Structural Modeling of HTS Cable-in-Conduit Conductor with Helically Slotted Aluminum Core for High-Field Magnet Applications

MT 26 International Conference on Magnet Technology
Vancouver, Canada | 2019

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Introduction

High current cable made with $REBa_2Cu_3O_{7-x}$ coated conductors will enhance a new generation of compact high field, high current density magnets due to the smaller influence of the magnetic field and temperature on the critical current density of the superconductor.

Among the cabling options, the **HTS Cable-in-Conduit Conductor** developed at ENEA is particularly suited for **high-field applications**.

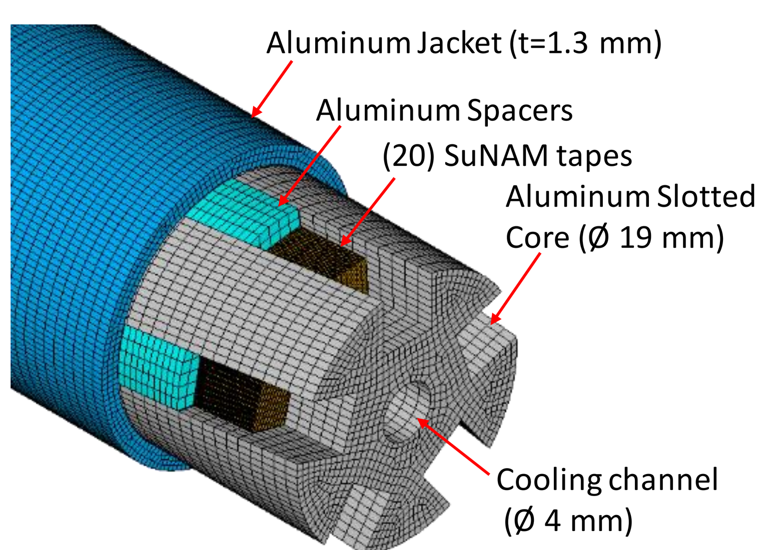
The cable consist of:

- Aluminum core with five helically slotted channel
- A stack of 20 SuNAM tapes in each channel
- Aluminum spacers
- Aluminum jackets, wrapped around the core and drawn to reduce gaps

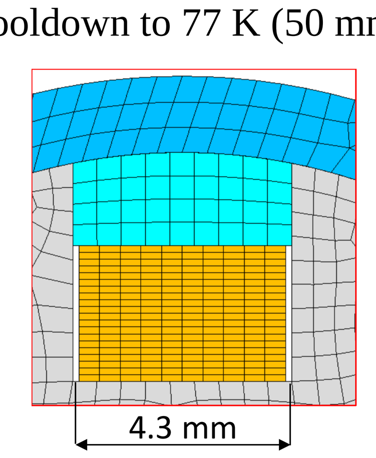
Finite element analysis was used to evaluate the strain distribution and ultimately the critical current degradation on the REBCO tapes in the cable caused by: *compaction* of the aluminum jacket (1), *bending* (2), and *thermal cooldown* (3).

Finite Element Model

A three-dimensional **finite element model** was developed in ANSYS to replicate the assembling process and testing of a five-channel HTS CICC cable.



The study is composed of **three steps**:
Step 1: Compaction of the aluminum jacket (50 mm)
Step 2 : Cable bending (full twist pitch, 500 mm)
Step 3 : Thermal cooldown to 77 K (50 mm)



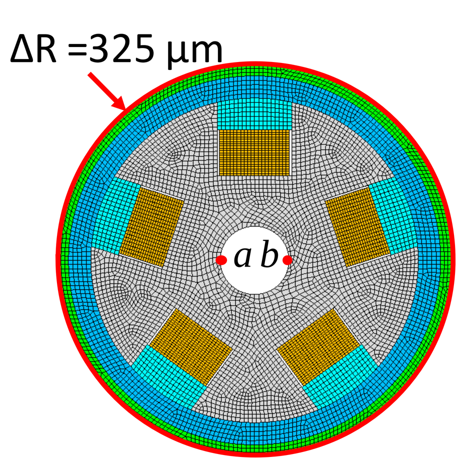
Model Details:

