MDP Modeling Working Group Presentation

REBCO tape modeling: residual thermal stress from manufacturing and mechanical loads

Presentation

Education :

Material Science Engineer
Polytech Paris Saclay, France
Graduated in November 2024

Master Large Facilities: **Plasmas, Lasers, Accelerators, Tokamaks**
Université Paris Saclay, France
Graduated in November 2024
With 5 weeks at the **Joint Universities Accelerator School**

Research experience :

Internship at CEA Paris Saclay, Laboratory of Superconducting Magnets
Mechanical characterization of Nb_3Sn strands
Supervised by Gilles Lenoir and Étienne Rochepault

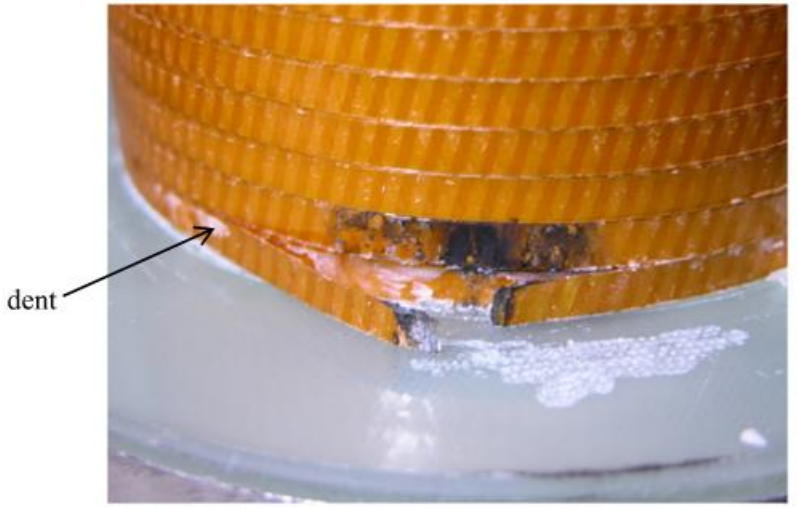
April – October 2024

PhD student at Polytechnique Montréal, Canada
Study of the origin of the **damages in REBCO superconducting cables**
Supervised by Frédéric Sirois, Christian Lacroix and Jean-François Croteau

Started in January 2025

Research question

Burnt zone of a magnet wound with STAR cables [1]



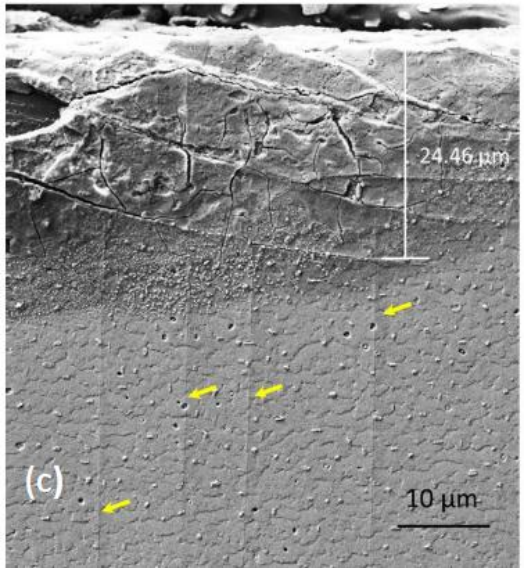
Burnt spot in ReBCO coil [2]

What local defects are leading to quench in ReBCO cables?

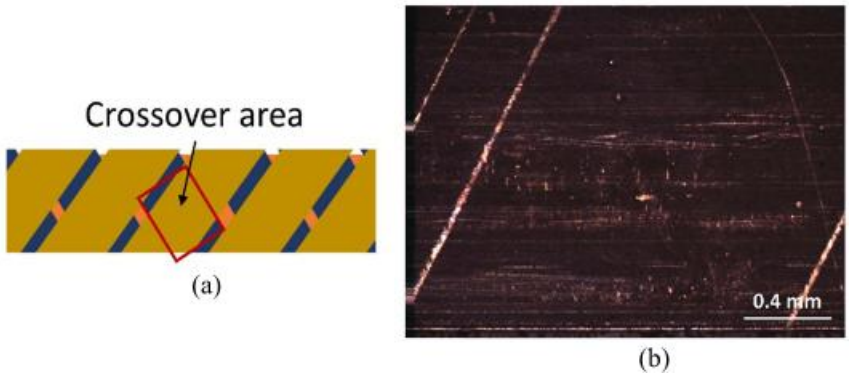
[1]Wang, Xiaorong, et al. "An initial magnet experiment using high-temperature superconducting STAR® wires." *Superconductor Science and Technology* 35.12 (2022): 125011.

[2] Ma, D. X., et al. "Degradation analysis of REBCO coils." *Superconductor Science and Technology* 27.8 (2014): 085014.

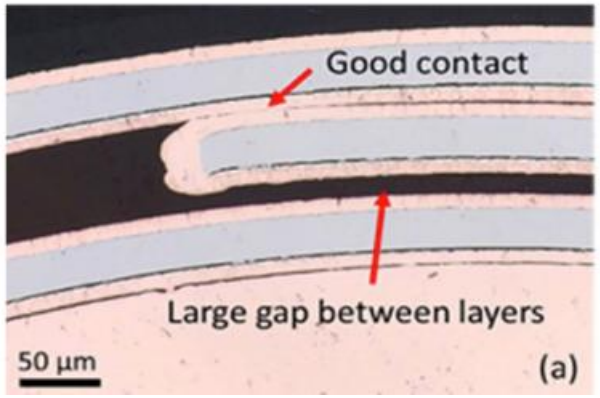
Research question



Slit-edge of a ReBCO tape [3]



(a)Diagram of a CORC cable, (b)Image of the crossover area of an unwound tape [4]



Cross section of a CORC cable showing the contacts between the tapes [4]

Hypothesis: slit edge defects, poor adhesion between layers, bad contact between tapes

