Numerical investigation on the thermo-electro-mechanical behavior of HTS tapes

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Abstract

This work extends to second generation **(Re)BCO tapes** an **experimental procedure** previously developed to analyze the impact of **double bending at room temperature** on the performance of BSCCO tapes. The modified procedure is applied to measure the critical current of a commercial (Re)BCO tape subjected to bending around a cylindrical mandrel first on one side then on the other side, followed by the cooldown to cryogenic temperature. In the bending loading phase**, mandrels of decreasing diameter** are used to identify the minimum curvature leading to a significant reduction of the tape critical current. Furthermore, a **novel numerical model** is developed to interpret the experimental results and investigate the **thermo-electro-mechanical behavior** of the tape. The model simulates the double bending, the following straightening of the sample and its cooldown to cryogenic conditions. The coupled thermo-mechanical numerical model together with the temperature-dependent mechanical properties allow investigating the combination of thermal contraction effects and bending loads **in every point of the domain** of the problem. The experimental and numerical results obtained help to give a better insight in the distribution of the strain and stress components inside the (Re)BCO tapes and to evaluate their impact on the conductor electrical performance in **relevant operating conditions**.

The experimental procedure

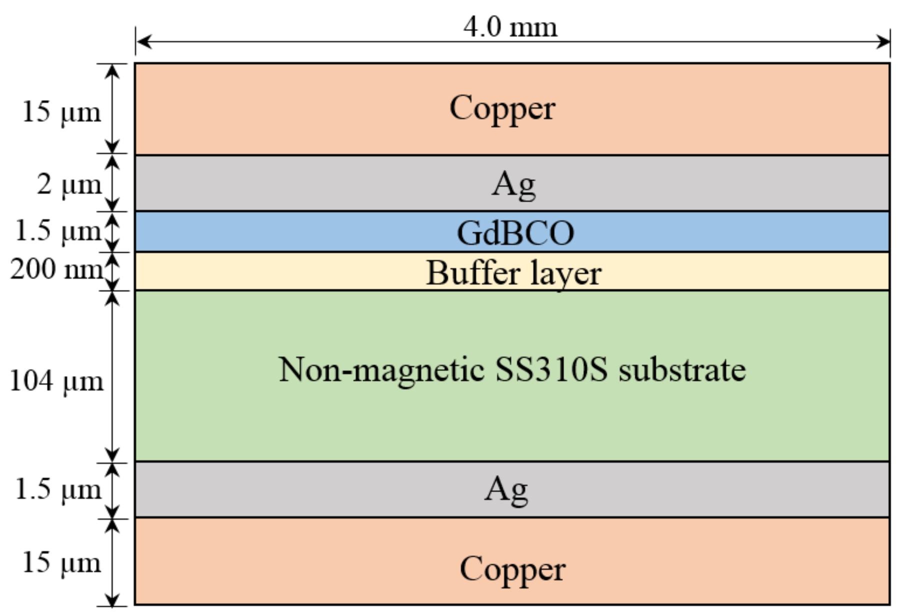
Three experimental steps:

