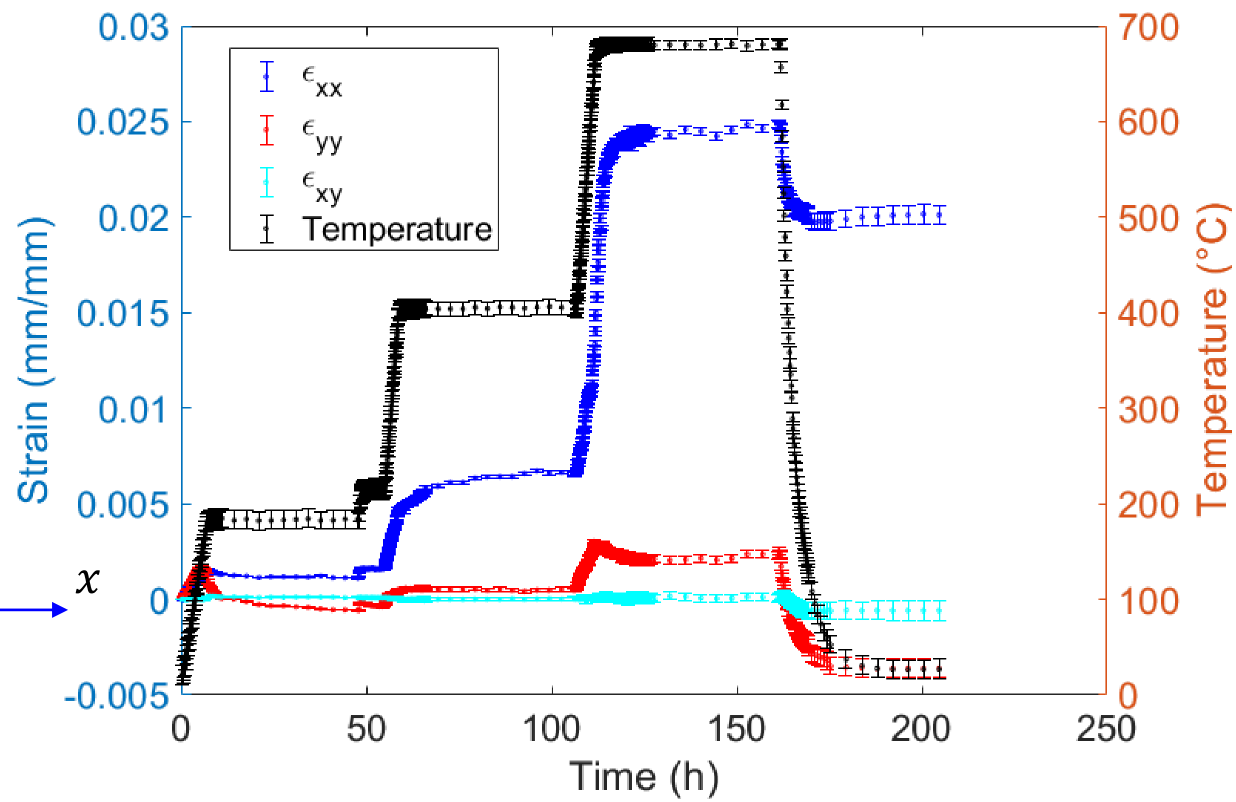
Strain Measurement on Nb_3Sn Cable

- Study on Nb_3Sn Fresca II Rutherford cable
- Average strain on both side of the cable