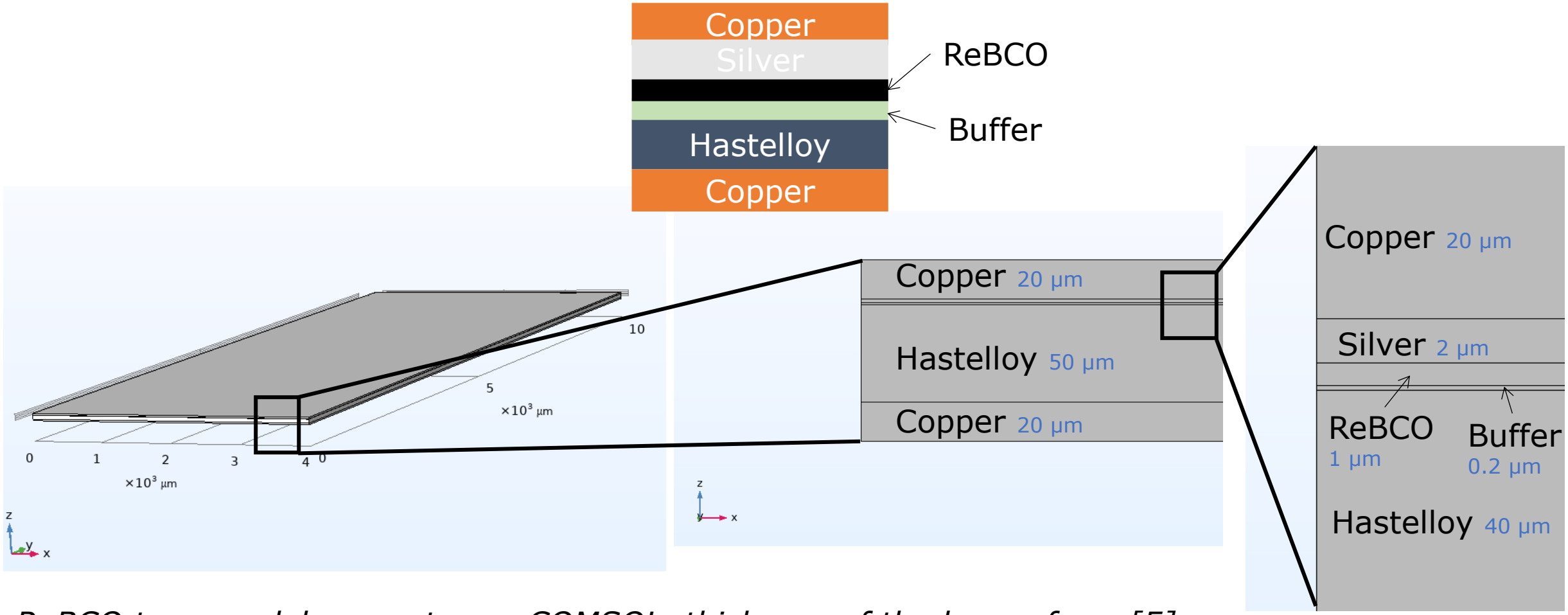
[3] Hu, Xinbo, et al. "Analyses of the plastic deformation of coated conductors deconstructed from ultra-high field test coils." *Superconductor Science and Technology* 33.9 (2020): 095012.

[4] Phifer, Virginia, et al. "Investigations in the tape-to-tape contact resistance and contact composition in superconducting CORC® wires." *Superconductor Science and Technology* 35.6 (2022): 065003.

Outline

1. **Residual stress and strain after fabrication: computation in COMSOL Multiphysics**
    1. Model parameters
    2. Temperatures at different manufacturing steps
    3. Residual stress and strain computation
2. **Mechanical loads after tape fabrication**
    1. Uniaxial tension
    2. Bending
    3. Torsion
3. **Simulation of the defects**
    1. Cracks simulation
    2. Delamination simulation

Geometry



ReBCO tape model geometry on COMSOL, thickness of the layers from [5]
Width : 4 mm
Length :10 mm

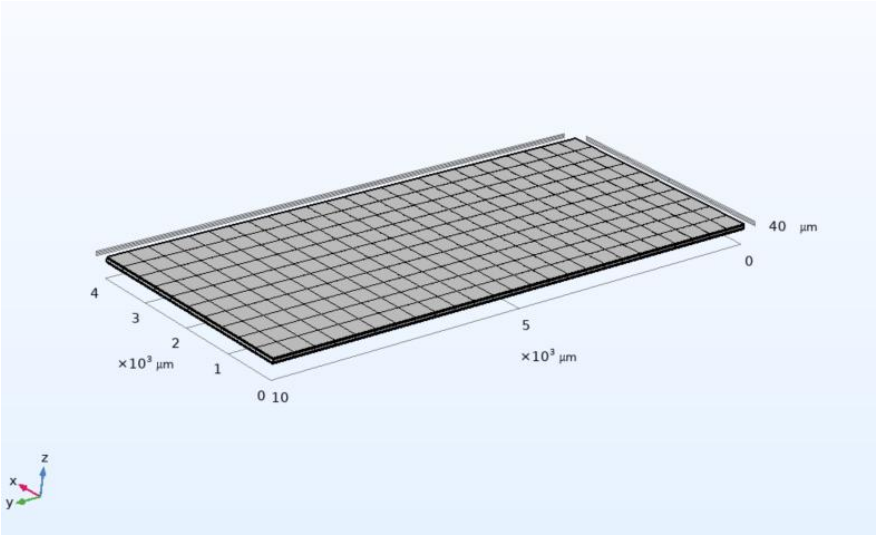
[5] Gao, Peifeng, et al. "Stress, strain and electromechanical analyses of (RE) Ba2Cu3Ox conductors using three-dimensional/two-dimensional mixed-dimensional modeling: fabrication, cooling and tensile behavior." *Superconductor Science and Technology* 33.4 (2020): 044015.

Mesh and material data

Table 1. Material properties of all the constituent materials of the REBCO conductor [8, 10, 11, 17, 25, 36–38].

	Young's modulus E (GPa)		Poisson's ratio υ	Yield strength σ_y (MPa)		Tangent modulus E_t (GPa)	CTE α ($\times 10^{-6}$ K^{-1})
Temperature (K)	77	300		77	300		
Copper	85	70	0.34	330	190	5	17.7
	[17]	[17]	[11]	[17]	[17]	[17]	[8, 10, 11]
Silver	76		0.37	14		1	17.1
	[36, 37]		[36]	[36, 37]		[36]	[10, 36]
REBCO	157		0.3	1030		1	11
	[8, 10, 11, 25, 38]		[10, 11]	[8]			[8, 10, 11]
Buffer	170		0.226	1030		1	9.5
	[25]		[25]				[25]
Hastelloy	178	170	0.307	1200	980	6	14
	[17]	[17]	[11]	[17]	[17]	[17]	[8, 10, 11, 25, 38]

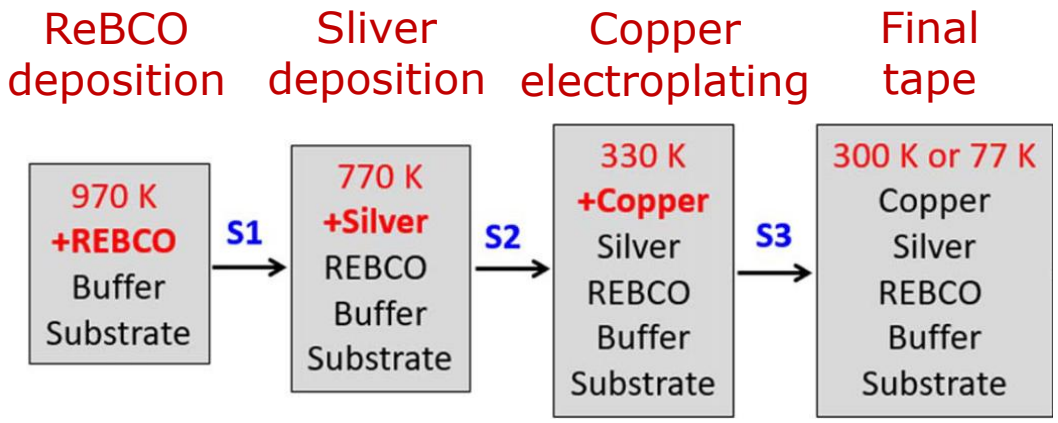
Material parameters used [5]