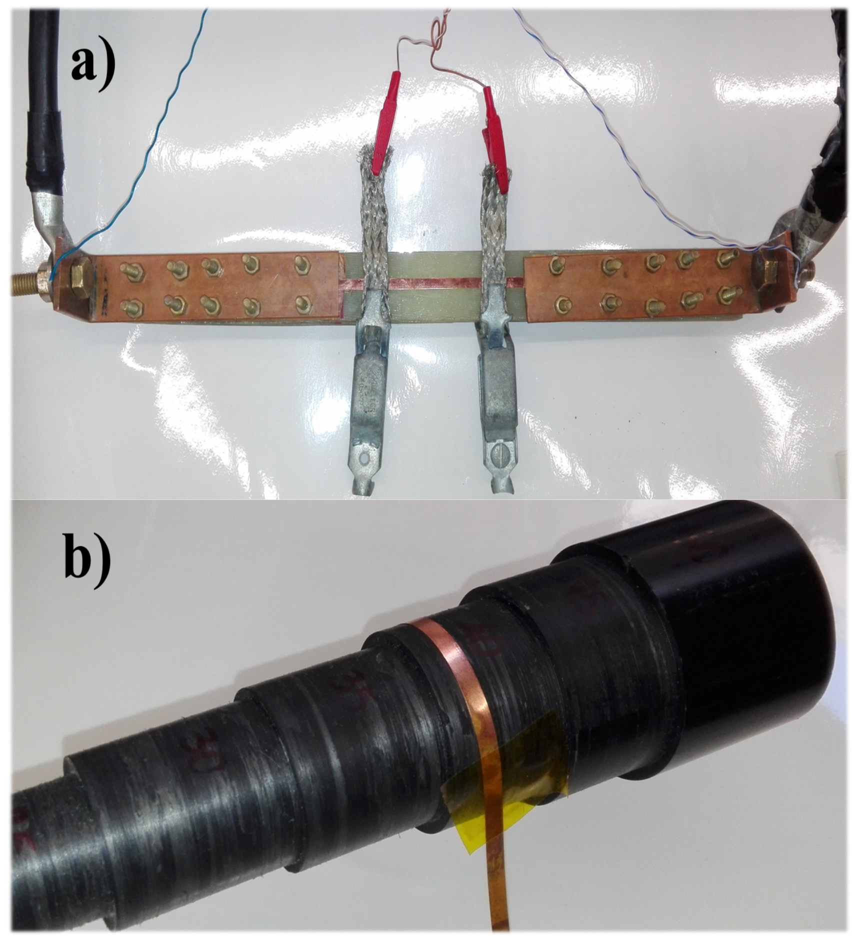
1) **Critical current measurement at 77 K** over a straight G10 support before double bending.
2) **Bending procedure** of the tape included between the voltage taps, **on a mandrel of known diameter**. The tape is released and subsequently bent over the same diameter on the other side. Afterward the tape is left free to recover the initial configuration.
3) Repositioning of the tape over the **straight support** and a **second critical current measurement** is performed.

A comparison of the critical current values found **before and after the double bending** is performed.

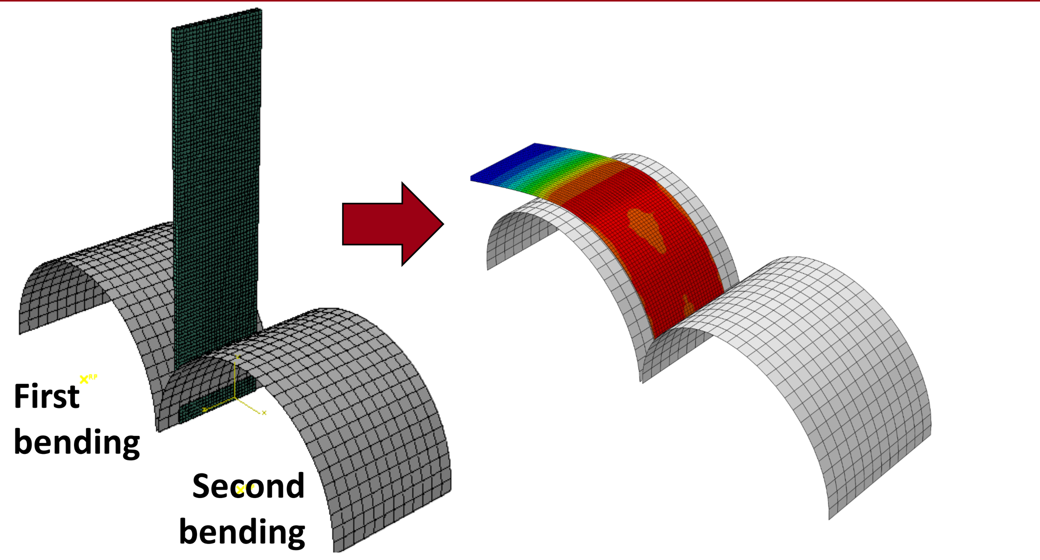
Different mandrel diameters are tested.