- Tape modeled using **SOLSH190** structural **solid-shell** elements.
- Surface-to-Surface contact pairs between adjacent tapes and the support structure.
- Bilinear stress-strain curves (elasto-plastic behavior) at 77 K and 295 K.
- Coefficients of thermal expansions (CTE) to predict residual thermal strain from cooldown.

Assumptions made to capture the overall behavior and reduce the computational time

- One slot full of tapes, no jacket
- Spacer merged to the core

Compaction



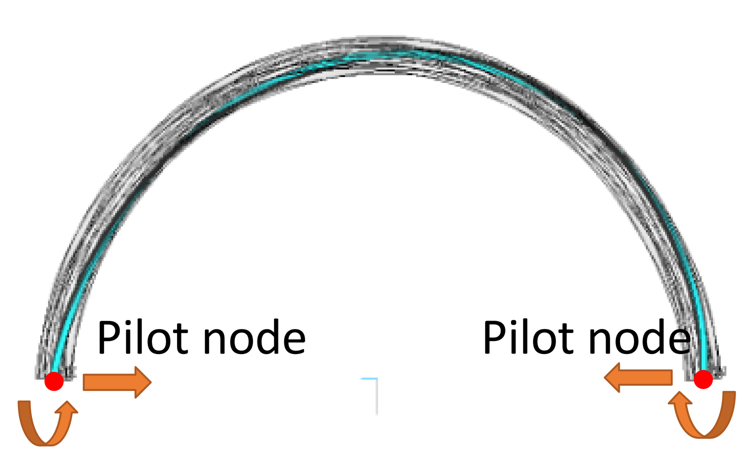
Boundary conditions and loading

- External ring (rigid body) positioned around the jacket to apply displacement
- Radial displacement of 325 µm (measured) applied to the ring
- *a* and *b* nodes constrained vertically
- One end of the jacket constrained longitudinally

Bending

Boundary conditions and loading

- Multipoint coupling constrain (pilot node) used to control the cable ends
- Equal and opposite displacement and rotation applied to pilot nodes



