Effect of transverse stress applied during reaction heat treatment on the stiffness of Nb_3Sn Rutherford cable stacks

Felix Wolf[1 2], Friedrich Lackner[1], Michael Hofmann[3], Christian Scheuerlein[1], Daniel Schoerling[1], Davide Tommasini[1]

[1] CERN, Genève , Switzerland, [2] TU Bergakademie Freiberg, Germany , [3] TU München FRM II, Garching, Germany

FCC Week, 2018, Amsterdam

Abstract

The stress-strain behaviour of the Nb_3Sn conductor blocks of the Future Circular Collider (FCC) superconducting magnet coils needs to be known in order to predict the stress state distribution in the coils during magnet assembly and operation. The stress-strain behaviour under compression of reacted and impregnated 11 T dipole Rutherford cable stacks has been determined. The effect of the compression applied on the cable stack during the reaction heat treatment (RHT) on the stiffness of the reacted and impregnated cable stack in transversal, radial and axial directions has been measured. The stiffness of the cable stacks and 11 T dipole coil block segments has been compared. In addition the effect of applied stress on coil block stiffness and the creep behaviour were studied.

1. Samples

- All samples are made from Nb_3Sn 11 T dipole Rutherford cable, with Mica and S2 glass insulation, and have a cube shape with approximate edge lengths of 15 mm (Figure 1).
- Ten-stack samples are reacted in a dedicated mould (Figure 2) with three different levels of compaction, due to a clearance variation.
- 11 T dipole coil block sample is machined out of the coil after magnet cold test, containing adjacent coil wedges to compensate the keystone angle.
- Impregnation with so-called CTD-101K epoxy resin from Composite Technology Development, Inc.
- Non-impregnated 11 T dipole ten-stack sample has been tested for comparison.

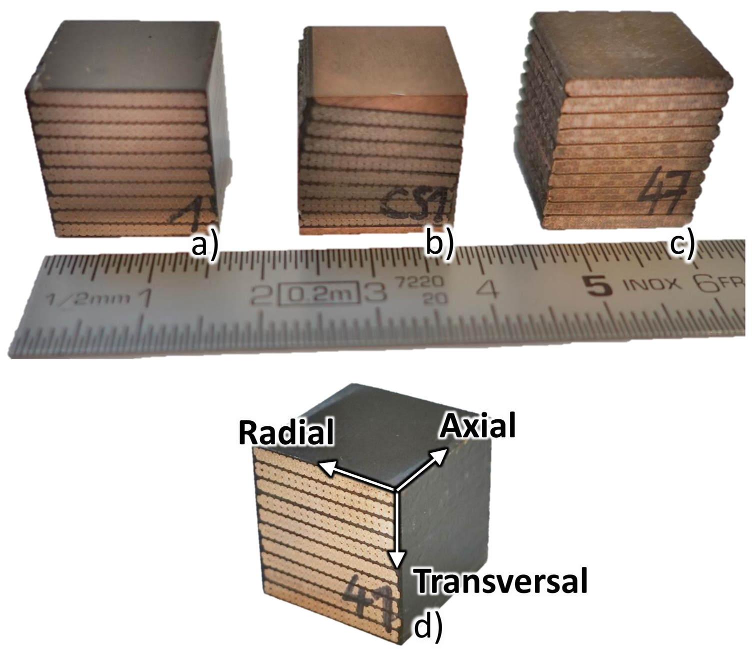

Fig. 1: Nb_3Sn Rutherford cable sample types: (a) ten-stack, (b) 11 T dipole coil segment and (c) non-impregnated ten-stack. (d) Sample orientations.

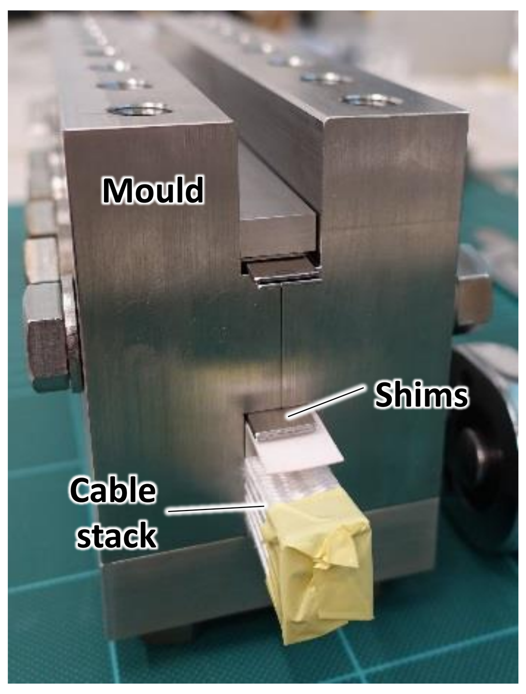

Fig. 2: Mould for curing and reaction heat treatment (RHT).