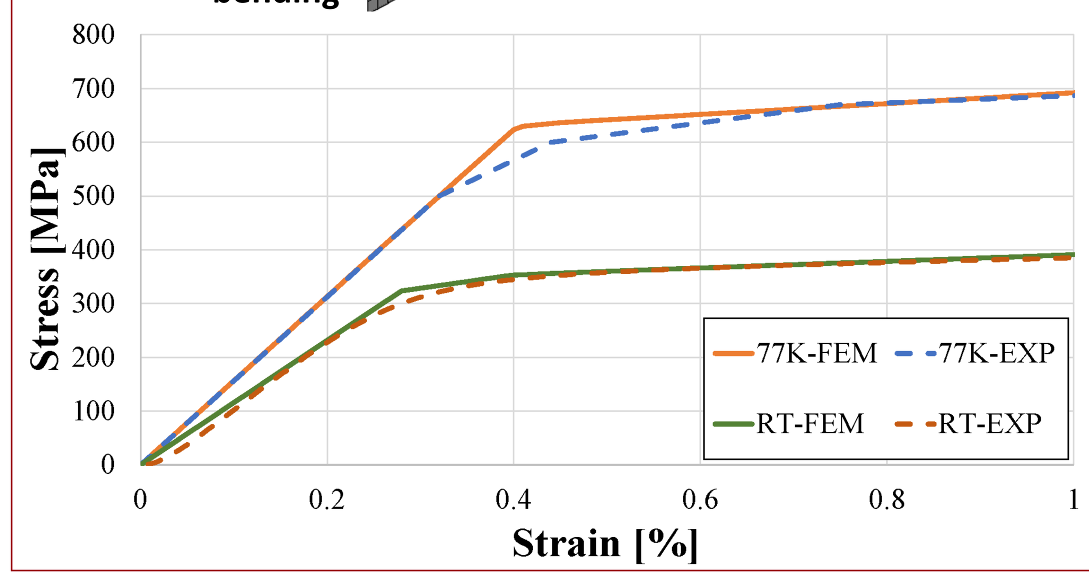
Tape model	SuNAM type SCN04
Tape length	30 cm
Voltage taps distance	5 cm
I_c (77 K)	242.6 A





