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

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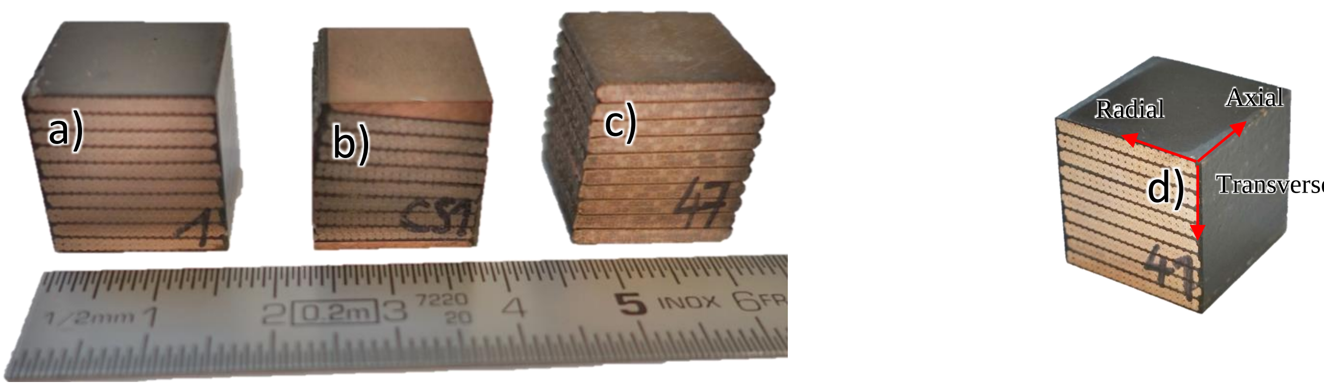
- Effect of epoxy volume fraction on transverse ten-stack stiffness
- Load direction dependency of the ten-stack stiffness
- Comparison of ten-stack and 11 T coil segment stiffness