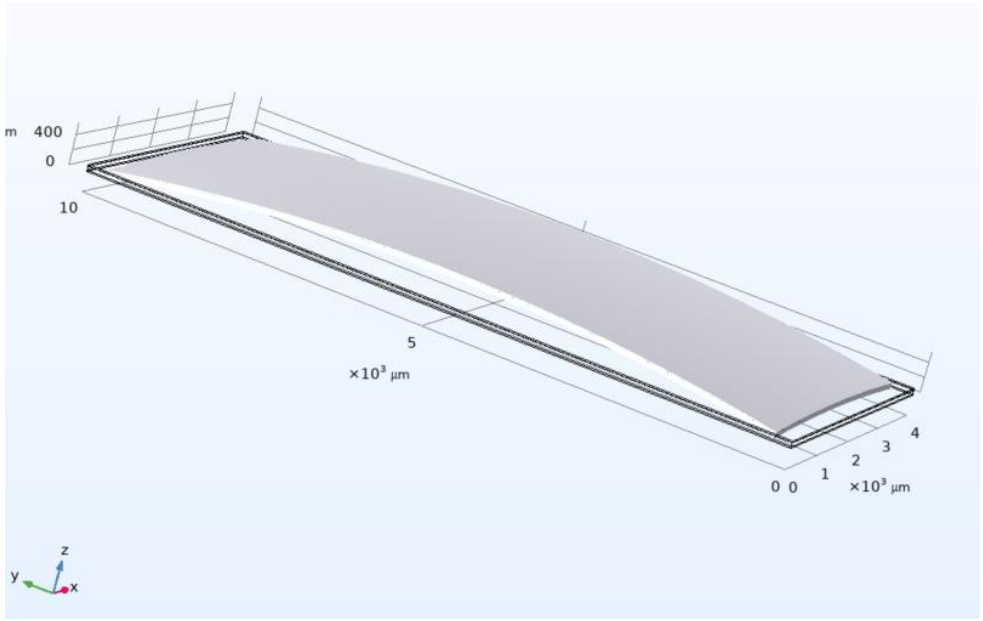
Mesh of the model

[5] Gao, Peifeng, et al. "Stress, strain and electromechanical analyses of (RE) Ba2Cu3Ox conductors using three-dimensional/two-dimensional mixed-dimensional modeling: fabrication, cooling and tensile behavior." *Superconductor Science and Technology* 33.4 (2020): 044015.

Steps during manufacturing



Manufacturing steps [5]

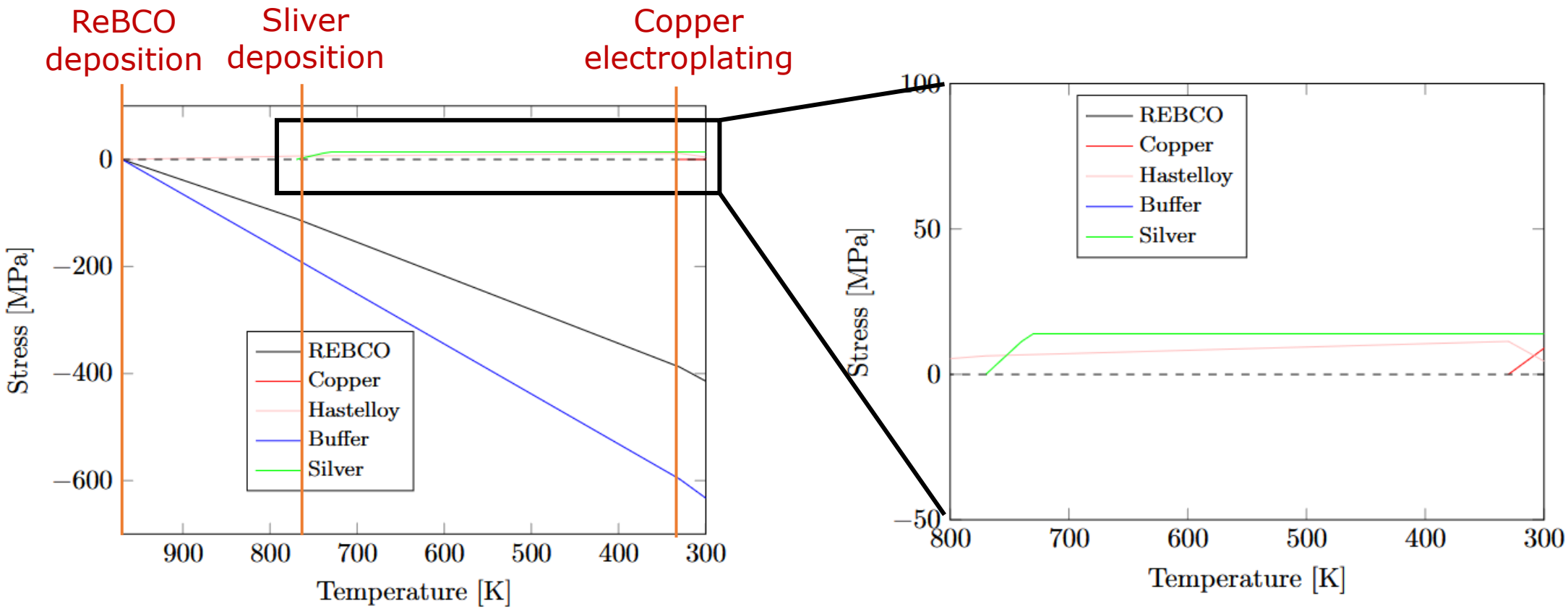


Tape after manufacturing at 300K

The silver layer is activated at 770K and copper at 330K

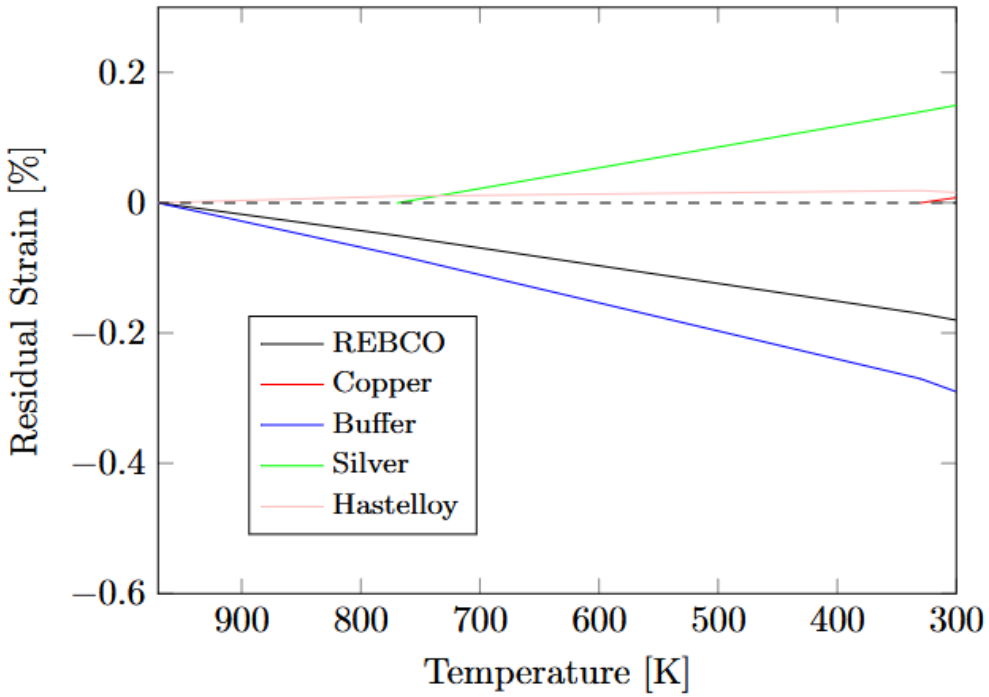
[5] Gao, Peifeng, et al. "Stress, strain and electromechanical analyses of (RE) Ba2Cu3Ox conductors using three-dimensional/two-dimensional mixed-dimensional modeling: fabrication, cooling and tensile behavior." *Superconductor Science and Technology* 33.4 (2020): 044015.