The numerical model





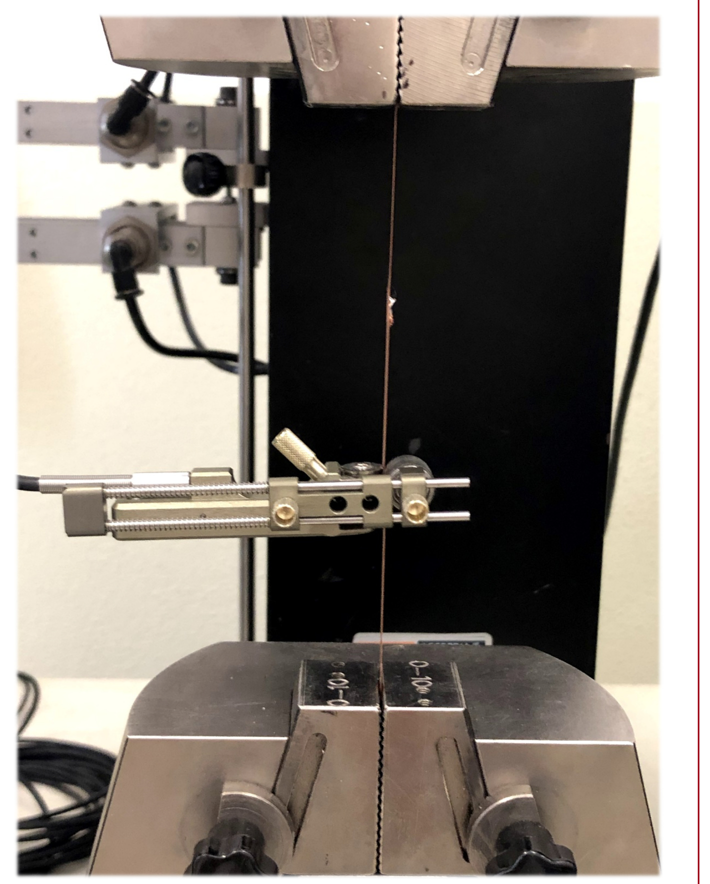
Finite Element model

Multi-layer shell elements, **4 nodes** and **6 dof per node** are chosen, with reduced integration (1 Gauss point in the mean plane) to avoid spurious modes. Out of plane **composite layup-type** section with **6 layers**, 3 Simpson integration points per layer, to reconstruct in detail the stress and strain distribution across the thickness of the tape.

Finite strain analyses, with **plasticity** of material and **contact** on the mandrels.

Material characteristics

Material data are obtained from **experimental tests** performed at the University of Padova at **293 K** and from **SUNAM** tests at **77 K**.