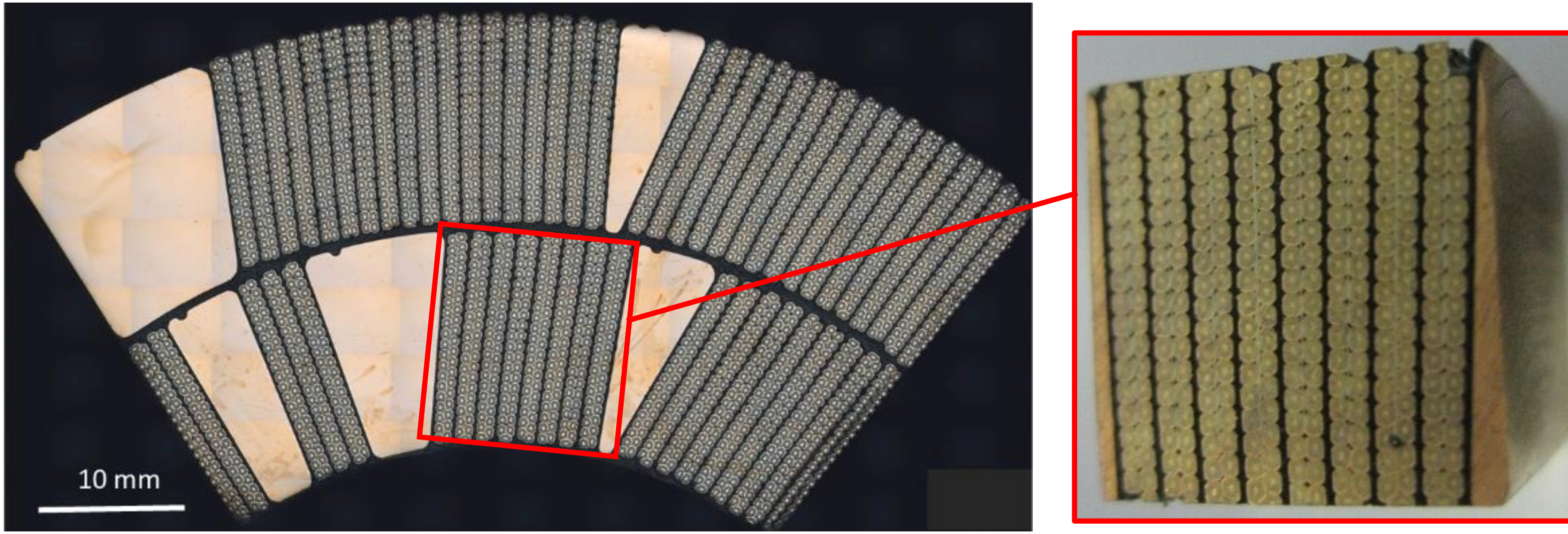
The samples

- All samples are made of Nb_3Sn 11 T dipole Rutherford cable.
- Cube samples with approximate edge lengths of 15 mm and with parallel surfaces enable compression tests in axial, transverse and radial directions.
- Ten-stack samples reacted in a dedicated mould with three different levels of compaction, due to a clearance variation.
- 11 T dipole coil block machined out of the coil after magnet cold test, containing adjacent coil wedges to compensate the keystone angle.
- The samples are impregnated with an epoxy resin system, so-called CTD-101K from Composite Technology Development, Inc.
- All samples have a Mica and S2 glass insulation.



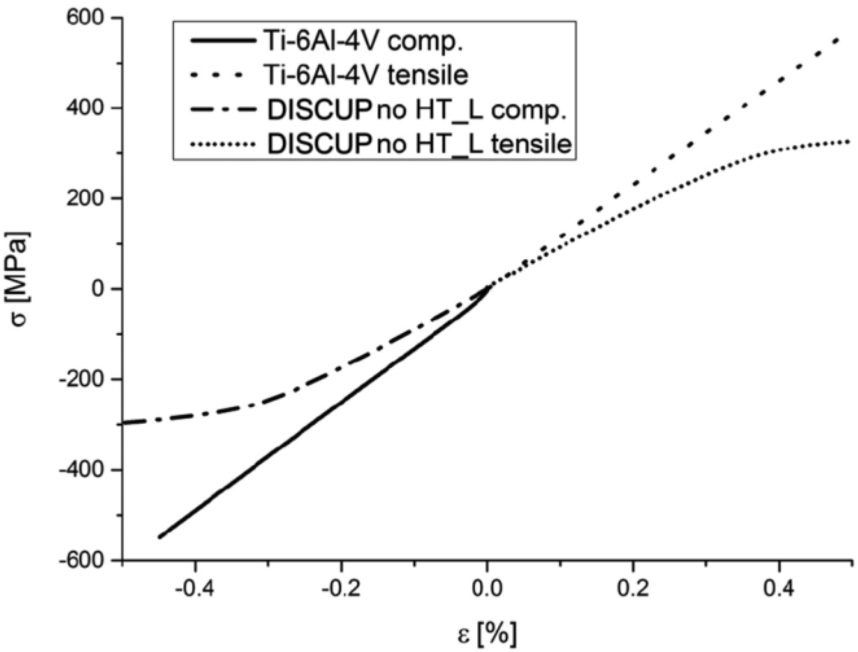
Nb_3Sn Rutherford cable sample types: (a) ten-stack, (b) 11 T dipole coil segment and (c) non impregnated ten-stack (d) Sample orientations.

11 T dipole conductor block segment



(a) Metallographic cross section of 11 T dipole coil CR107 with six conductor blocks. Courtesy M. Meyer, CERN. (b) Extracted conductor block sample used for compression tests. Courtesy CERN central workshop team.

Stress-strain measurements in tension and in compression



Comparison of tensile and compressive stress-strain curves of Ti-6Al-4V and DISCUP up to 0.5 % strain [1].