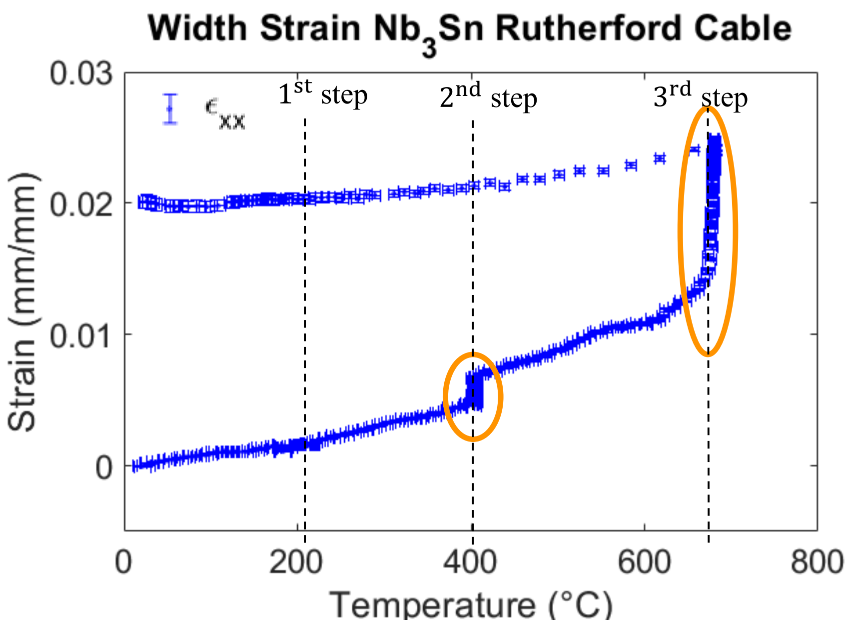
Mesh

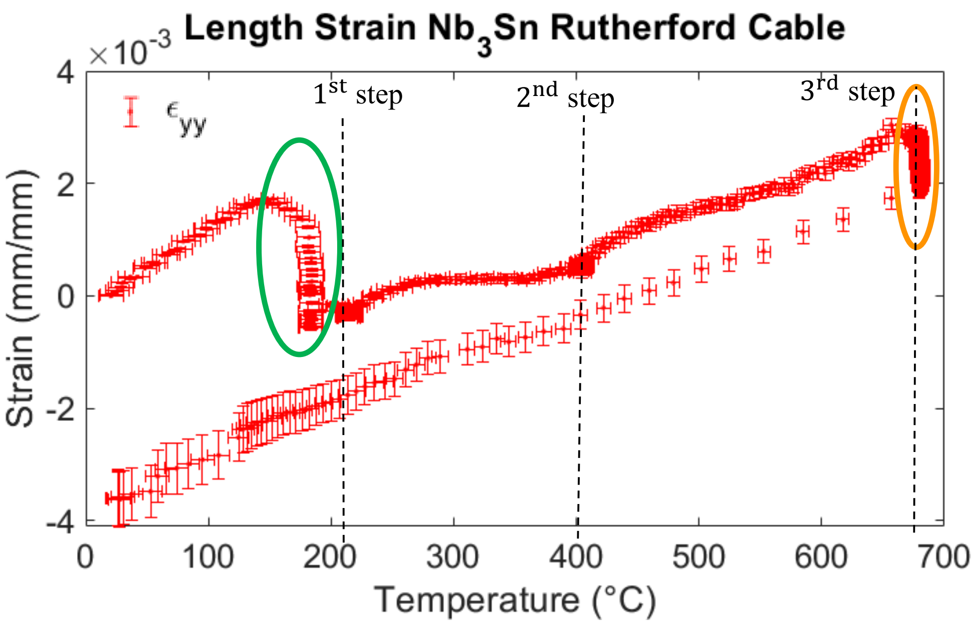


Macroscopic strain of Nb_3Sn Rutherford cable



STRAIN MEASUREMENT ON Nb_3Sn CABLE

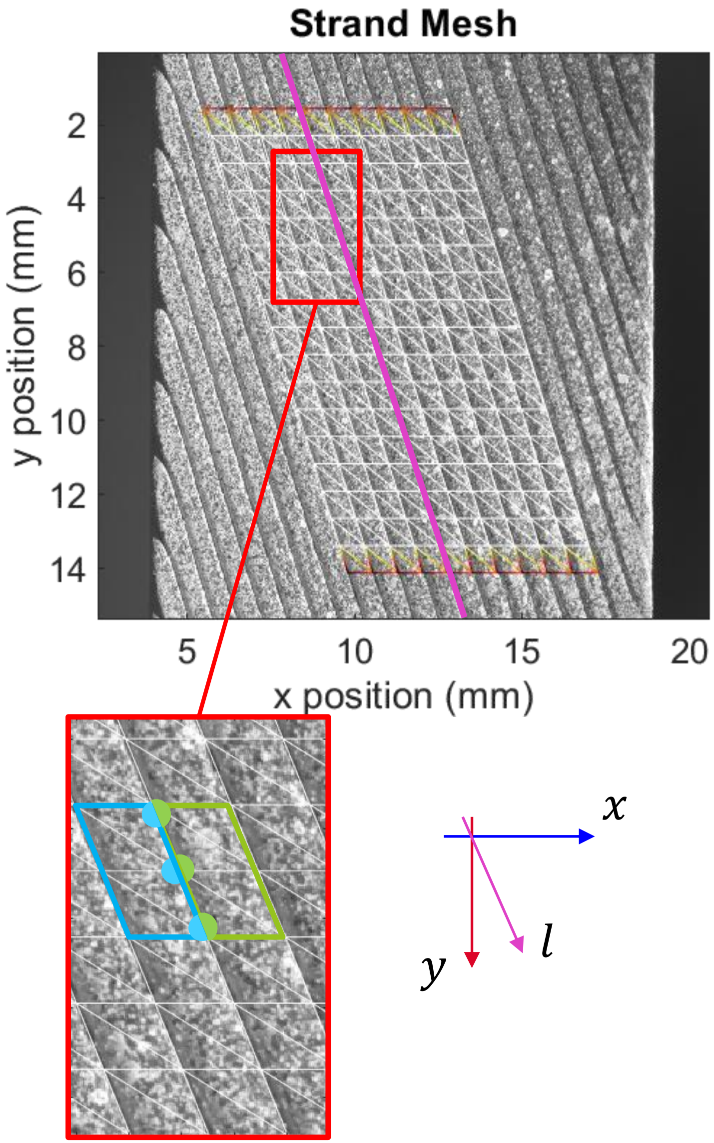