Residual thermal stress



Residual thermal stress along the length of the tape in each layer

Residual thermal strain

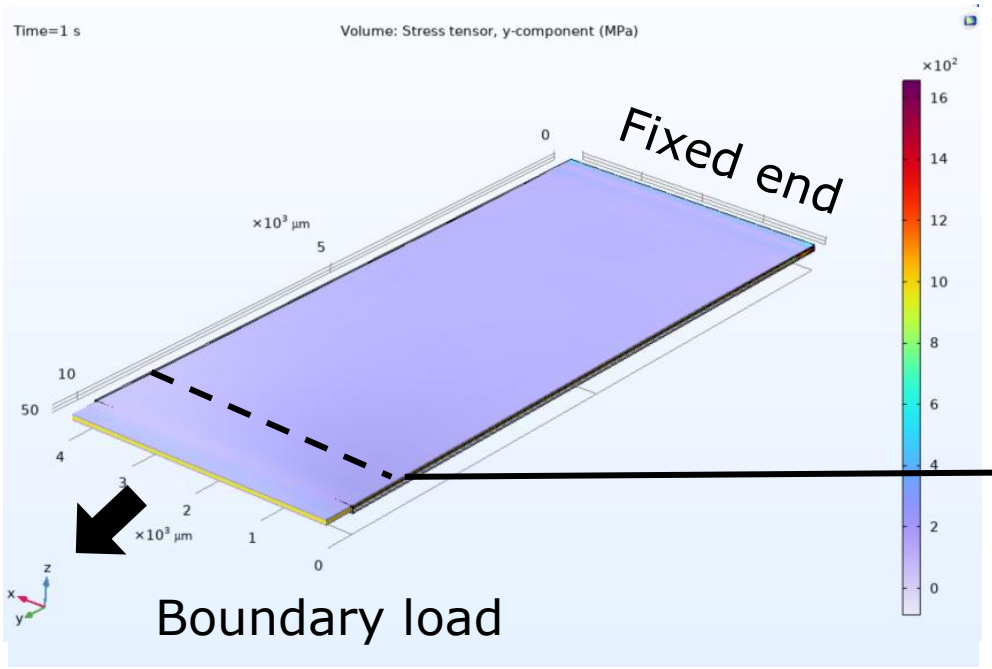


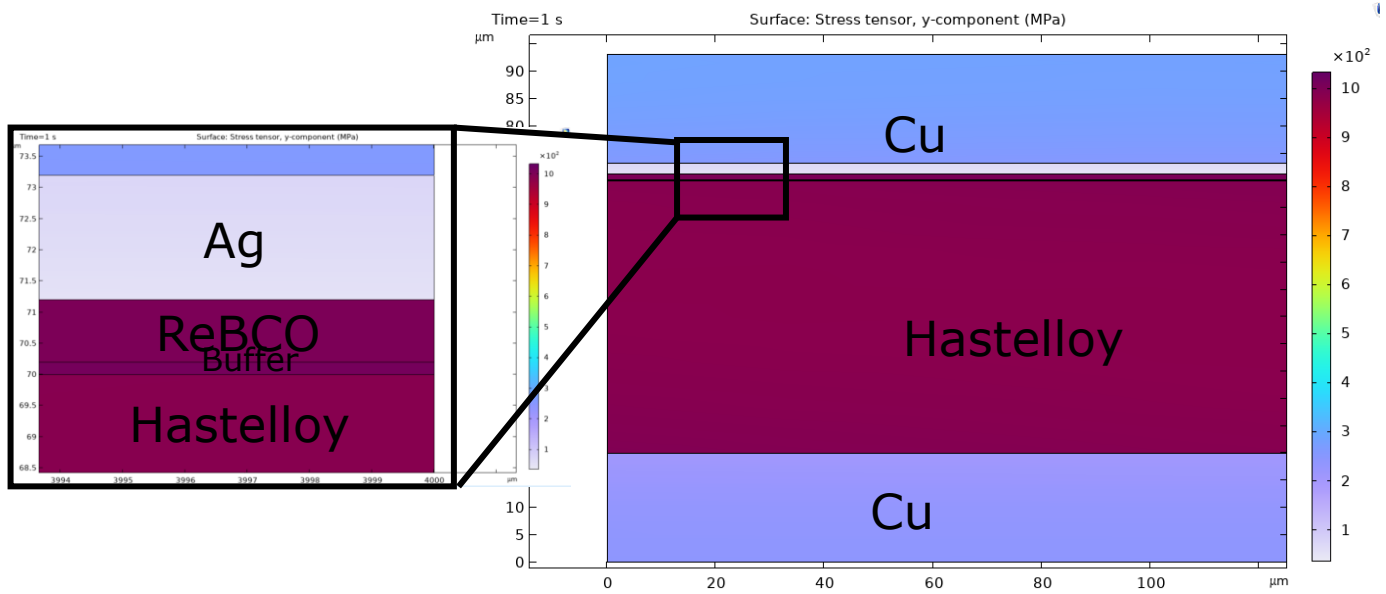
Residual thermal strains in the longitudinal direction in each layer of the tape

The residual strain ε_{res} is given by : $\varepsilon_{res} = \varepsilon_{real} - \varepsilon_{th}$
Where ε_{real} is computed by the FE software and $\varepsilon_{th} = \int_{T_{ref}}^{T} \alpha \, dT$ with α the thermal expansion coefficient [5]

[5] Gao, Peifeng, et al. "Stress, strain and electromechanical analyses of (RE) Ba2Cu3Ox conductors using three-dimensional/two-dimensional mixed-dimensional modeling: fabrication, cooling and tensile behavior." *Superconductor Science and Technology* 33.4 (2020): 044015.