Results

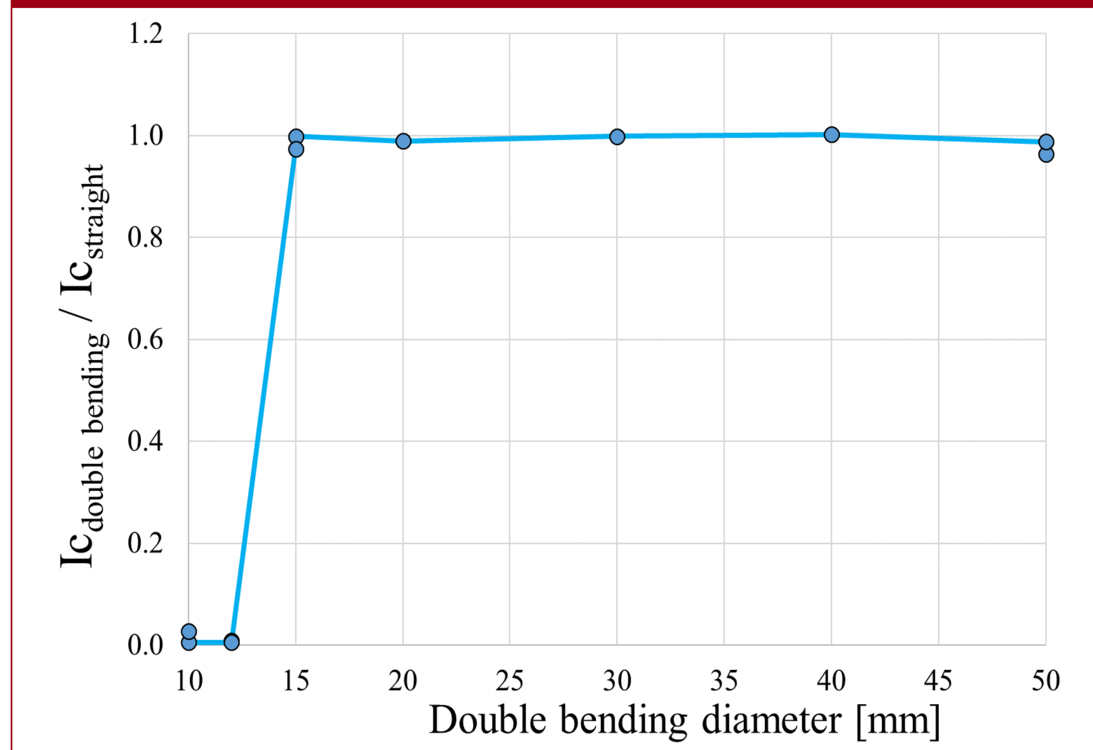


Figure 1: experimental results

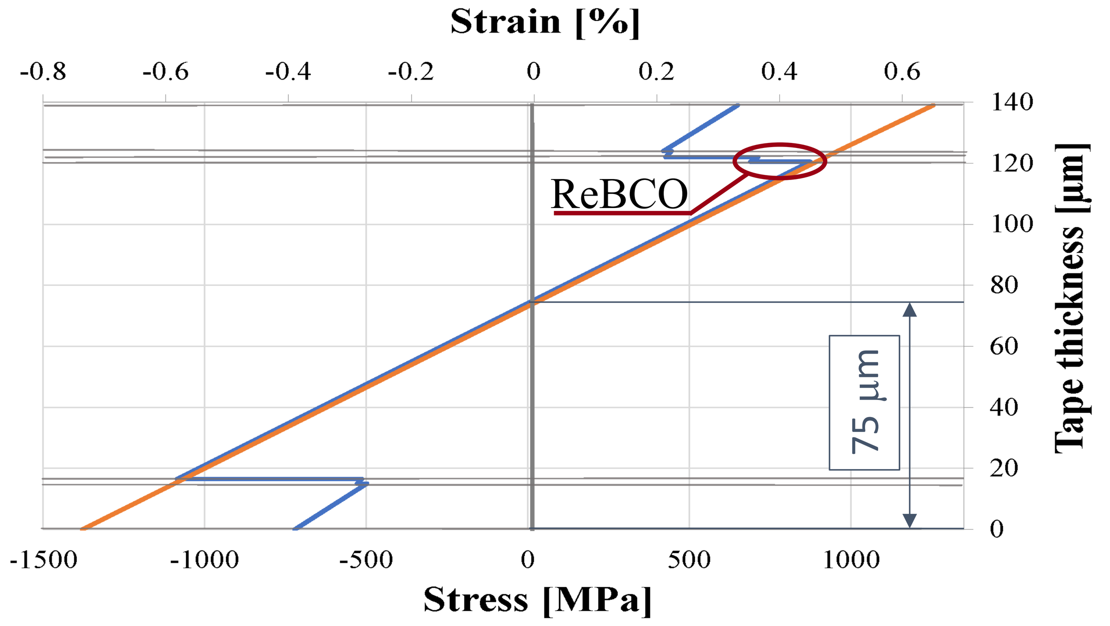


Figure 2: longitudinal stress and strain across the tape thickness