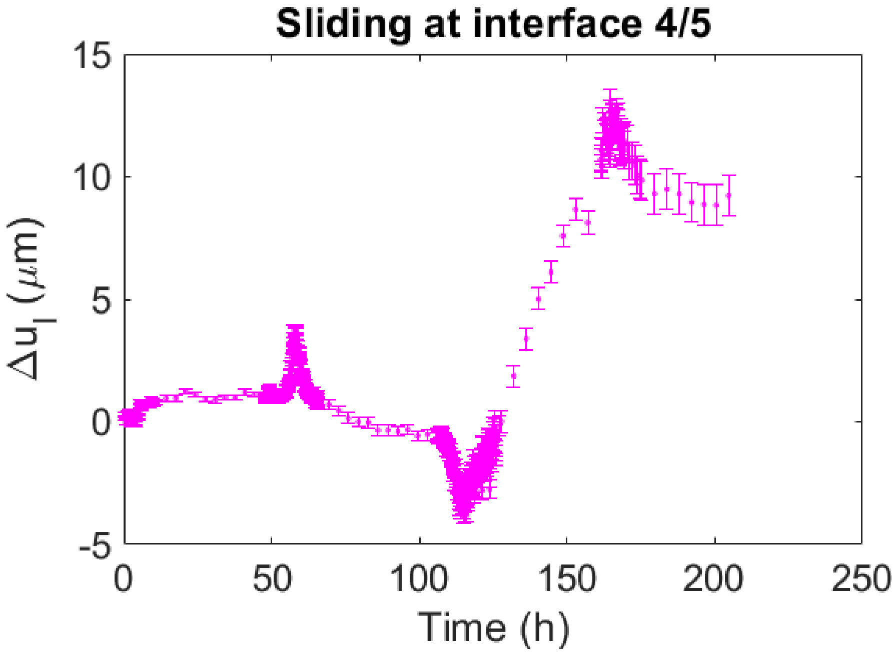
3 phenomena observed

1. Thermal expansion
2. Phases formation ➔ Mainly transversal @ 650°C
3. Copper annealing (literature) ➔ Mainly longitudinal