Uniaxial tension of ReBCO tape

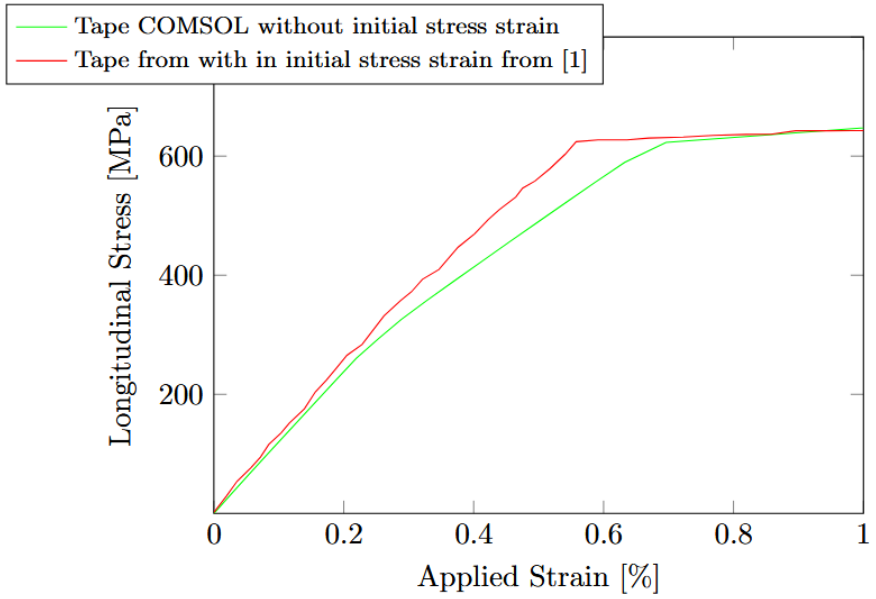




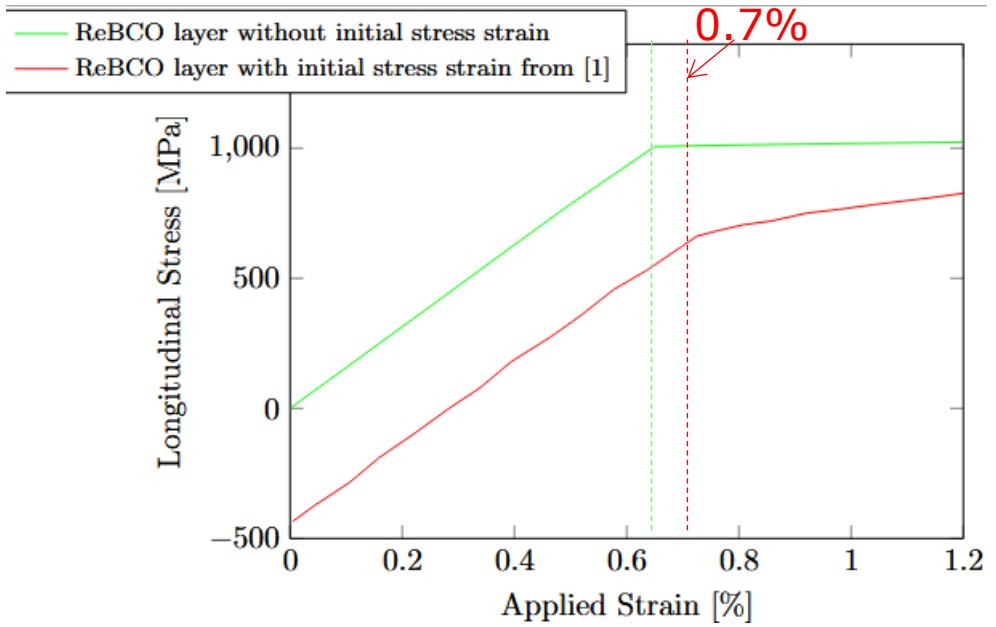
Stress distribution in the tape under uniaxial tension with an applied stress of 650 MPa

Cross-section of the tape showing the stress concentration in the layers at y = 9 mm

Effect of residual thermal stress in uniaxial tension



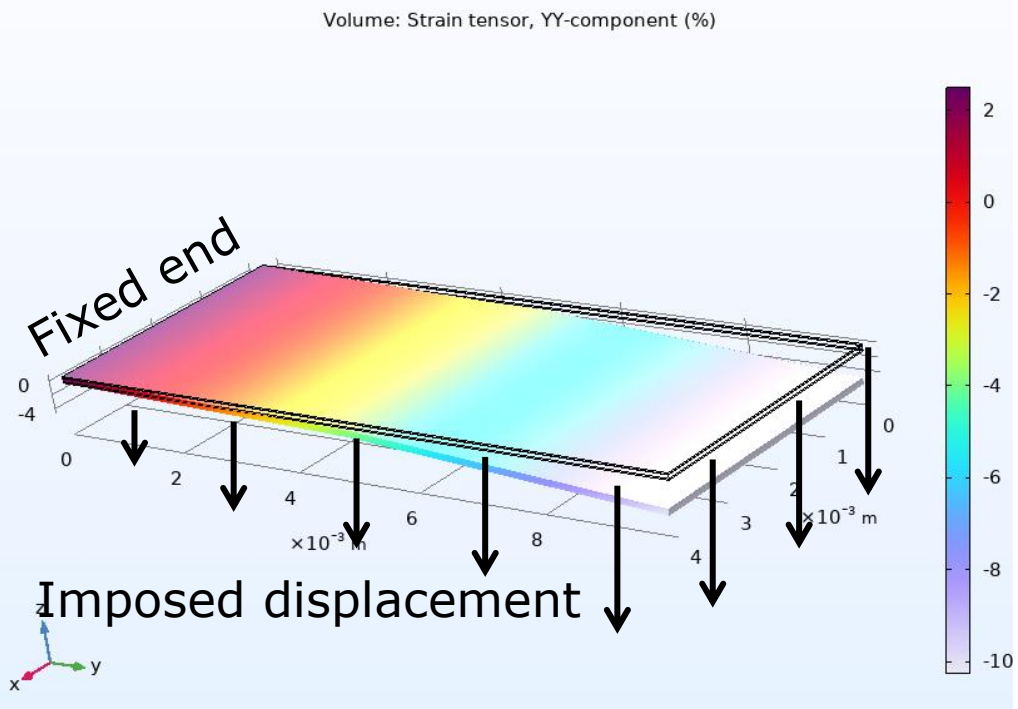
*Numerical tensile test of **ReBCO tape** with and without residual thermal stress*



*Numerical tensile test of **ReBCO layer only** with and without residual thermal stress*

[1] Gao, Peifeng, et al. "Stress, strain and electromechanical analyses of (RE) Ba2Cu3Ox conductors using three-dimensional/two-dimensional mixed-dimensional modeling: fabrication, cooling and tensile behavior." *Superconductor Science and Technology* 33.4 (2020): 044015.

