Finite Element Investigation of the Mechanical Behavior of Twisted Stacked-Tape Cables Exposed to Large Lorentz Loads

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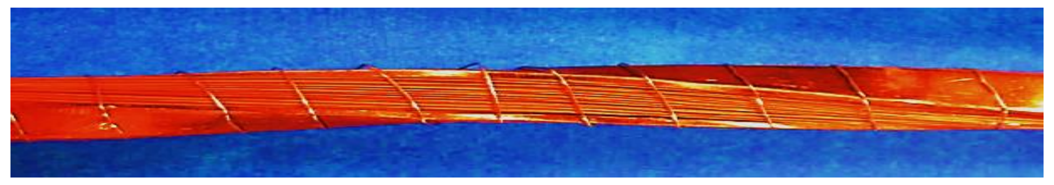
Introduction

The **Twisted Stacked-Tape Cable (TSTC)** is a cabling method suitable for developing a high current conductor for high-field magnets used in fusion and high energy physics applications.

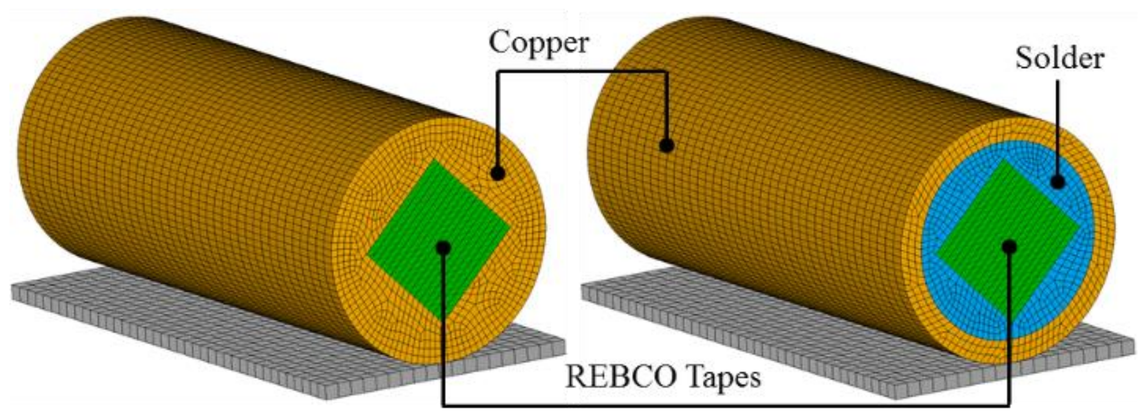
When operating in high magnetic field, high current environment, the conductor can experience **transverse compression** generated by electromagnetic **Lorentz loads**. Without an appropriate support structure, these high loads can degrade the performance of the conductor.



This work investigated, using three dimensional finite element analysis, the cable support structure for TSTC conductors necessary to avoid or limit the degradation caused by the accumulating transverse compression due to the Lorentz load generated during operations.

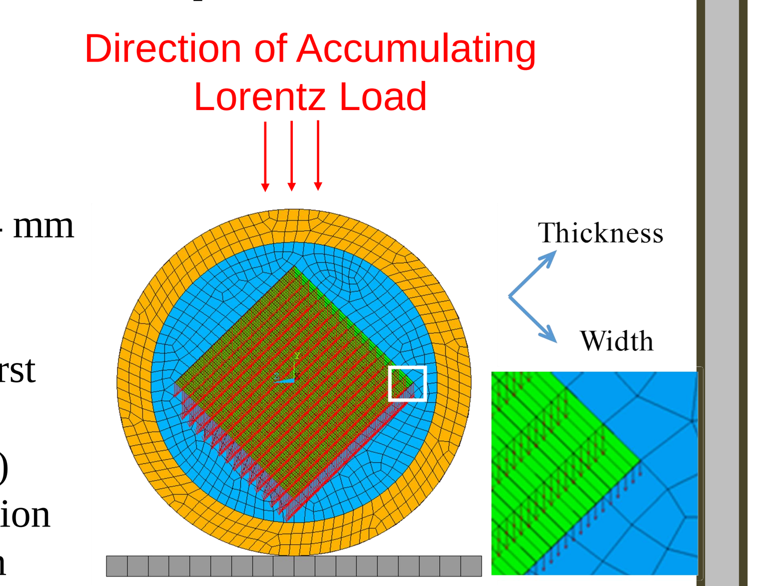
Finite Element Analysis

Structural finite element analysis (FEA) using ANSYS® was done to investigate the mechanical behavior of HTS tapes in a Twisted Stacked-Tape Cable under transverse compressive load. A 40-tape TSTC made from 4 mm wide SuperPower tapes was modeled with two different cable support methods: a **solid cylindrical copper core** and a **solder filled copper tube**. In the FEA models the tape stack was straight and the stack orientation was rotated while the load remained constant. A rigid plate was used to support the cable structure against the applied load.



