ANALYSE MULTI-ÉCHELLE DE CÂBLÉS SUPRACONDUCTEURS

G. Lenoir, P. Manil, F. Nunio

CEA Paris-Saclay – IRFU, Université Paris-Saclay

Club Cast3m 2018 - Paris
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Principle of a circular accelerator, to ensure the collision of the 2 beams:

1. accelerate the particles
   \( \Rightarrow \) radiofrequency cavities: \( \vec{F} = q \vec{E} \)

2. deviate the particles (bend the trajectory)
   \( \Rightarrow \) dipolar magnets: \( \vec{F} = q \vec{V} \times \vec{B} \)

3. focus the beam (concentrate the bunches)
   \( \Rightarrow \) quadrupolar magnets

4. reduce aberrations
   \( \Rightarrow \) multipolar magnets

The LHC today:
- \( \sim 1200 \) dipole magnets (L=14m)
- \( \sim 400 \) quadrupole magnets (L=3m)

The future of LHC:
- HL-LHC (luminosity upgrade X 10) \( \rightarrow 2022 \)
- HE-LHC (energy upgrade X 2,5) \( \rightarrow 2035 \)
A MULTISCALE STRUCTURE ...

- **State of the art**
  - NbTi alloy currently used can reach 9/10T
  - LHC’s upgrade aims beyond 10 T

- **Development of Nb$_3$Sn based conductor**
  - Complex manufacturing process
  - Brittle material
  - Electrical performances depends on mechanical state (strain)

  - Influence of local phenomena *must be understood* ⇒ *relevant criterion*
  - Superconductor behaviour should be anticipated ⇒ *predictive approach*
  - Cable features should be *optimized mechanically*
• **Geometric Model (F. Nunio)**
  - Rutherford cables considering bi-metallic model
  - Impregnation region
  - Stack of conductors

• **Mechanical Model (G. Lenoir)**
  - Bi-metallic strand model based on RVE at the $\mu$-scale
  - Inverse identification of material parameters
  - Validation of the model
Cabling Model Methodology

Initial model
- Helical geometry
- Bimetallic description

Cable compaction by 4 planes

Application of the displacement field

Stack of impregnated conductors

Impregnation region

Impregnation insulation

Epoxy matrix

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**Cabling Model**

- **Parametrization of the model:**
  - Strand parameters
  - Cable parameters:
    - Number of strands
    - Twist pitch P
    - Final size of the Rutherford shape W x H

- **Benefits:**
  - Cast3m script generates EPx input file
  - Persistence of the model’s hierarchical structure during all modeling steps

⇒ *Adaptative tool for the prediction of the cable geometry*

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**CT scan comparison**

- 9 strands
- 18 strands
- 40 strands
Matrix filler construction:
- not fully successful with reverse engineering methods (surface reconstruction, Boolean operators ...)
- no improvements with direct Boolean cut at the level of the mesh
- method: rebuild the skin of the matrix filler by a “sewing” technique, and mesh the volume
Model of impregnated Rutherford cable

Analysis of numerical compressive test on one stack

⇒ Representative results of cable requires adapted mechanical model at the strand scale
• **Geometric model (F. Nunio)**
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THE BI-METALLIC MODEL

- Detailed mesh of strands in cable model numerically too expansive
  - Simplified representation of the strands

- Filament scale
  - Representative Volume Element (RVE)
    - Interfilamentary matrix
    - Superconducting phase
    - Filament Barrier
    - Filament Core

- Strand scale
  - Filamentary Region
  - Outer Layer
  - Strand Core

⇒ Definition the composition of the bi-metallic model sets and their mechanical behavior

SEM transverse observation of a Powder-In-Tube strand [Lenoir 17]

Cu

Nb

Nb₃Sn

Homogenized mechanical model


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Non-linear behavior of strands

- Adapted constitutive equation for elasto-plastic materials
- Predictibility of non-monotonic behavior

Mechanical modeling [Lemaître 94]