Strand Displacement within Nb_3Sn Cable

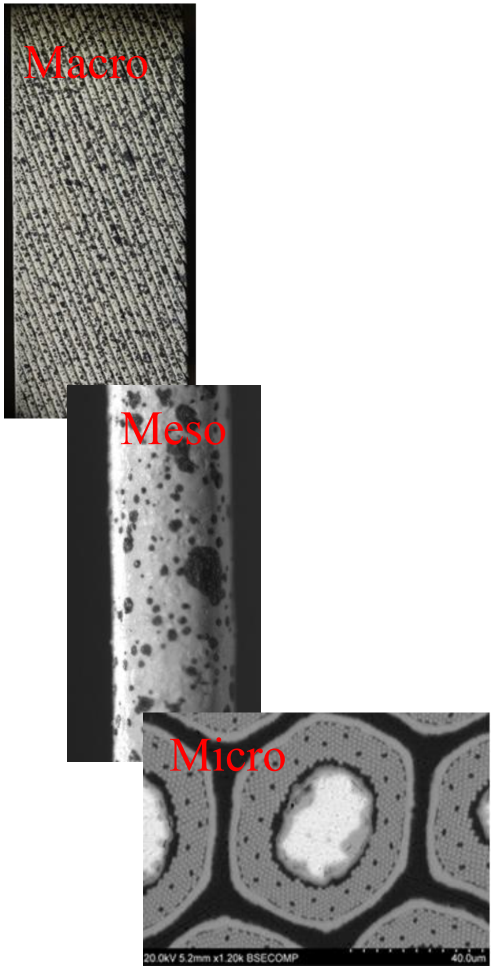


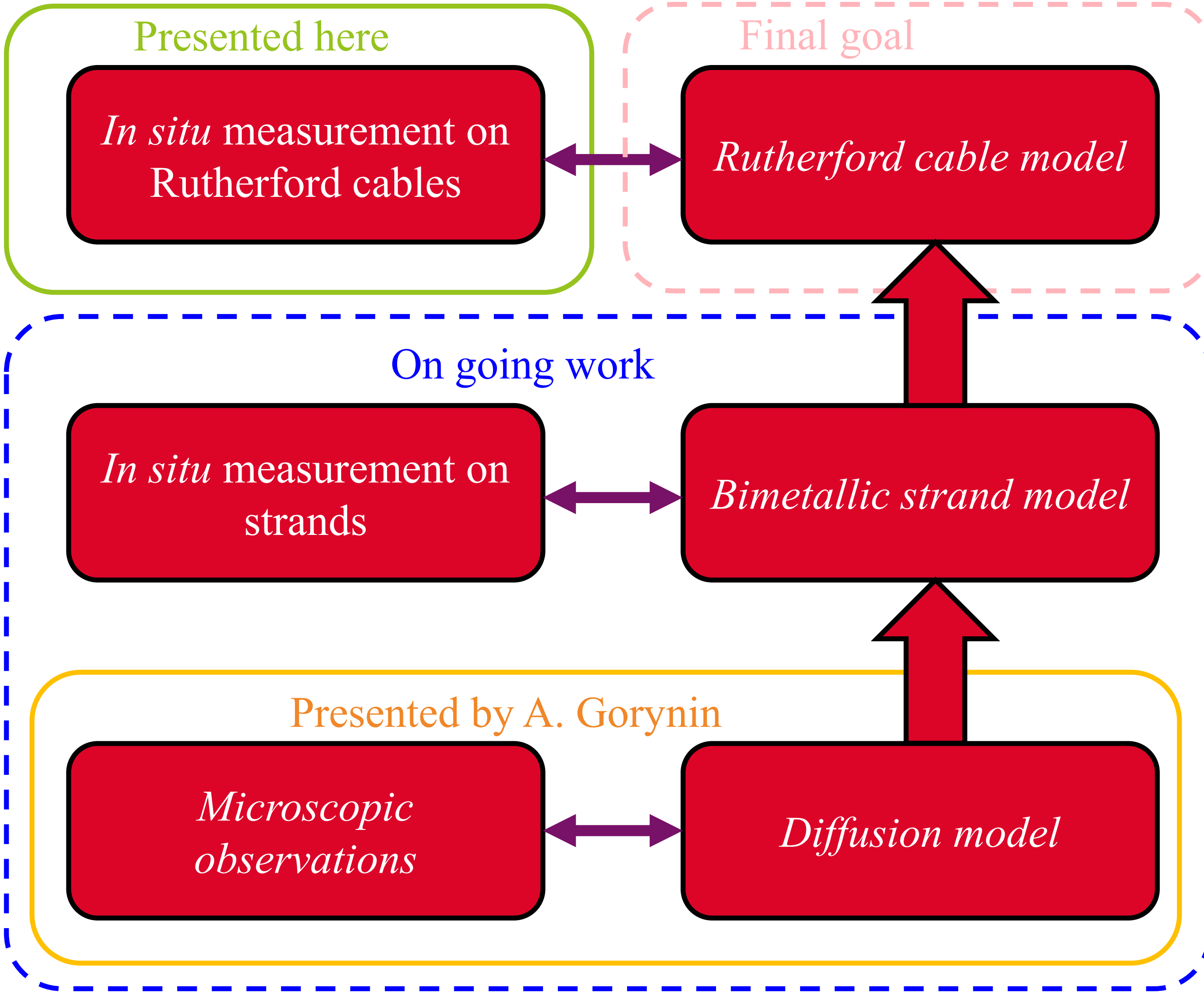
- Strands independently meshed
- Split nodes at strands interfaces