Each tape was modeled using SOLSH190 structural **solid-shell** elements. Surface-to-Surface contact pairs were used for the interactions between adjacent tapes, between the tape stack and the support structure, and between the support structure and the bottom plate.

- 40 SuperPower tapes (4 mm x 0.1 mm) 40 elements along the width, 1 element trough the thickness
- Tube outer diameter (OD) – 8.4 mm
- Tube thickness – 0.8 mm
- Friction coefficient – 0.2
- Configuration for analysis (worst configuration)
  - Straight stack (**no twist**)
  - 45 degree stack orientation
  - Evaluation of maximum compressive stress experienced by 95% of elements



- Electromagnetic load is applied as nodal force representing the accumulating transverse Lorentz load due to the magnetic field and current in each tape of the stack.
- The total Lorentz load is between 100 kN/m and 1000 kN/m with 100 kN/m increments.

Support Method Investigations

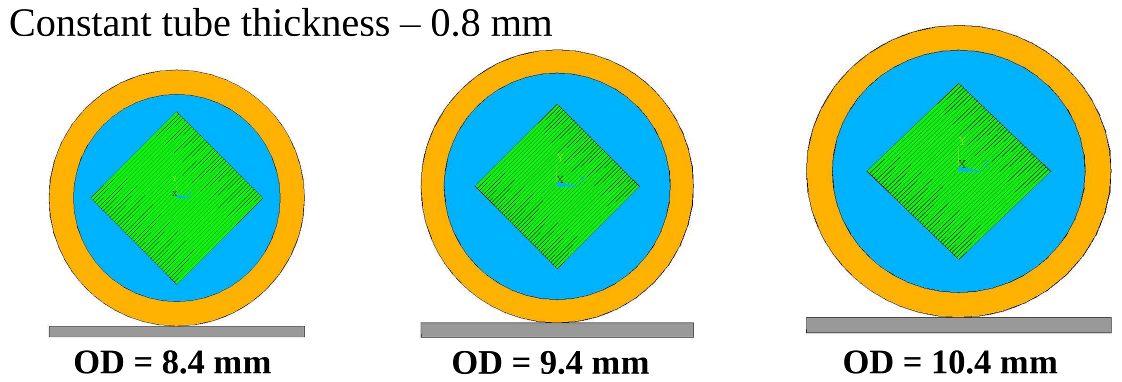
Finite element simulations performed:

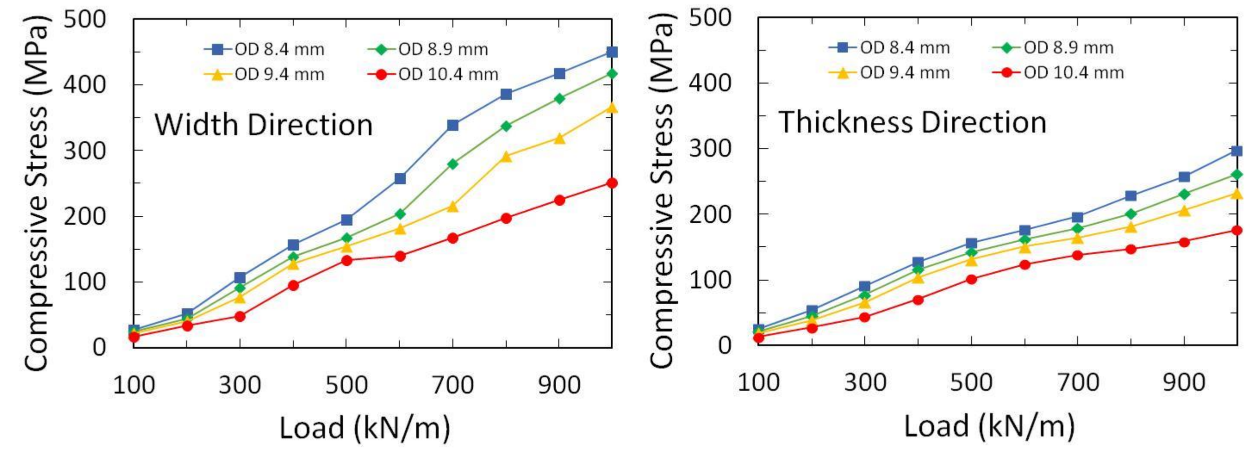
- Design optimization of solder filled tube configuration, to define an optimal ratio between the thickness of the copper tube and the amount of solder used
- Tape width investigation, to highlight the advantages and disadvantages of using a wide tape compared to a narrow tape
- TSTC surrounding conditions, to investigate the effect of an external rigid support on the stress/strain state of the TSTC
- Prediction of critical current behavior of TSTC under applied load