Bending of ReBCO tape



Longitudinal Strain distribution in the tape after bending with R = 20 cm

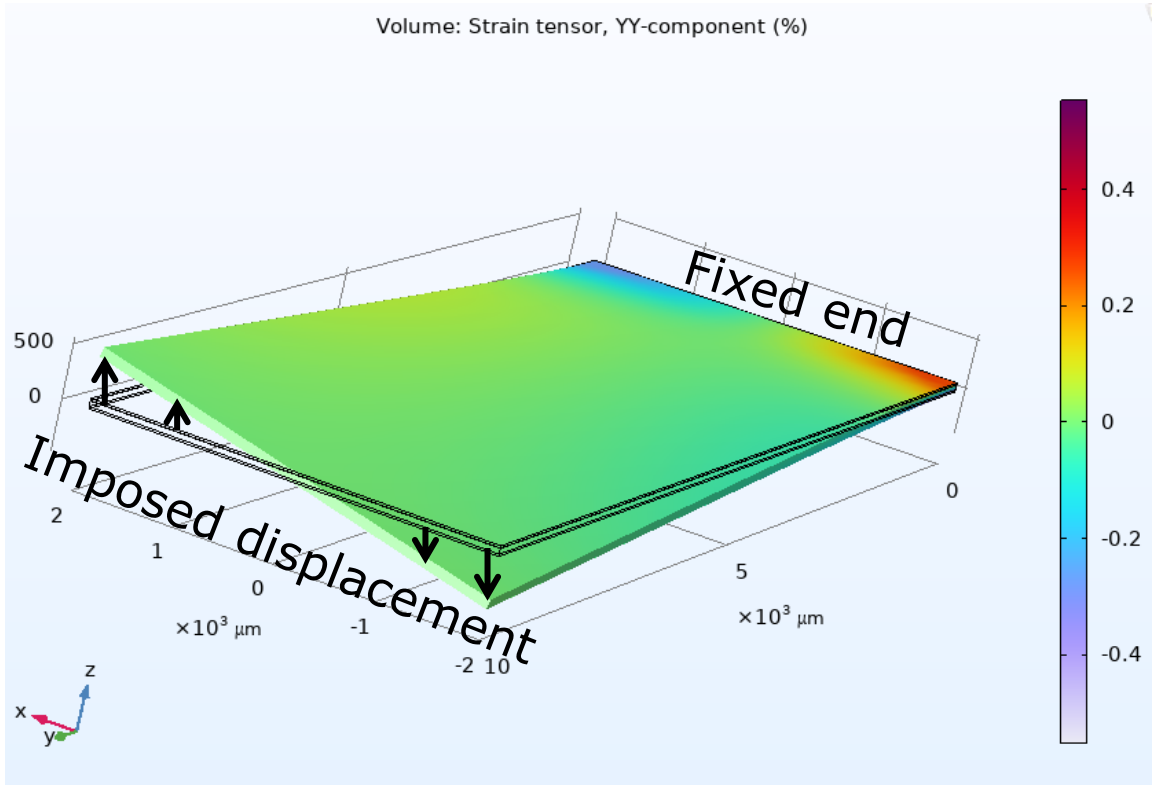
Bending radius R=20cm

$$\begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} = \begin{bmatrix} -\left(x - R\sin\left(\frac{x}{R}\right)\right) \\ 0 \\ -R\left(1 - \cos\left(\frac{x}{R}\right)\right) \end{bmatrix}$$

Prescribed displacement used [6]

[6] Li, Xianhao, et al. "Effects of bending and torsion behavior on Ic degradation and microstructure of ReBCO coated conductors." *Cryogenics* 126 (2022): 103523.

Torsion of ReBCO tapes

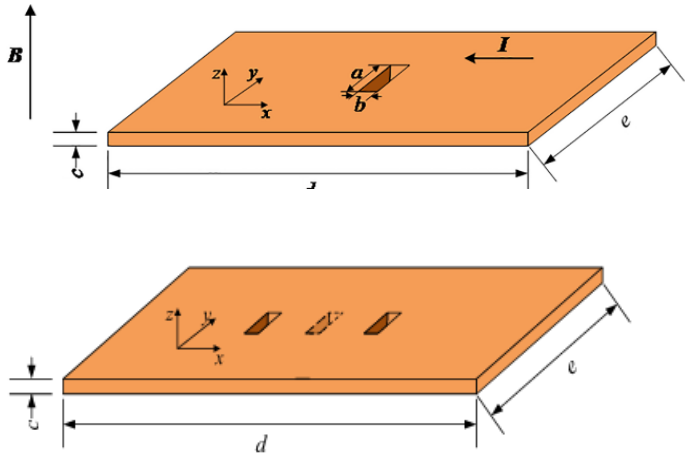


$$u_x = -z \cdot \theta$$
$$u_y = 0 \text{ (without uniaxial tension)}$$
$$u_z = x \cdot \theta$$

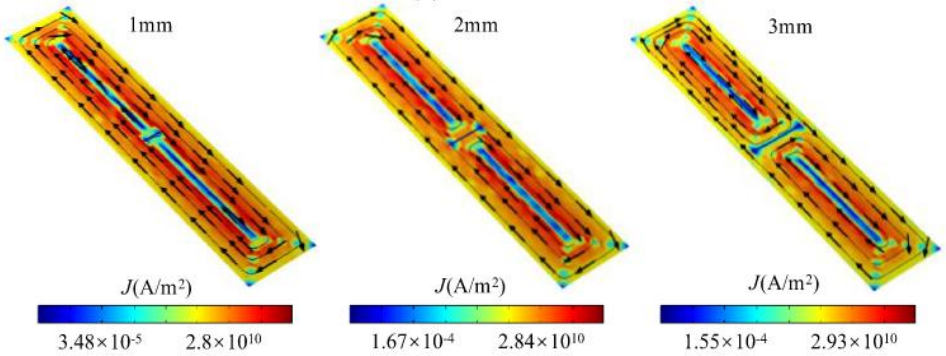
Prescribed displacement used for torsion around the y axis

Longitudinal strain distribution in the tape under torsion
With θ=0.5 rad (~29°)

Crack simulation – Literature review

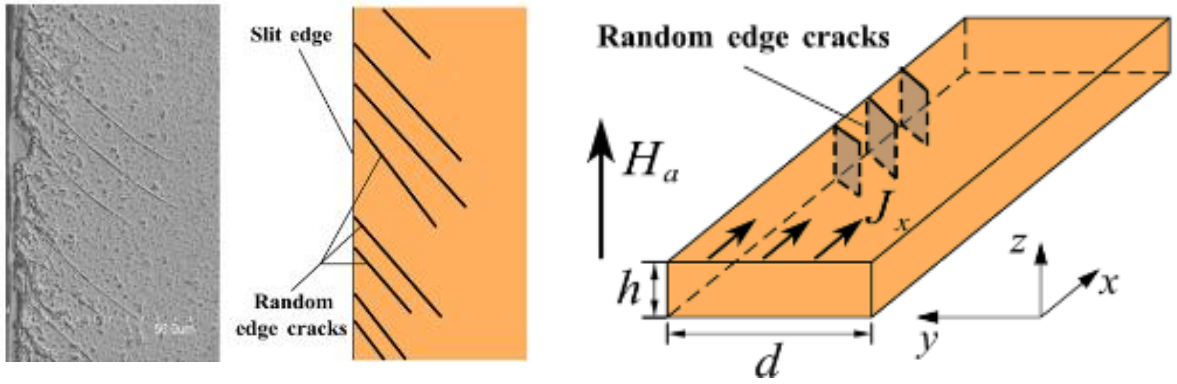


Schematic of the ReBCO film with cracks

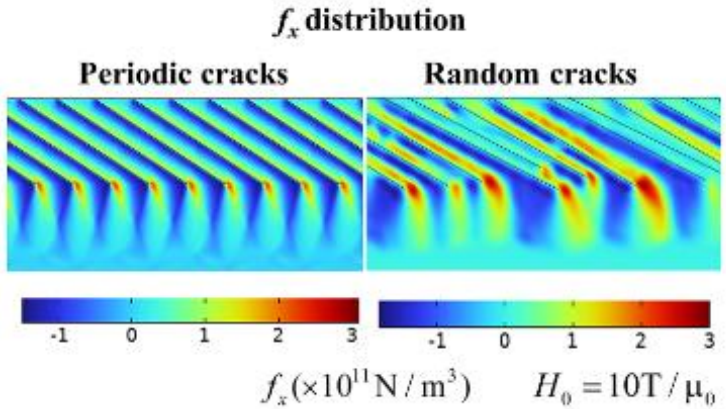


Current density of ReBCO films with different crack locations [7]

[7] Yan, Liang, et al. "In-field electro-magnetic-force characteristics of high-temperature superconducting films containing cracks." *Physica C: Superconductivity and its Applications* 615 (2023): 1354378.