2. Compression tests

- Identical samples were tested with two independent set-ups.
- Direct strain measurement using clip-on extensometers with a gauge length of either 6 mm or 12 mm in order to avoid the influence of machine compliance.
- Stiffness is defined as the initial linear slope of the unloading stress-strain curves
- Iso-stress plateaus are kept for one hour before unloading.
- Load rate between iso-stress plateaus 50 N/s.

Fig. 3: Ten-stack sample with clip-on extensometer with 6 mm gauge length.

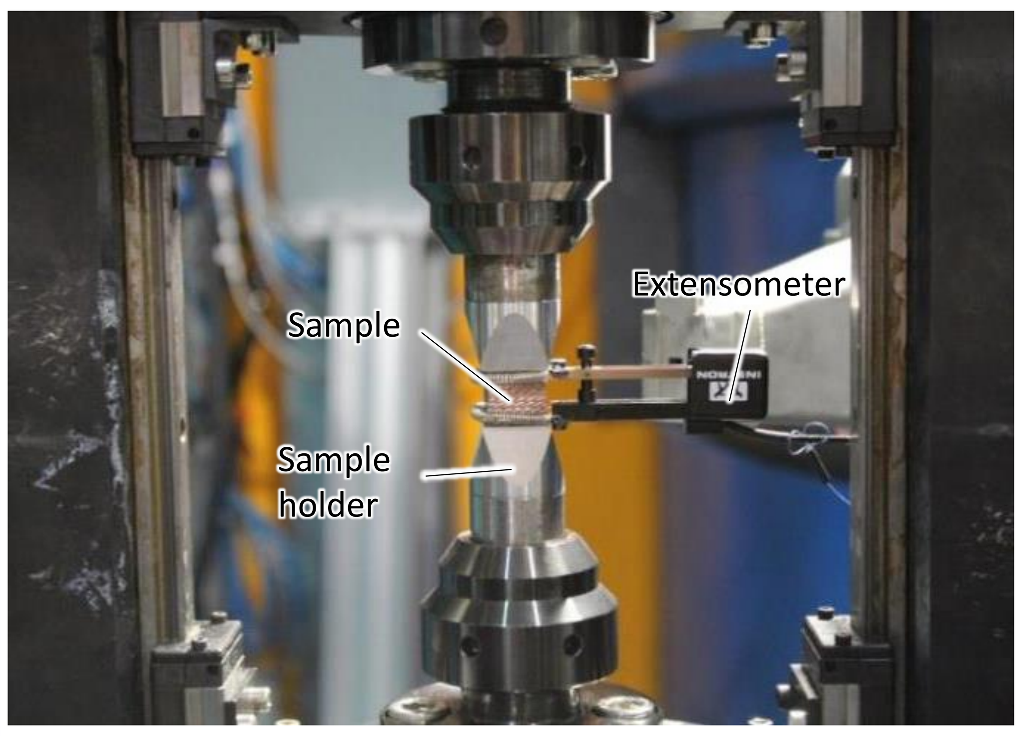

Fig. 4: Sample with clip-on extensometer with 12 mm gauge length installed in the load frame.