Design Optimization - Solder Filled Tube

I. Tube Outer Diameter OD (constant tube thickness)

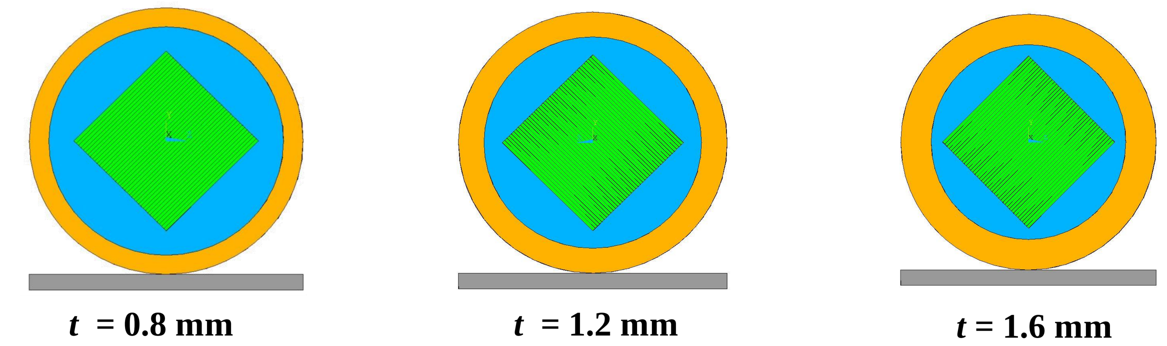
- Constant tube thickness – 0.8 mm

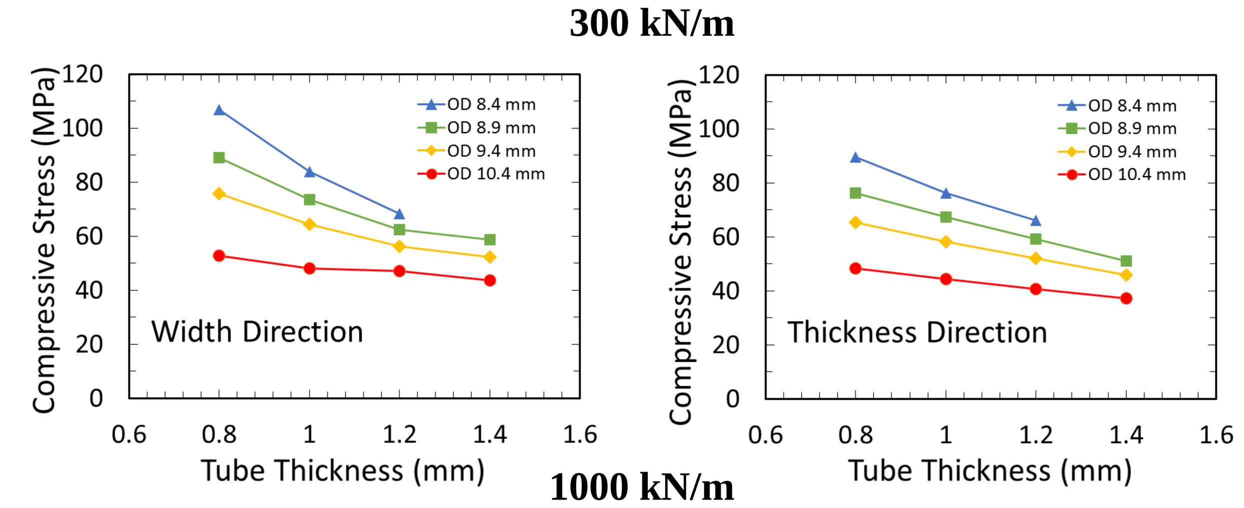


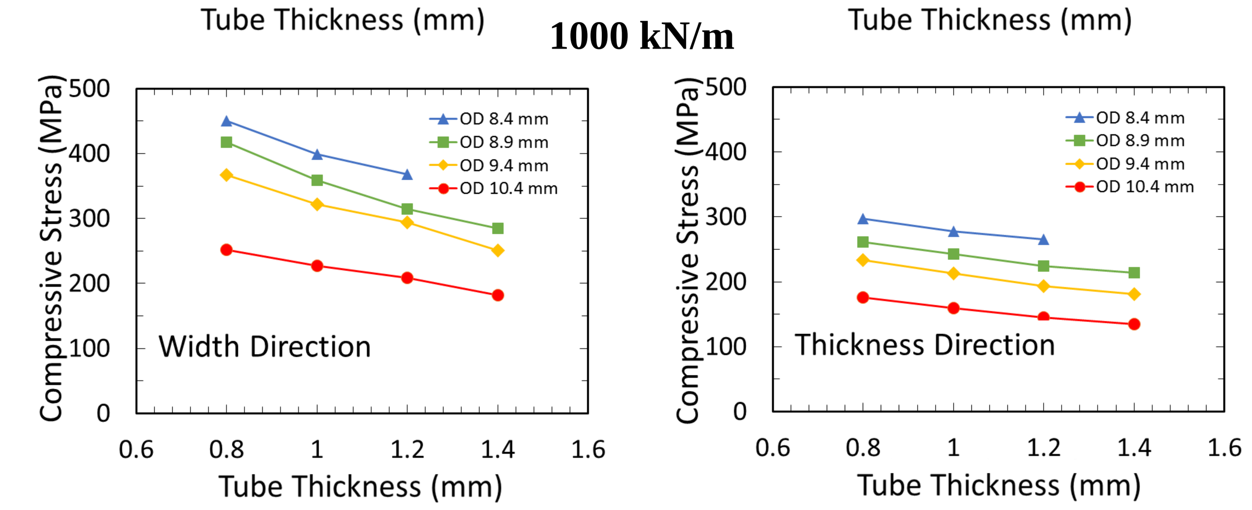


- Increasing the tube outer diameter results in a reduction of stress