- Von Mises yield criterion \( f(\sigma, X, R) \)
- Elasticity with Hooke’s law: \( \sigma = E \ast \varepsilon \)
- Elasto-plasticity with hardening
  [Armstrong 66] [Lemaître 94]
  \[
  \dot{R} = b \ast (Q - R) \ast \dot{\varepsilon} \\
  \dot{X} = C \ast \varepsilon \dot{\varepsilon} - \gamma \ast X \ast \dot{\varepsilon}
  \]

3D-model based on internal variables of individual components

Tensile test on Nb\(_3\)Sn strands [Lenoir 17]
Observations

![Image showing nano-indentation results](image)

### Table: Nano-Indentation Results

<table>
<thead>
<tr>
<th>PIT</th>
<th>Indents number</th>
<th>E [GPa]</th>
<th>H [GPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu OL</td>
<td>18</td>
<td>133 ±5</td>
<td>1,25 ±0,08</td>
</tr>
<tr>
<td>Cu CO</td>
<td>15</td>
<td>125 ±4</td>
<td>1,14 ±0,07</td>
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<tr>
<td>Cu IF</td>
<td>92</td>
<td>132 ±6</td>
<td>1,33 ±0,13</td>
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<tr>
<td>Nb</td>
<td>13</td>
<td>125 ±13</td>
<td>1,69 ±0,43</td>
</tr>
<tr>
<td>Nb$_3$Sn SG</td>
<td>35</td>
<td>171 ±6</td>
<td>13,1 ±0,56</td>
</tr>
</tbody>
</table>

Results

- **Copper** considered as homogeneous
- **Niobium** behavior close to copper’s
- **Nb$_3$Sn**
  - Small grain phase purely elastic
  - Large grain phase not characterized
- **{Tin, porosities}** not characterized
Composition & mechanical parameters

- Strand Core, Outer-layer & Interfil. Matrix – Copper
  - Elasto-plastic with hardening - $E_C$, $\nu_C$, $\sigma_C$, $b_C$, $Q_C$, $C_C$, $\gamma_C$

- Supercond. – Nb$_3$Sn
  - Elastic - $E_S$, $\nu_S$

- Filament Core - Sn / Porosities
  - Elastic - $E_F$, $\nu_F$

Geometrical parameters from Image analysis using ImageJ software

- Strand: $\phi_{str}$, $\phi_{SFR}$, $\phi_{core}$
- RVE: $\phi_{SC}$, $\phi_{FC}$, $D_f$, $\alpha_f$

⇒ Model parameters identify by direct measurements & inverse identification
Inverse identification of material parameters

- Finding the parameters which minimize the error between a model response and experimental data

Tensile tests
- Performed at CEA
- SCUTT device [Lenoir 17]
- Room temperature
- Reacted strands

Tensile tests model
- Parallel materials
  - Homogeneous strain
    - strain: $\varepsilon = \varepsilon_{SC} = \varepsilon_{FC} = \varepsilon_{Cu}$
  - Stress distribution
    - stress: $\sigma = f_{vSC} \cdot \sigma_{SC} + f_{vFC} \cdot \sigma_{FC} + f_{vCu} \cdot \sigma_{Cu}$

- Behavior of the sets
  - Copper $\Rightarrow E_{Cu}, \nu_{Cu}$
  - Supercond $\Rightarrow E_{SC}, \nu_{SC}$
  - Filament Core $\Rightarrow E_{FC}, \nu_{FC}$

- Mech. differential system solved using a Runge-Kutta method

Optimization process
- Iteratively generate a set of parameters
- Compare the responses with a least square error
- Choose the set of parameters which minimize the error

Genetic & gradient-based algorithms
**Inverse Identification Results of PIT**

- **Comparison with the tensile tests used to identify the parameters**

  ![Graphs showing experiment vs simulation results for tensile tests.]
  - Fixed parameters: $E_{Cu}, E_{SC}$
  - Optimized parameters: $E_{FC}, \sigma_{yCu}, C_{Cu}, \gamma_{Cu}$

- **Comparison with independent tests**

  ![Graphs showing experiment vs simulation results for independent tests.]
  - Comments:
    - Elastic moduli
    - Loading plastic behavior
    - Elasto-plastic unloading
    - Initial slope / high $\sigma_{yCu}$
  - Improvements:
    - Copper data
    - Transverse tests on strand
    - Adding kinematic hardening