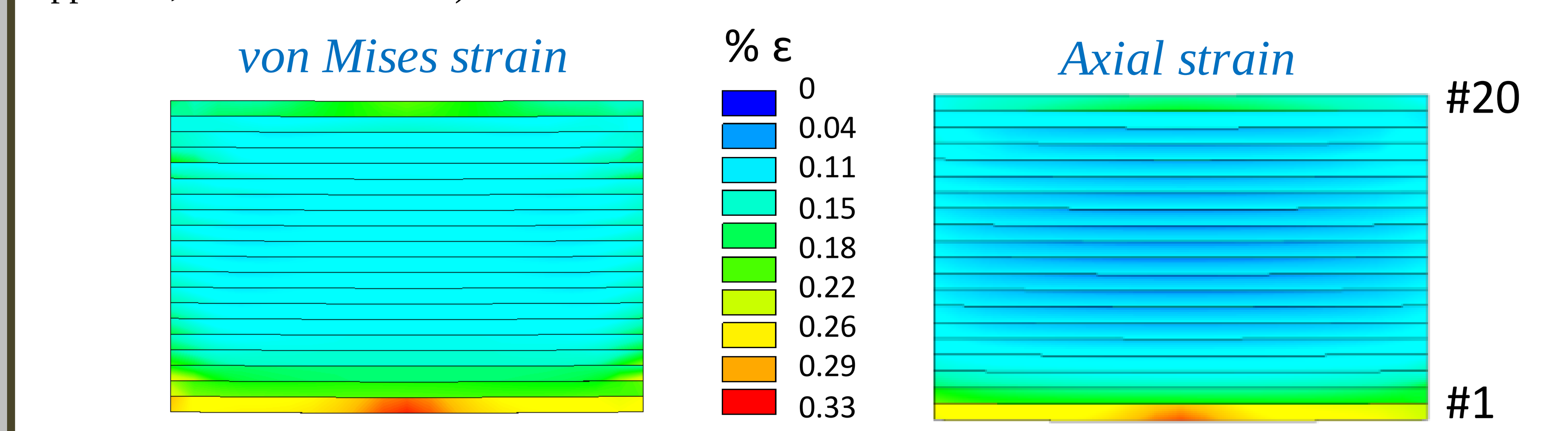
Cooldown

- Temperature gradient from 295 to 77 K.
- Same boundary conditions as compaction

Data Analysis Technique

The average **critical current** in each tape was calculated combining **experimental** I_c **vs. axial strain data** from literature and the **strain distribution** obtained **from ANSYS**

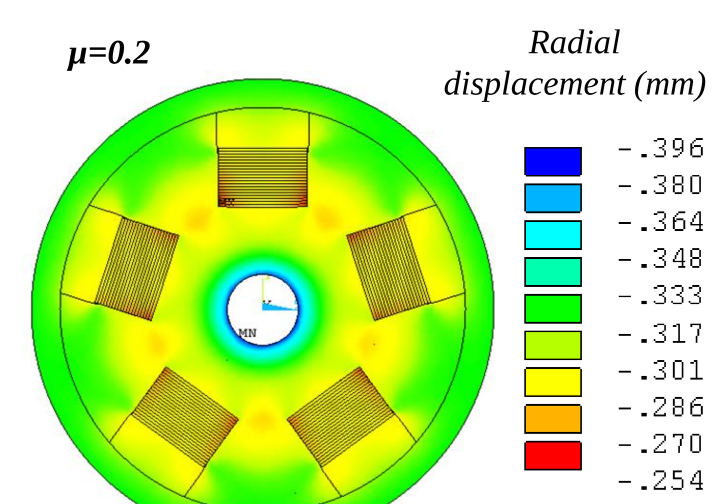
Von Mises strain was used instead of axial strain for a multiaxial loading scenario (more conservative approach, but similar results)

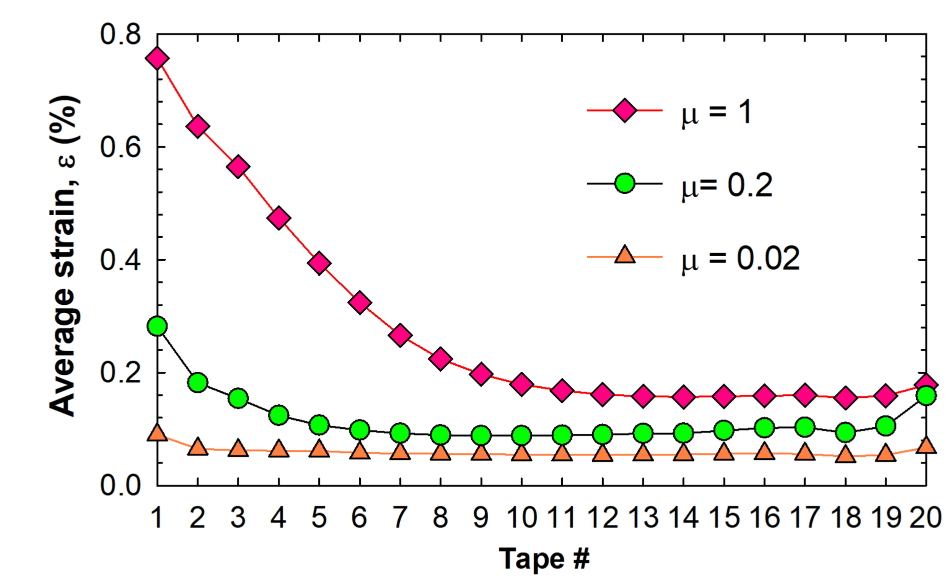


- Von Mises strain collected at 80 locations across the width of each tape at 72 location along the length of the cable