➔ Need to measure the dimensional changes on a strand

Development Plan





CONCLUSION

- 2D *in situ* Macroscopic strain measurement of Nb_3Sn Rutherford cables during heat treatment has been performed

- 3 phenomena can be determined by these measurements :
    - Copper annealing
    - Phase transformation
    - Thermal dilatation

- Strand measurement and modelling are in progress in order to predict dimensional changes on ≠ Nb_3Sn conductors

DE LA RECHERCHE À L'INDUSTRIE

References

[Besnard et al., 2006] *G. Besnard, F. Hild, and S. Roux, "Finite-element displacement fields analysis from digital images: Application to Portevin–Le Châtelier bands". Exp Mech, 2006.*

[Sanabria, 2017] *C. Sanabria, "A new understanding of the heat treatment of Nb-Sn superconducting wires,"thesis, 2017.*

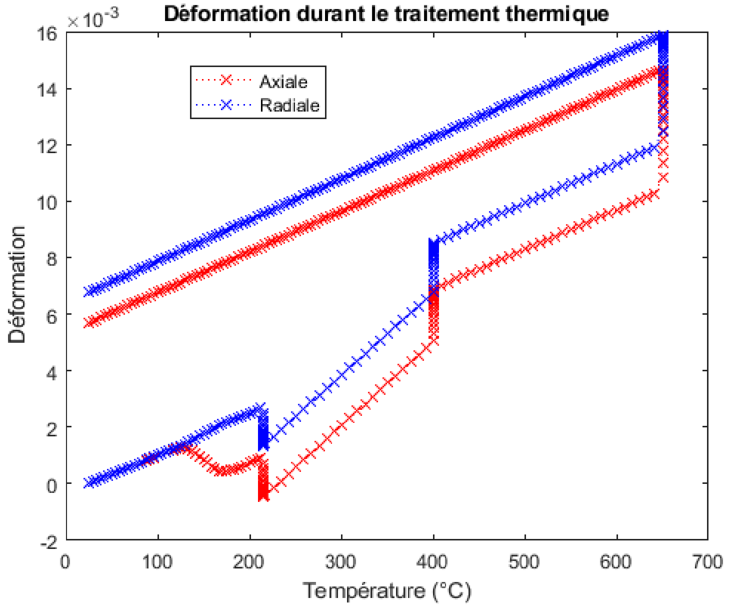
[Pong et al., 2013] *I. Pong, L.-R. Oberli, and L. Bottura, "Cu diffusion in nb3sn internal tin superconductors during heat treatment", Superconductor Science and Technology, vol. 26, no. 10, 2013.*

[Ebermann et al., 2018] *P. Ebermann et al, "Irreversible degradation of* Nb_3Sn *Rutherford cables due to transverse compressive stress at room temperature" Supercond. Sci. Technol, 2018.*

[Michels et al., 2019] *M. Michels, F. Lackner, C. Scheuerlein, A. Carlon Zurita, S. Ferradas Troitino, N. Bourcey, F. Savary, and D. Tommasini, "Length changes of unconfined* Nb_3Sn *Rutherford cables during reaction heat treatment", IEEE Transactions on Applied Superconductivity, vol. 29, no. 5, 2019.*

THANK YOU !