II. Tube Thickness *t* (constant tube outer diameter)



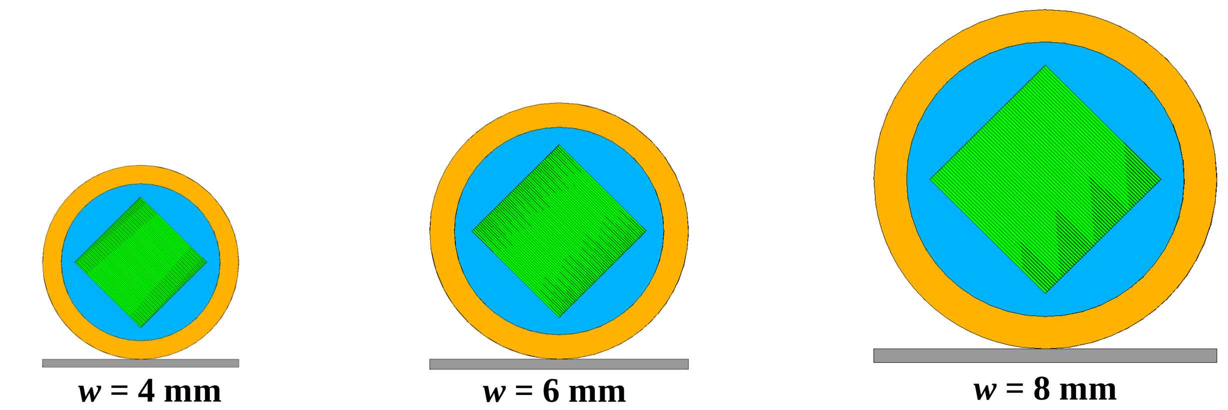


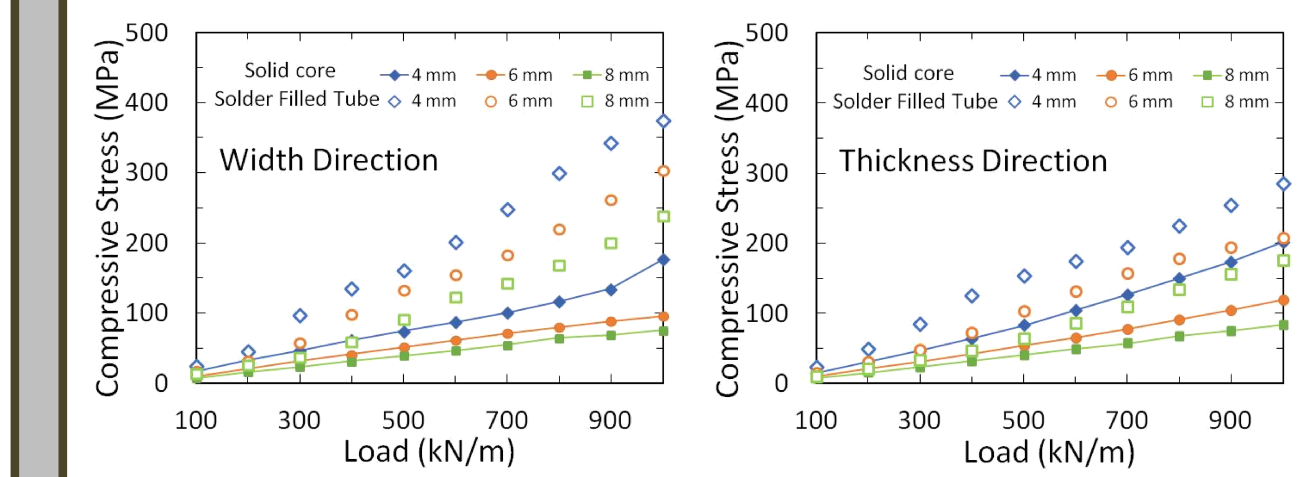


- Increasing the tube thickness decreases stress in the tape stack

Tape Width (*w*) Investigation

- Number of tapes modified to preserve the square shape of stack
- Dimensions of the support structure linearly scaled with the tape width