Tensile tests:

- Flat tensile test samples DIN 50125-E 3mm × 8mm × 30mm
- Clip on extensometer with 25 mm gauge length

Compression tests

- Cylinder sample ∅ 10 mm, height 15 mm (small ratio height to diameter in order to sample buckling)
- Use lubricant between contact surfaces to limit friction artefacts
- Clip on extensometer with 8 mm gauge length

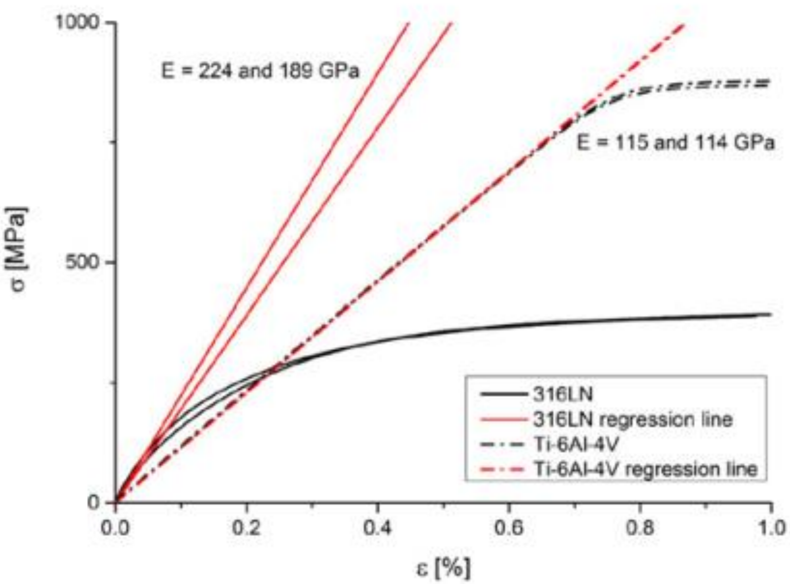
- The direct strain measurement using extensometers is crucial in order to avoid an influence of the load frame compliance.

- For metals differences between tensile and compression stress-strain curves are usually small.

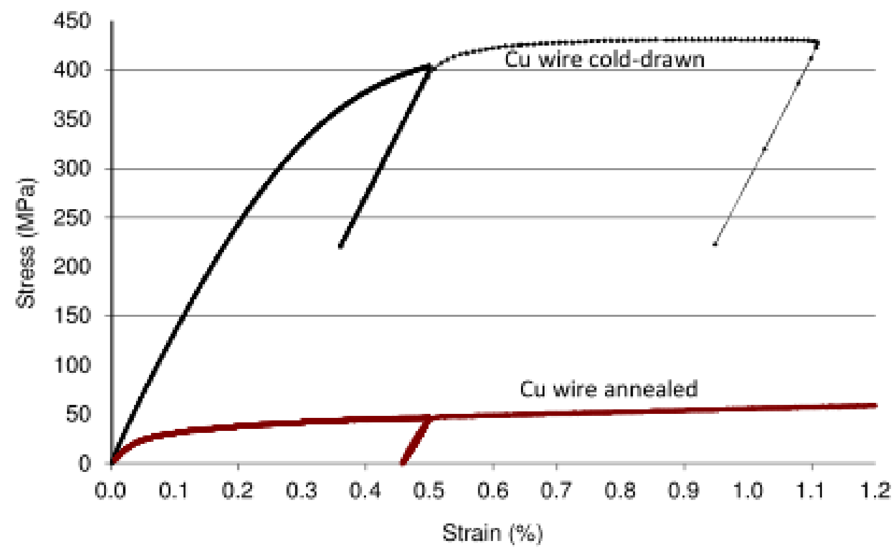
[1] IEEE Trans. Appl. Supercond., 27(4), (2017), 4003007

Determination of elastic moduli from stress-strain curves

- In favourable cases the elastic modulus can be determined from the initial linear slope of the stress-strain curve (e.g. for Ti-6Al-4V).
- Many metals like Cu or stainless don't exhibit linear elastic behaviour. For these metals the elastic modulus can be estimated from unloading stress-strain curves.