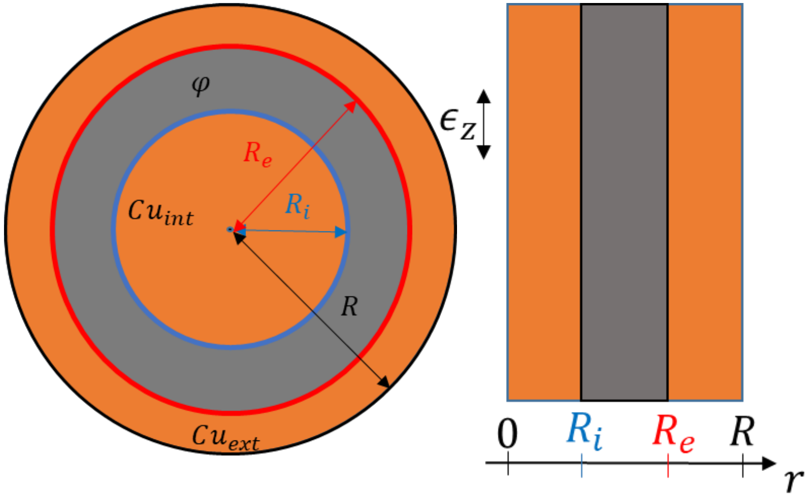
MODEL VS EXPERIMENT



Missing φ thermomechanical properties

Upcoming : Strain measurements on Nb_3Sn strands

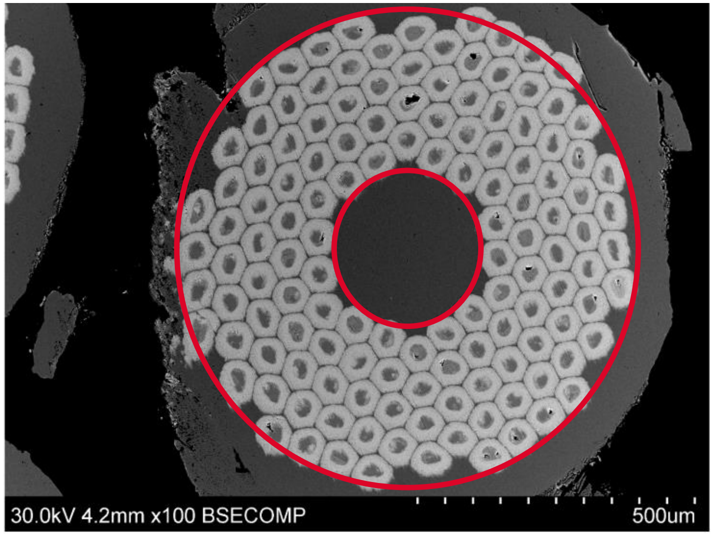
For each i phases in φ

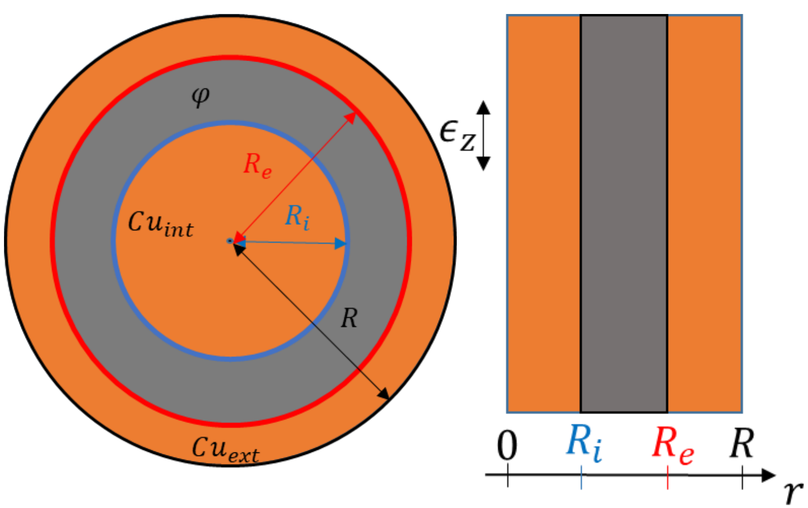


$$F\left(E_i, \nu_i, \alpha_i, f_i(t)\right)$$

- $f_i(t)$ → *Sub-element analysis* (Arsenii's Work)
- E_i, ν_i, α_i → *Literature*

Strand Displacement Within Cable





3 Kinds of deformation

ϵ^e Mechanical strain, related to stress
ϵ^{th} Thermal strain, related to thermal expansion
ϵ^{ch} Chemical strain, related to phase changes

2 Area

Cu Copper releasing stresses from 150 to 200°C
φ Homogenized area, transversal isotropic