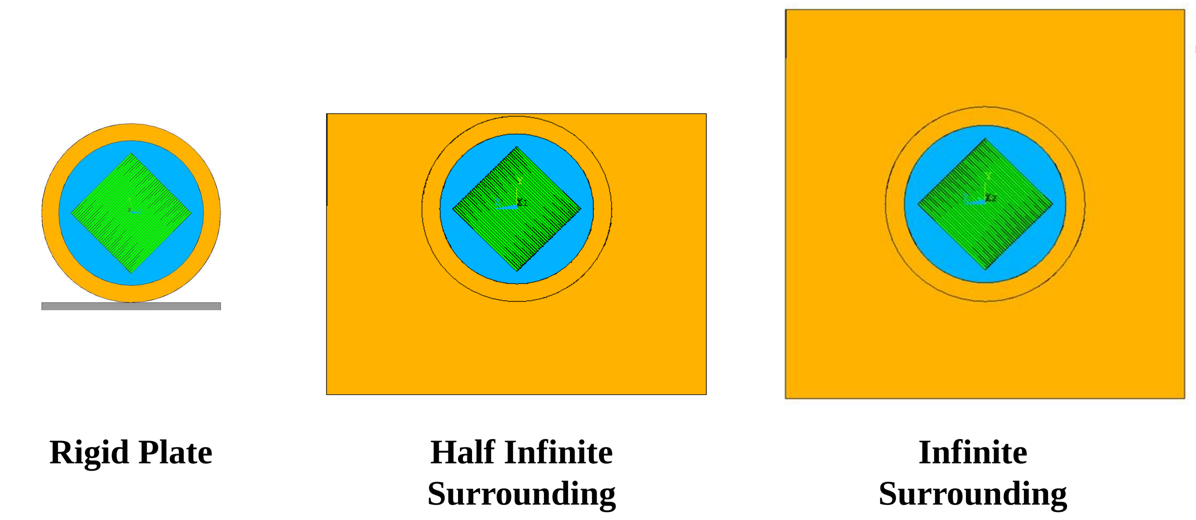


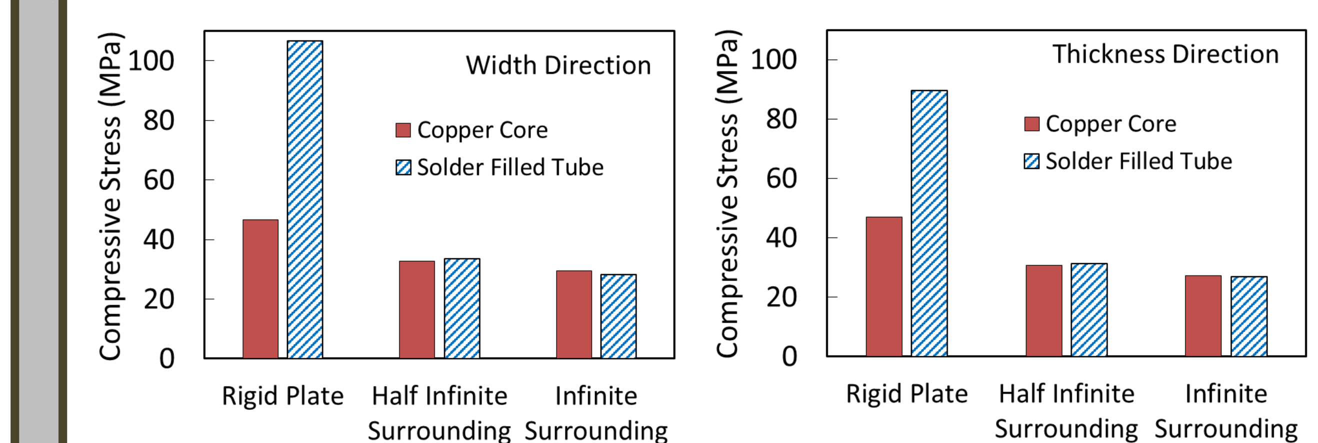


- A TSTC made with wider tapes experiences a smaller compressive stress for the same applied load in both width and thickness direction

TSTC Surrounding Conditions

- Copper edge to tube external diameter ratio of two
- Applied load **300 kN/m (20 kA, 15 T)**





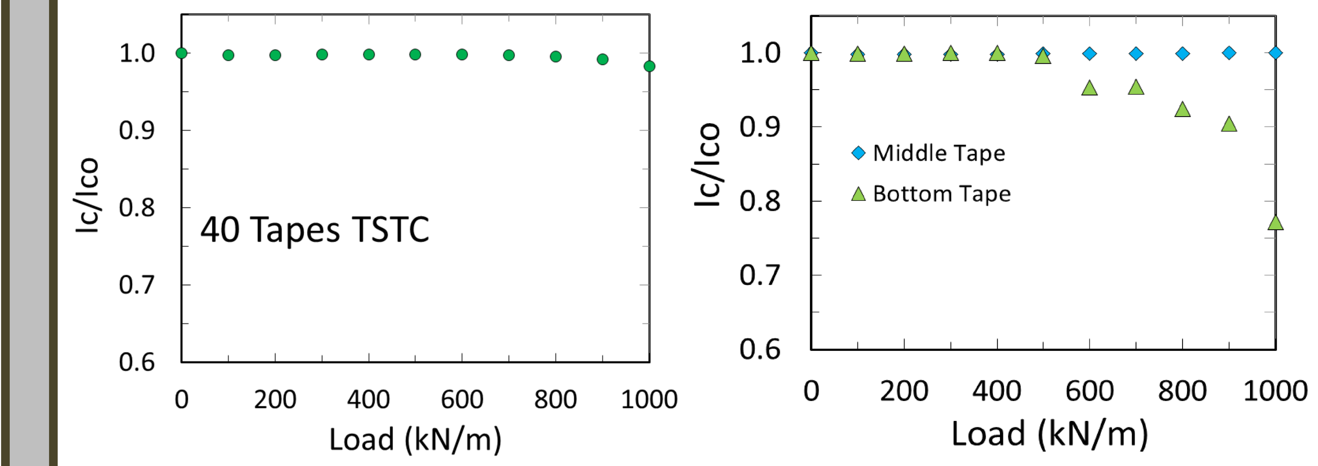
- Rigid cable surrounding lowers the stress accumulation in the tape stack
- Copper Core configuration has lower stress accumulation in the tape stack for all surrounding conditions
- Having additional copper around the conductor reduces the difference between the copper core and the solder filled tube configurations (50% in rigid plate condition, 2% in infinite condition)
- The external copper surrounding may have a significant role in stabilizing the conductor.