3. Results

Virgin samples

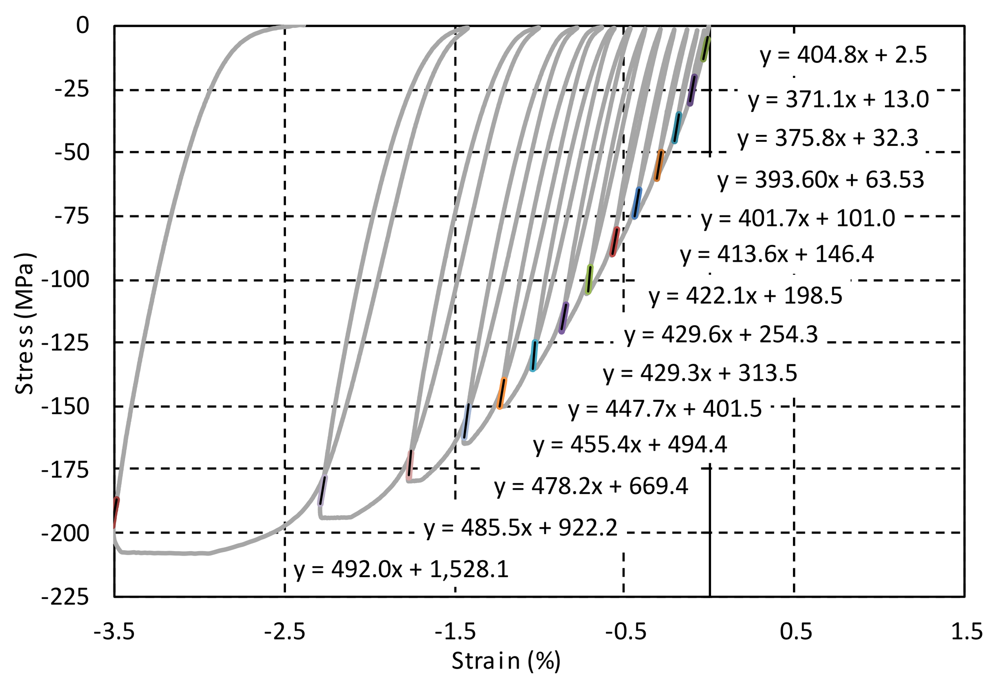

Fig. 5: Transverse compressive stress-strain curve of the ten-stack sample reacted with the lowest compaction.

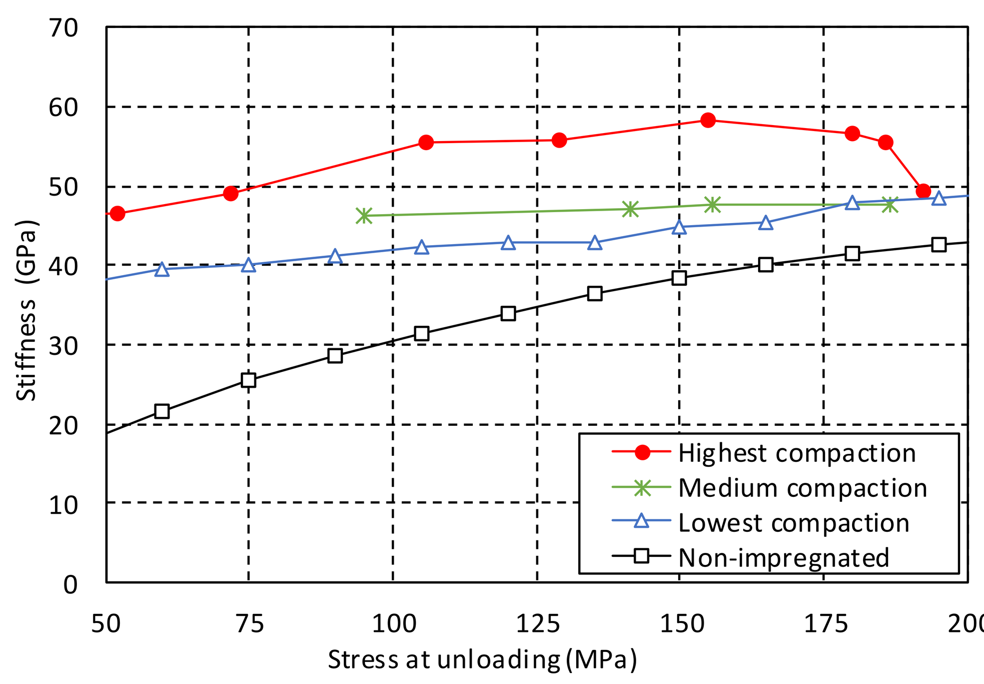

Fig. 6: Comparison of the transverse compressive stiffness at different unloading stress levels of 11 T dipole cable ten-stacks produced with different compression during RHT.