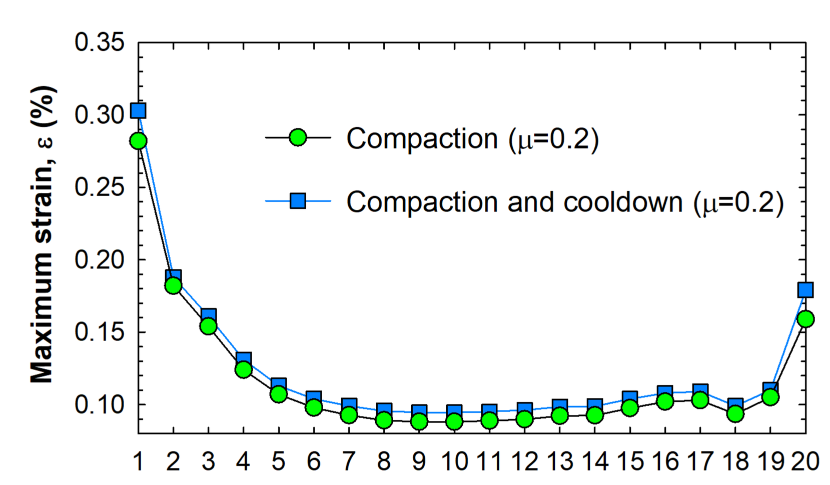
Results: Compaction

A model to replicate the jacket compaction was created. The influence of friction between tapes and the support structure was investigated. The same coefficient was defined for all contacts





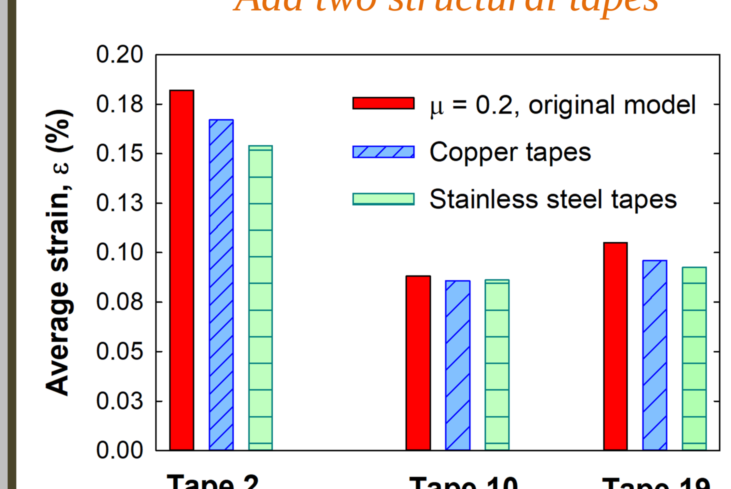
- The highest strain is accumulated in top and bottom tapes
- Highest von Mises strain obtained with a friction μ = 1 (150% higher than μ = 0.2 for tape 1)
- For μ = 0.02, the average strain varies between 0.09% (tape 1), 0.07 (tape 20) and 0.055% (tape 10)
- The effect *compaction cannot be neglected*

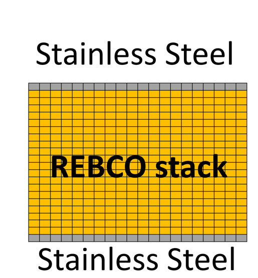


- Cooldown applied to the straight cable after compaction
- *Higher von Mises strain in tape 1 and 20 (~7% higher)*
- *Cooldown negligible for the inner tapes*
- *For tape 1, I_c/I_{co} is 0.98*