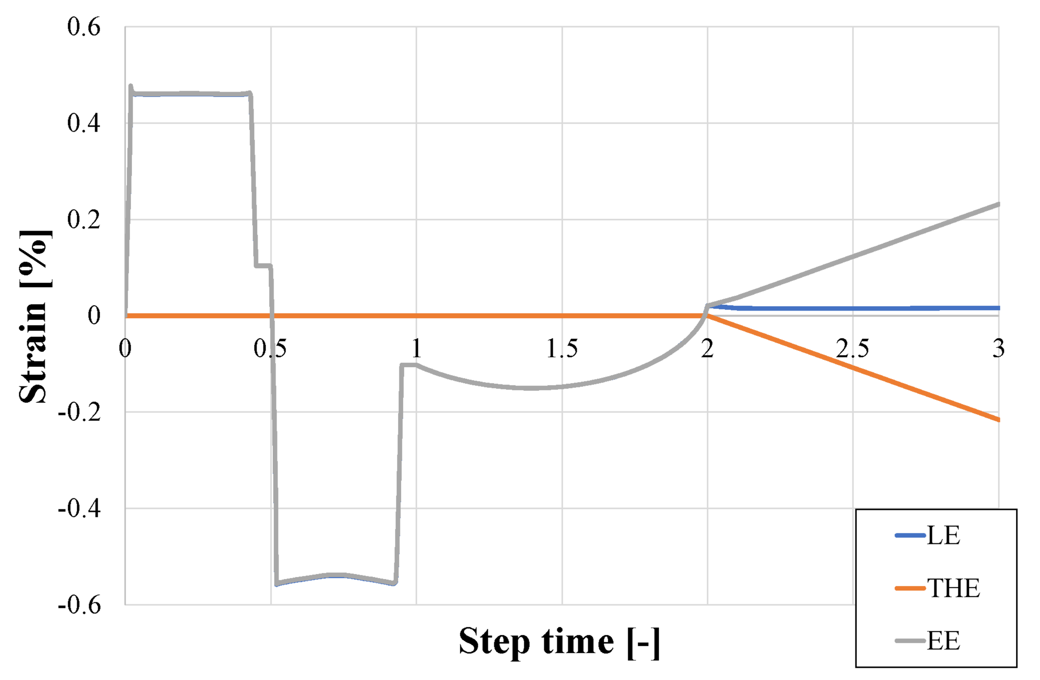


Figure 3: strain components in the (Re)BCO layer (20 mm diameter)

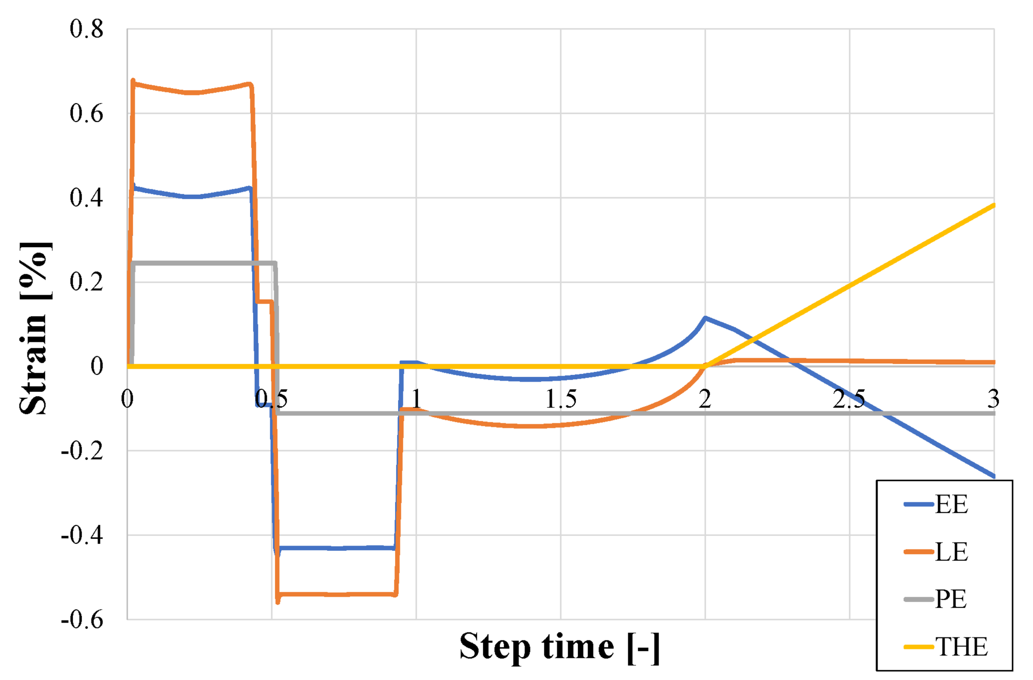


Figure 4: strain components in one copper layer (20 mm diameter)