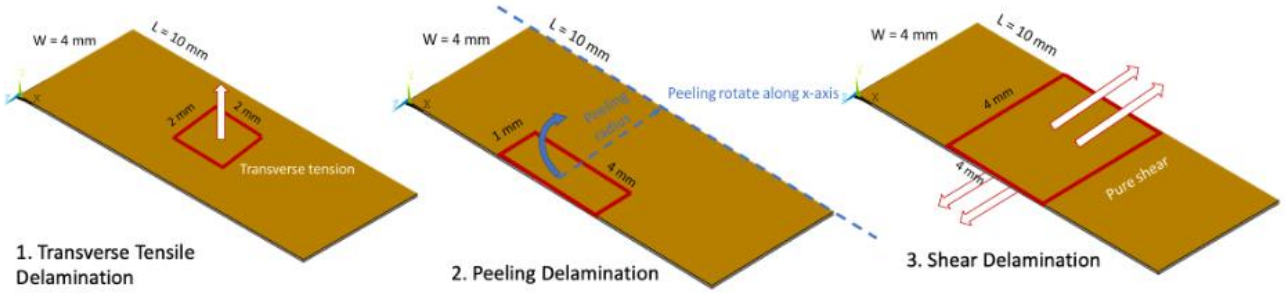
Schematic of the model with edge cracks



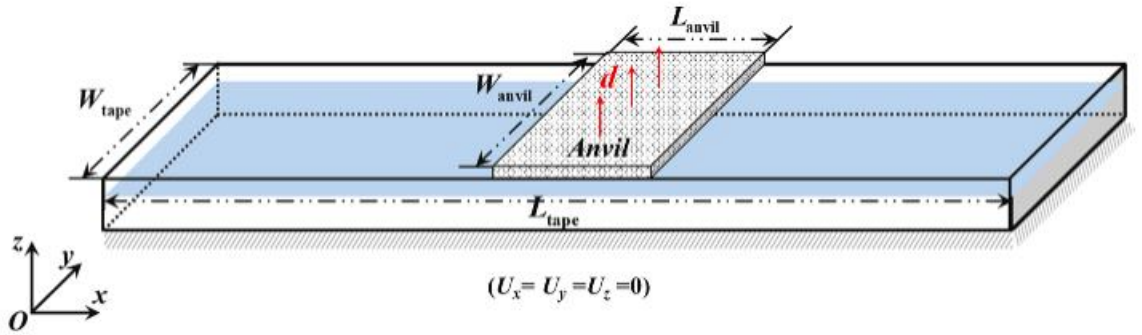
Comparison of the electromagnetic body force distribution between periodic and random cracks [8]

[8] An, Dongming, Pengpeng Shi, and Xiaofan Gou. "Fracture behavior of superconductor REBCO tapes with multiple edge cracks under electromagnetic force." *Engineering Fracture Mechanics* 295 (2024): 109794.

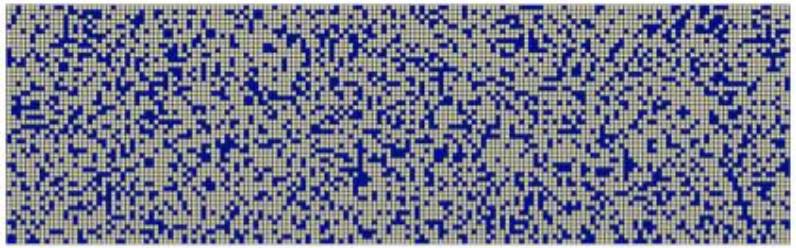
Delamination simulation - Literature review



Three loading conditions to simulate delamination in ReBCO tapes [9]



Geometry of the tape for the delamination test [10]



Distribution of the defects (blue elements) with weak interfacial strength in the tape [10]

[9] Zhao, Zijia, Peter Moore, and Luisa Chiesa. "Structural finite element analysis of REBCO tape delamination with solid-shell element under various loads." *IOP Conference Series: Materials Science and Engineering*. Vol. 1241. No. 1. IOP Publishing, 2022.