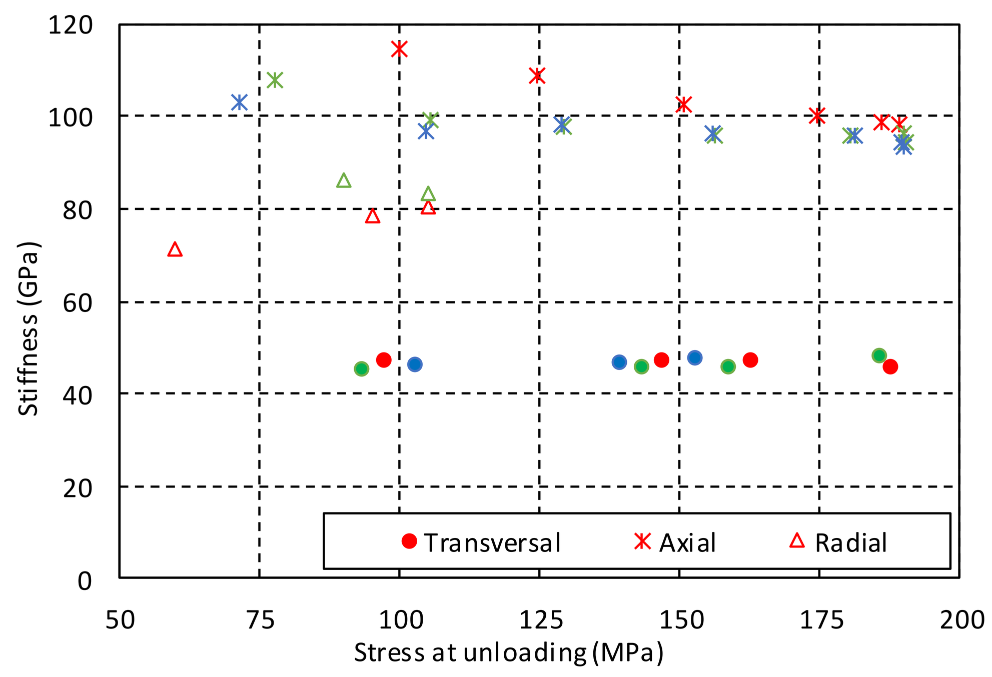

Fig. 7: Comparison of the ten-stack stiffness with respect to the load direction (medium compaction during ten-stack reaction heat treatment).

Reloaded samples

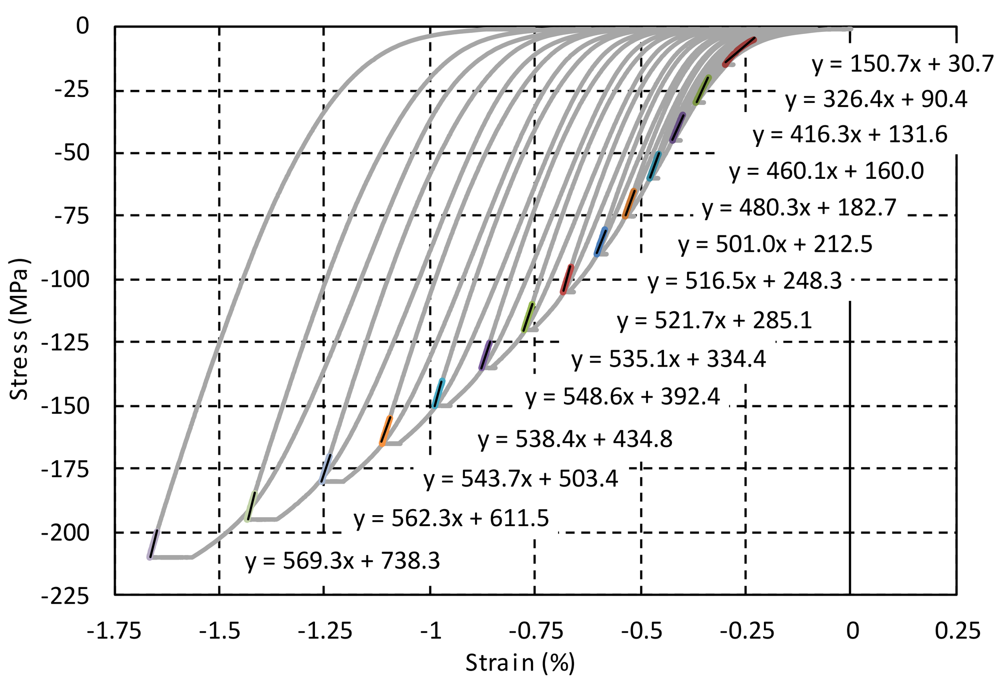

Fig. 8: 11T dipole coil segment compressive stress-strain curve.