[1] Allen NC *et al.* 2016, IEEE Trans. Appl. Supercond., vol 27, no. 4, 2017
[2] N.C. Allen, L. Chiesa and M. Takayasu, *Cryogenics*, http://dx.doi.org/10.1016/j.cryogenics.2016.02.002, 2016.
[3] M. Takayasu, L. Chiesa, N.C. Allen, and J.V. Minervini, *IEEE Trans. on Applied Superconductivity*, vol. 25, no. 3, March 2016
[4] Barth, Christian, Giorgio Mondonico, and Carmine Senatore, *Superconductor Science and Technology* 28.4 (2015): 045011.

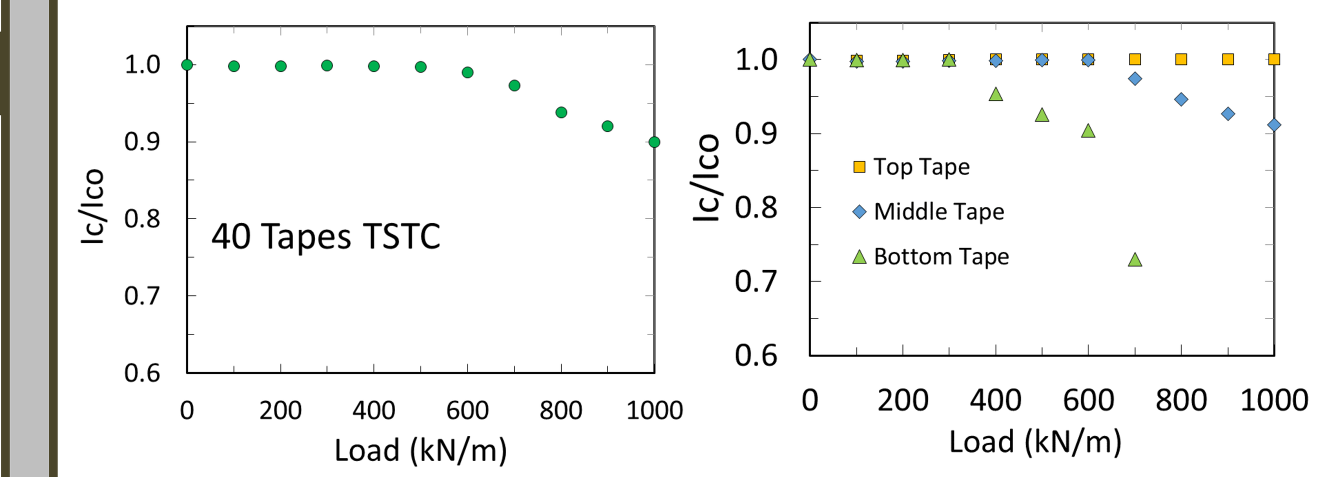
Critical Current Behavior

- Straight configuration, 45 degrees stack orientation (worst case scenario)
- Load applied up to **1000 kN/m** with increments of 100 kN/m
- Critical current performance estimated using **von Mises** strain results
- Critical current performance estimated for each tape of the stack using available literature data of critical current as function of strain at 4.2 K and 19 T [4].
- Electrical behavior of the stack calculated averaging single tape results

Solid Core



Solder Filled Tube



- Bottom tape experiences the highest degradation in both configurations
- Solder filled configuration experiences higher degradation than the solid core configuration

Conclusions

Finite element investigations of the **Twisted Stacked-Tape Cable (TSTC)** under accumulating **electromagnetic Lorentz load** were presented for two cable configurations (**coper core and solder filled)**.

The following results were discussed:

- The maximum compressive stress in the soldered filled configuration can be reduced by increasing the tube outer diameter (constant thickness) or its thickness (constant outer diameter).
- **Wider tapes** reduce the maximum compressive stress experienced by the tape stack for the same Lorentz load in both solid core and solder filled configurations.
- Material surrounding the cable (structural and/or copper stabilizer) effectively lowers the stress accumulation in the tape stack in both configurations.
- **The cable critical current** as a function of Lorentz load was estimated indicating a minimal degradation up to **1000 kN/m for** the **copper core** configuration and up to **500 kN/m** for the **solder filled tube** configuration. In both cases the degradation observed is driven by the behavior of the tapes at the bottom of the stack.
- **A fully twisted model** will be investigated in the future and the results will be compared to available **experimental results.**