[10] Ma, Jintao, and Yuanwen Gao. "Delamination analysis of high-temperature superconducting tapes based on a random defect model." *Cryogenics* 135 (2023): 103729.
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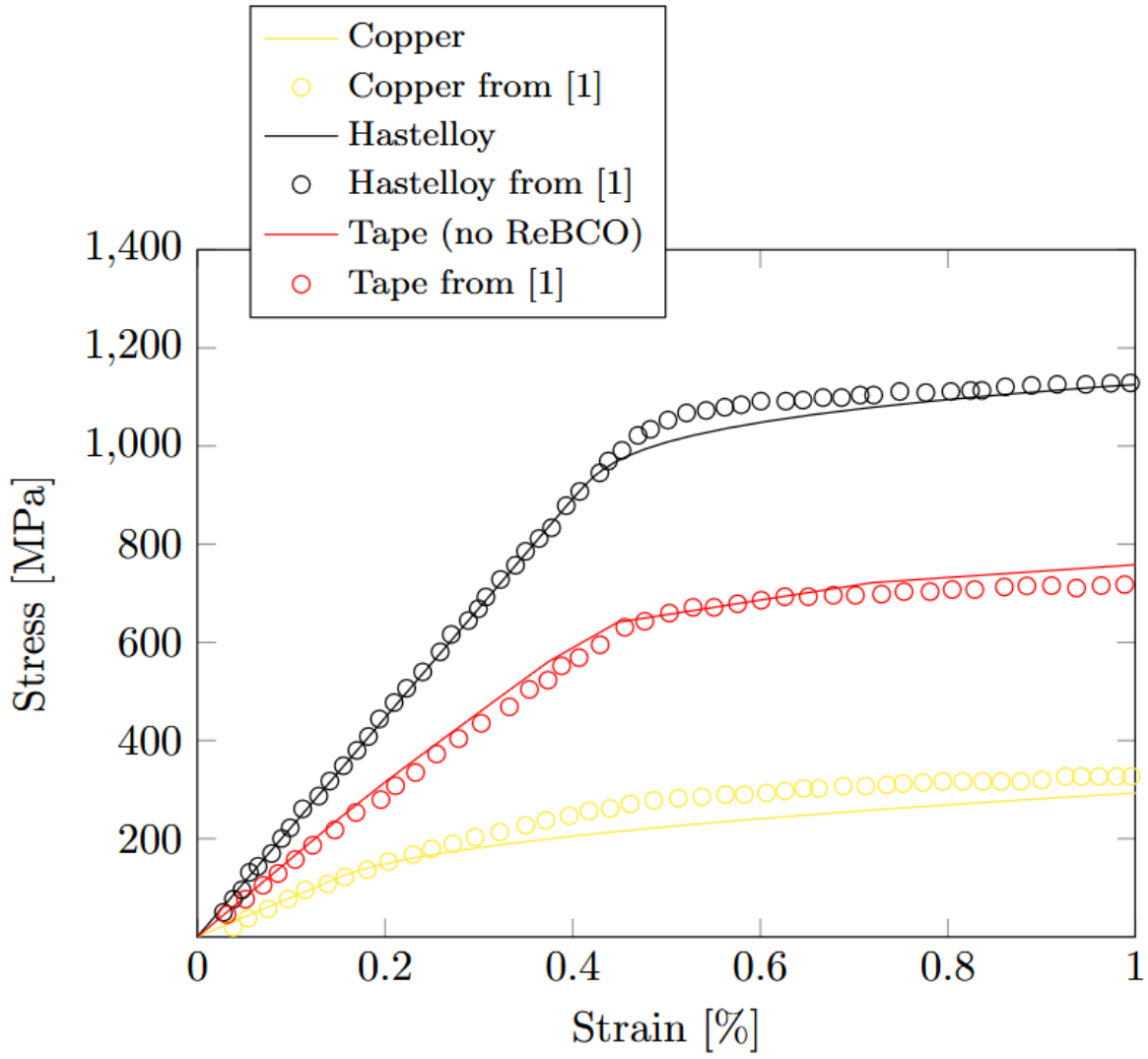
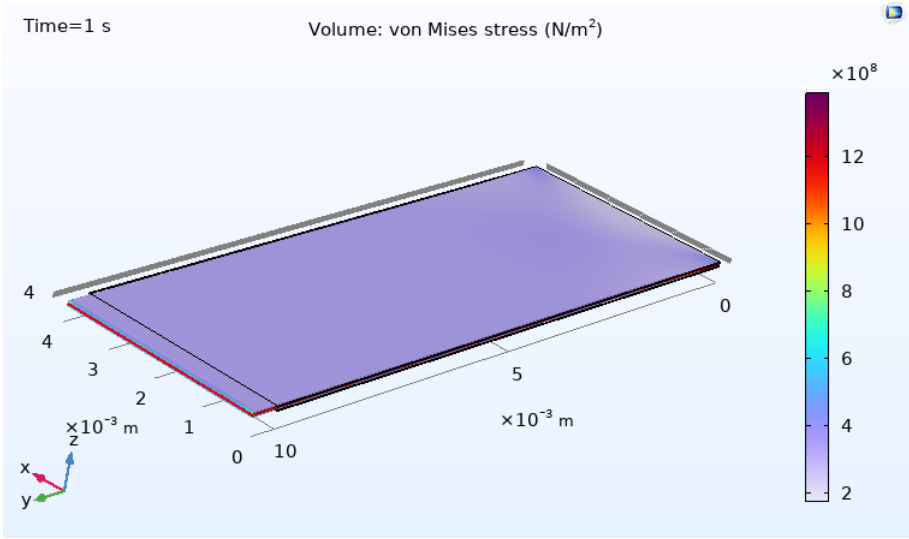
Conclusion

- **The residual stress and strain from manufacturing have an impact on the mechanical behavior of the ReBCO layer**
- **Defect simulation could help to understand the origin of quench in ReBCO cables**

Thank you for your attention!

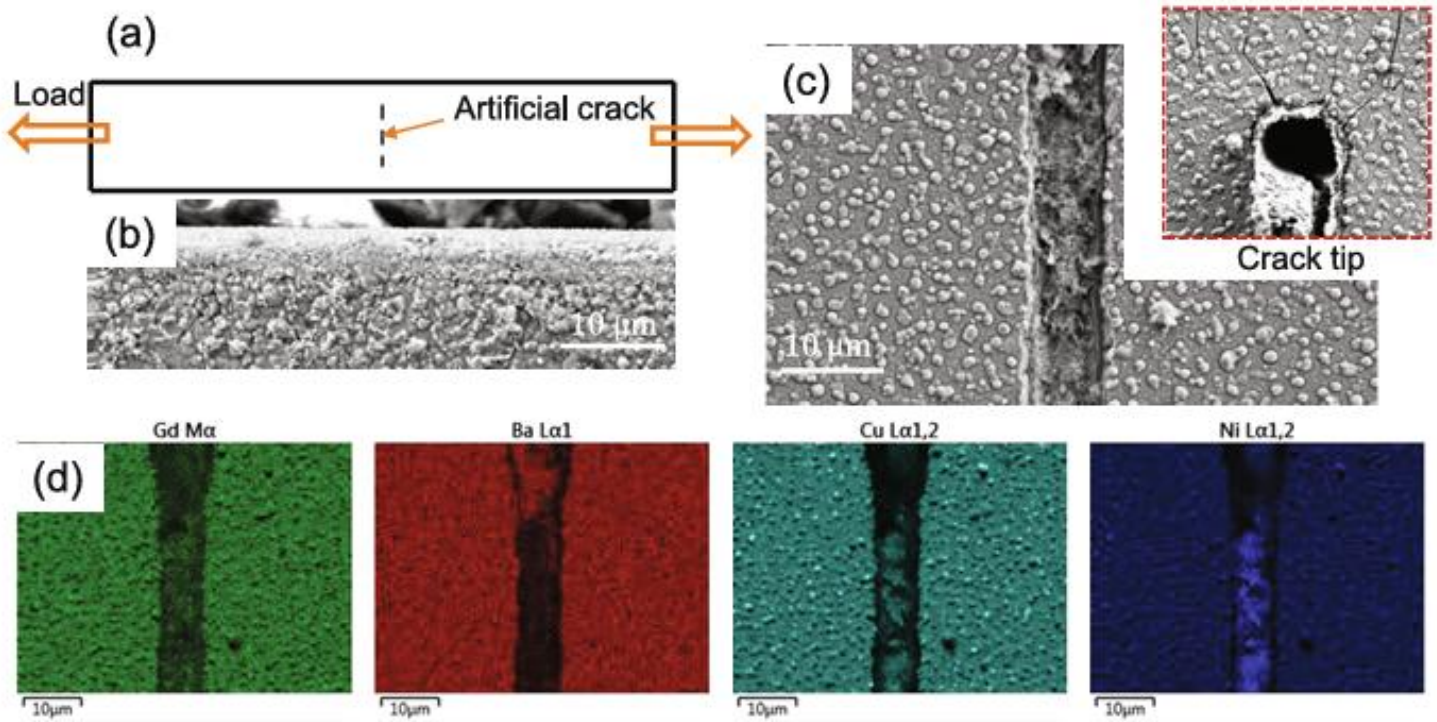
Non-linear hardening





[1]Ilin, K., et al. "Experiments and FE modeling of stress–strain state in ReBCO tape under tensile, torsional and transverse load." *Superconductor science and technology* 28.5 (2015): 055006.

Artificial cracks made by laser



Artificial crack created by femtosecond pulse laser

Yang, Zhirong, et al. "Effect of edge cracks on critical current degradation in REBCO tapes under tensile stress." *Superconductivity* 1 (2022): 100007.