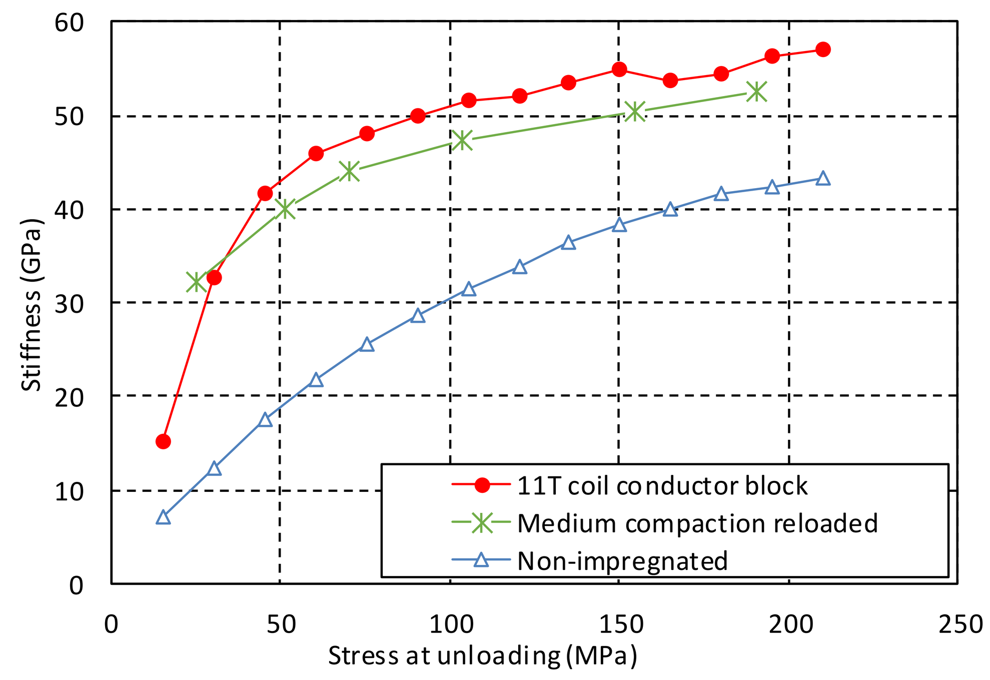

Fig. 9: Stiffness comparison of 11 T dipole coil block after cold testing, and ten-stack sample with medium compaction (2nd load cycle) in comparison with a non-impregnated ten-stack sample.

Table 1: Comparison of coil block and ten-stack stiffness

Sample type and RHT clearance	Load direction	Stiffness (average in unloading range 100-150 MPa)
Epoxy-14.6 mm	Transversal	56.6 ± 1.5 GPa
Epoxy-14.8 mm	Transversal	46.6 ± 0.8 GPa
Epoxy-14.8 mm	Radial	76.1 ± 6.9 GPa
Epoxy-14.8 mm	Axial	101 ± 6.4 GPa
Epoxy-15.0 mm	Transversal	43.2 ± 1.1 GPa
No epoxy-15.7 mm	Transversal	35.0 ± 3.0 GPa
11 T dipole block	Transversal	53.0 ± 1.4 GPa
Epoxy-14.8 mm reloaded	Transversal	50.0 ± 2.2 GPa

Summary

Table 1 summarises the main stiffness results:

- The ten-stack stiffness is highest in axial direction and lowest in transverse direction (axial stiffness is 2x transverse stiffness, radial stiffness is 1.3x transverse stiffness).
- The stiffness in transverse direction increases with increasing compaction level during the RHT.
- Stiffness increases with increasing unloading stress, and depends on the load history.
- The transverse stiffness of the ten-stack samples with the medium compression during RHT matches well the 11 T dipole coil block stiffness.
- A strong creep behaviour is observed when the transversal load exceeds about 125 MPa.

4. Conclusion & outlook

- **Good agreement of the stiffness results for identical 11 T dipole Nb_3Sn Rutherford cable stacks measured with two independent test set-ups.**
- **Uncertainties caused by the compliance of the test set-ups are avoided by using extensometers for direct strain measurements.**
- **In the 11 T coil block and in the ten-stack samples made of the same conductor and with similar epoxy volume fraction, the macroscopic stiffness and creep behaviour under compressive loading are similar, suggesting that the mechanical coil behaviour can be represented well by ten-stack samples.**
- **It remains to be studied if the test configuration of free-standing samples can represent the conductor loading in a magnet coil, where the conductor is constrained in axial and radial directions.**
- **Results can be compared with neutron diffraction measurements to determine the strain and stress state in the Nb_3Sn filaments and the Cu matrix.**

Presented at the FCC Week, 2018, 9 – 13 April, Netherlands, Amsterdam; Program I.D. number: 2AMSP32