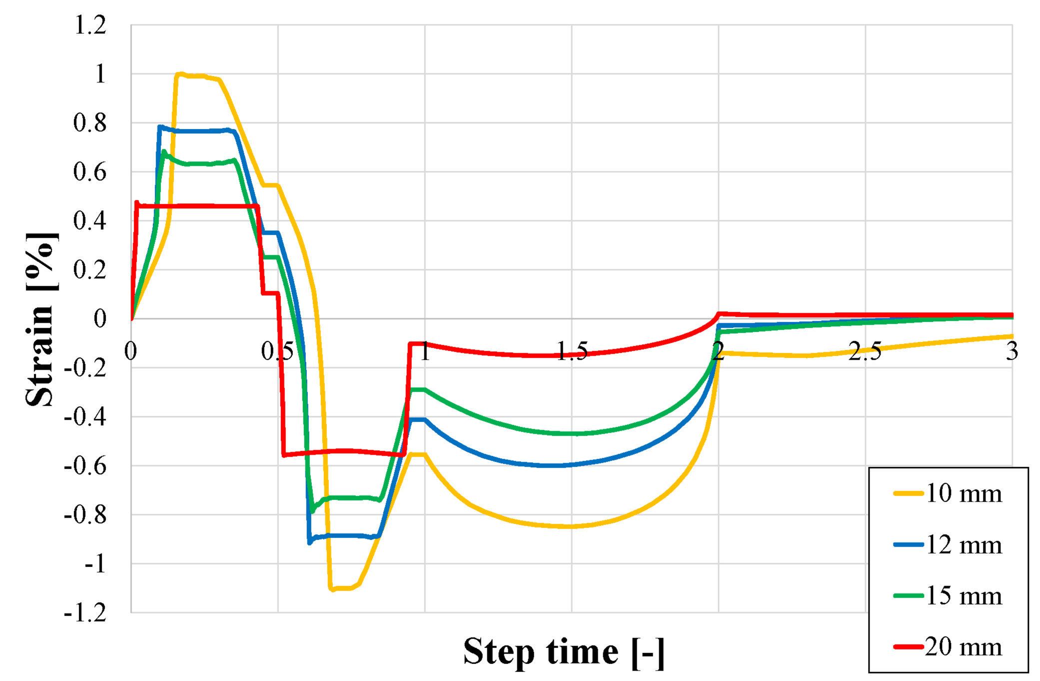


Figure 5: (Re)BCO strain components vs. mandrel diameter

This work aims at identifying the strain limit at which a reduction of the tape critical current occurs.

The double bending experiments reveal the existence of a **critical value of the mandrel diameter** between **15 and 12.5 mm (see Figure 1)**. Since the curvature is proportional to strain, these tests give an indirect measure of the critical strain.

The model developed allows computing the strain and stress field in the **whole domain of interest**.

Since there is no delamination, **the strain is linear** over the whole thickness, while **the jumps in the stress values** are due to the different Young moduli of the various layers (see Fig. 2).

Figure 3 shows the progression of the thermal, elastic and total (logarithmic) strain in the (Re)BCO layer for the 20 mm diameter case taken as an example.

It can be noted that **the maximum strain is reached during the bending phase**, with a slight difference in the absolute value reached in the two bending phases, due to the asymmetric position of the superconducting layer with respect to the neutral axis.

The same strain component is plotted in figure 4 for the copper, where **the yielding of the material is clearly visible**. Figure 5 shows the results obtained for the different diameters: between the 15 and 12.5 mm diameter cases the numerical model identifies a strain value ranging from 0.75 to 0.9%. This tape exhibits a 0.75% irreversible strain limit [4], which is in agreement with the experimental tests.

Conclusions

A novel thermo-mechanical model of (Re)BCO tapes was developed, which allows computing the strain distribution in the tape volume under bending and thermal loading. The model was applied to interpret the results of critical current measurements performed after double bending tests at room temperature.

The critical bending diameter of the mandrel identified in the tests corresponds to peak strain values in the range 0.75 to 0.9% computed by the model, which exceed the irreversible strain limit of the tape. The abrupt performance drop found in the experiments suggests a possible rupture of the (Re)BCO layer.

References

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[2] IEC 61788
[3] N.C. Allen et al., *Cryogenics* **80**, 405 (2016).
[4] SUNAM, *private communication.*