1. Definition of the geometry and the materials parameters from the identification process
2. Numerical tests in the different directions
3. Integration of stress and strain in the total volume
4. Plot of stress-strain curve in the total volume on the aimed direction
5. Extraction of the bi-linear model in the different directions

Homogenized mechanical properties (bi-linear model in each direction)
FUTURE VALIDATION OF THE MODEL

⇒ Comparison of the bi-metallic model response, detailed strand models & experimental data

- Mechanical behavior
  - Copper
    - behavior laws from identification process
  - Filamentary area
    - bi-linear model from homogenization process

- Numerical tests
  - Transverse direction
  - Tensile direction
SUMMARY OF THE MODEL

Analysis of strand observations and material properties

Definition of the RVE

Numerical tests

Homogenized mechanical model

Generation of cable shape

Generation of the impregnation

Strand #1 (twisted pattern)
SUMMARY

• **GEOMETRIC MODEL**
  - **Predictable** definition of the geometry of Rutherford cables considering **bi-metallic** model
  - **Robust and automated** creation of the **impregnation region**
  - Mechanical modelling of a **representative stack** of conductors

• **MECHANICAL MODEL**
  - **Bi-metallic strand model** based on **RVE at the μ-scale**
  - Elasto-plastic behavior with **internal variables**
  - Can be used for **predictable modeling** of cables
• Tensile tests at cryogenic temperature (on-going)
• Nano-indentation at cryogenic temperature
• Enrichment of the experimental database with transverse tests and copper data (on-going)
• Validation of model prediction on experimental tests at strand scale & cable (stack) scale
• Add initial residual stress to account for strand heat treatment (experimental data needed)
• Improve the behavior law
• CoCaSCOPE platform

PERSPECTIVES

• Electrical prediction
SPECIAL THANKS TO DEN/DM2S/SEMT/DYN (V. FAUCHER, O. JAMOND, T. LAPORTE)

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**LOCAL PROPERTIES — NANO-INDENTATION TEST**

- **Principle [Oliver 04]**
  - Mark (indentation) on the material surface realized with a tip (indenter)
  - Load and displacement measured during indentation
  - Contact stiffness and indenter properties
    - local elastic modulus and nano-hardness of the material

- **Procedure**
  - MTS-XP nano-indenter (MSSMat - CentraleSupélec)
    - (Continuous/Dynamic Stiffness Measurement technique)
  - Dimension: Imposed depth 200nm
    - Indents size ≈1,4µm
  - Indents grid for statistical results
  - Transverse cross-section of strands
    - Surface preparation by manual and vibratory polishing of epoxy impregnated strand [Bajas 11]

- **Validation of each indents**
  - Contact stiffness and elastic modulus with penetration depth curves
  - SEM observations

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## Elastic Properties Database in Community

### Material | E (GPa) | Reference |
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<tr>
<td></td>
<td>105-110</td>
<td>[Mitchell 05]</td>
</tr>
</tbody>
</table>

- **E\textsubscript{Nano-ind.}**
  - 129 GPa
  - 171 GPa

### Differences in
- **Manufacturing process**
  - Of materials
  - Of strands
- **Measured object**
  - Complete strand
  - Filaments bundles (w/o matrix)
  - Single filament
  - Tapes (ex: Nb\(_3\)Sn layers/ductile substrate)
  - Single crystal

### Measurement methods
- Axial extensometer and load cell
- Optical extensometer
- Resonant Ultrasound Spectroscopy
- Crystallographic orientation

### Direct measurement vs Mixture laws

### Based on literature values
- \(E_{Nb}\) - single crystal properties, ASM International
Collaboration with ENSAM Châlons (R. Rotinat, R. Moulart, L. Fouilland, C. Person)

Digital Image Correlation during an in-situ transversal compression test

Objective
- Quantify anisotropy
- Include additional data for behavior laws identification

Planeity analysis of a copper wire and a strand

Compression device inside the interferometric microscope

Compression device

450N