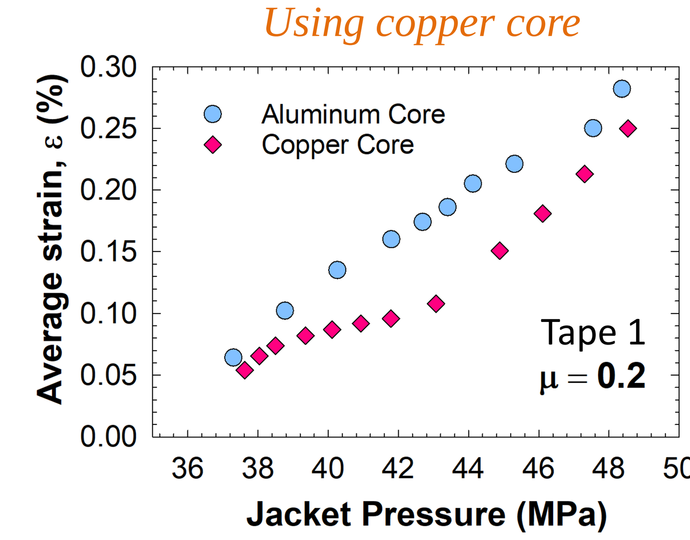
How to reduce the effect of compaction

Add two structural tapes



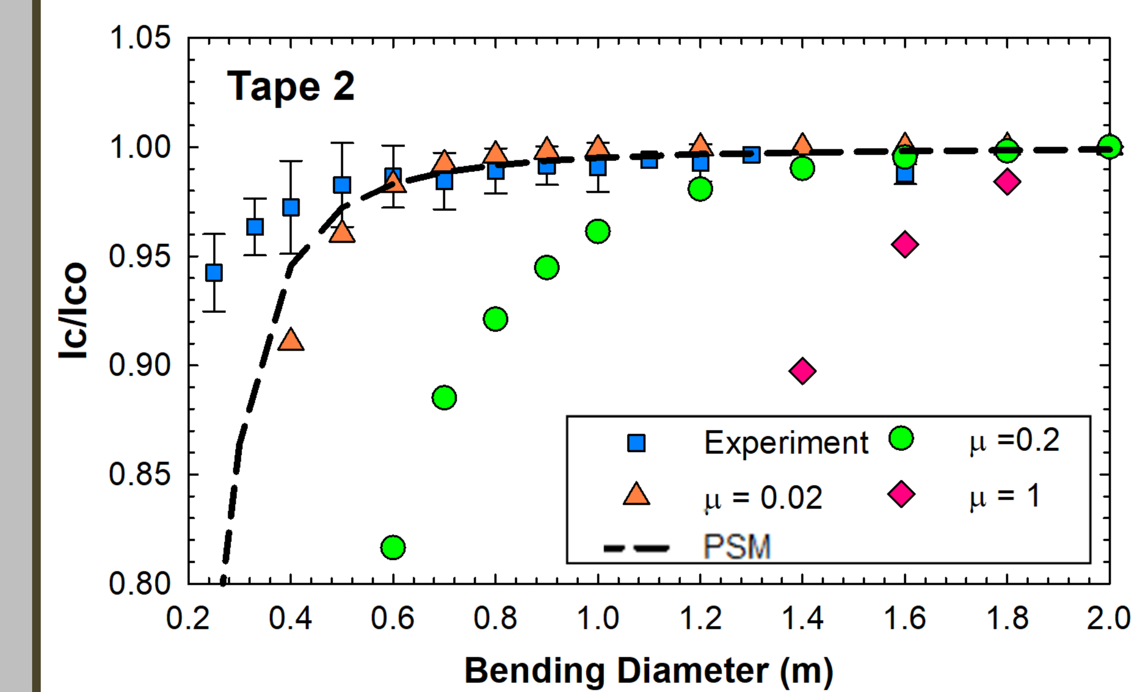


Using copper core



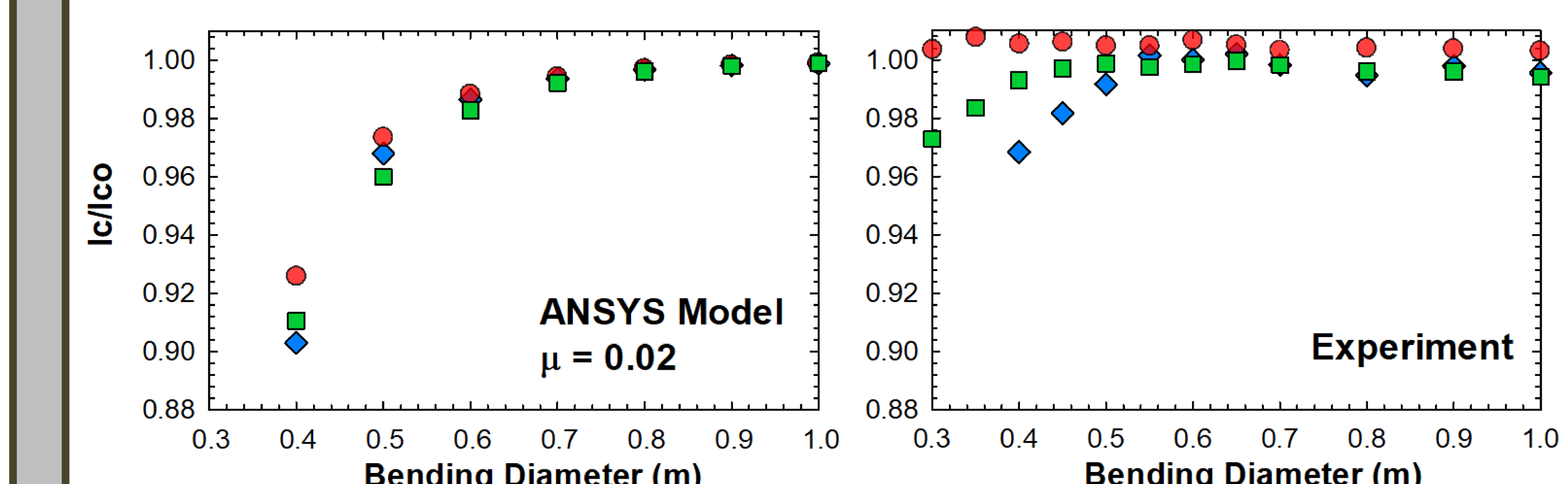
Results: Bending

The *normalized critical current* is calculated by considering the total strain from compaction, bending and cooldown. The results are very sensitive to the friction utilized in the model.



- Highest degradation observed with μ = 1
- Frictionless model (μ = 0.02) match well with experimental data and PSM analytical model

- The FEA model successfully predict the behavior of the real cable under bending
- Current sharing between tapes was experienced in the experiment, but cannot be reproduced in the structural mode



- For small bending diameters the **outer tapes** of the stack experience significant **higher degradation**.
- The same behavior was **observed experimentally** for the top and bottom tapes of the stack.
- **Compaction** is believed to be the **major cause** of this behavior (almost frictionless model)

Conclusion

A finite element model was developed to predict the strain generated in an aluminum slotted core cable-in-conduit conductor filled with five stacks of SuNAM tapes.

- Strain cased by the compaction of the jacket can affect the electrical performance of the tapes
- Two design modifications were proved to reduce the strain caused by compaction
- The strain due to cooldown is significant for the top and bottom tapes of the stack
- A **good agreement** was found **between** the bending **model** (which include compaction and cooldown strain) and **experiments**, when defining a friction coefficient of 0.02.

Future work

- Investigate the impact of compaction with a designated experiment to validate the model
- Use the optimized FEA tool to investigate possible changes to the cable design with the goal of reducing the critical current degradation

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