Comparison of stainless-steel 316LN and Ti-6Al-4V stress-strain curves. For 316LN a precise measurement of elastic modulus from the initial loading curve is not possible [1].



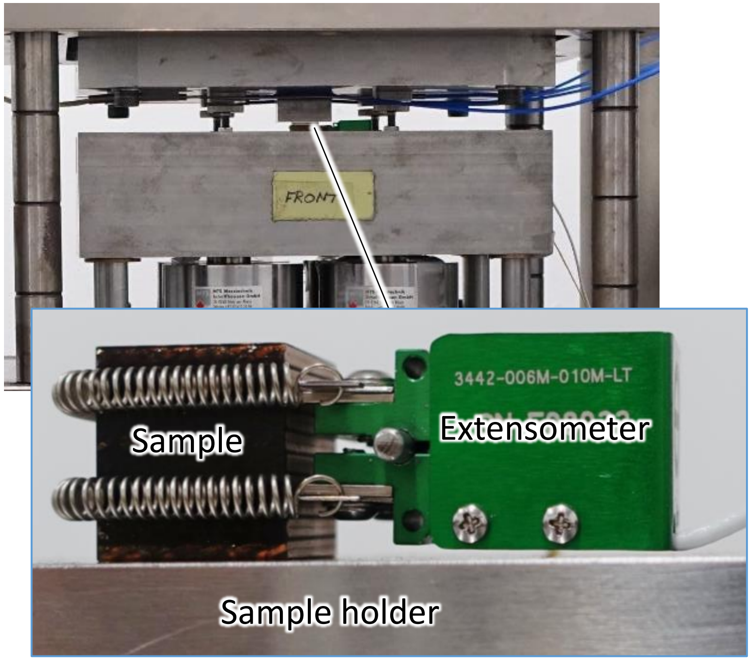
Comparison of hard-drawn and annealed Cu wire stress-strain curves with unloading slopes for determination of the elastic modulus [1].

[1] IEEE Trans. Appl. Supercond., 27(4), (2017), 4003007

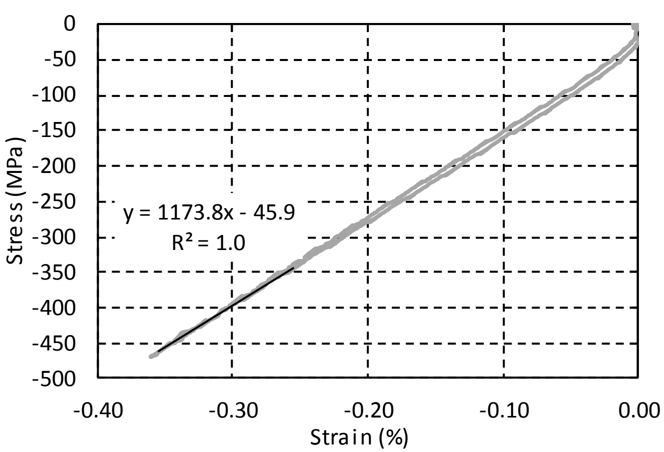
Test parameters for ten-stack sample compression tests

- Two different setups have been used for compressive stress-strain measurements.
- The sample strain in load direction was directly measured with calibrated clip-on extensometers.
- Load plateaus were kept constant for one hour/
- Load rate between plateaus was 50 N/s.
- Stiffness is defined as the initial linear slope of the unloading engineering stress-strain curves.
- Validation tests were performed with known materials (Ti-6Al-4V and Al 7075).
- Good agreement of stress-strain results achieved with both compressive stress-strain measurement set-ups.

Two setups used for stress-strain measurements in compression



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



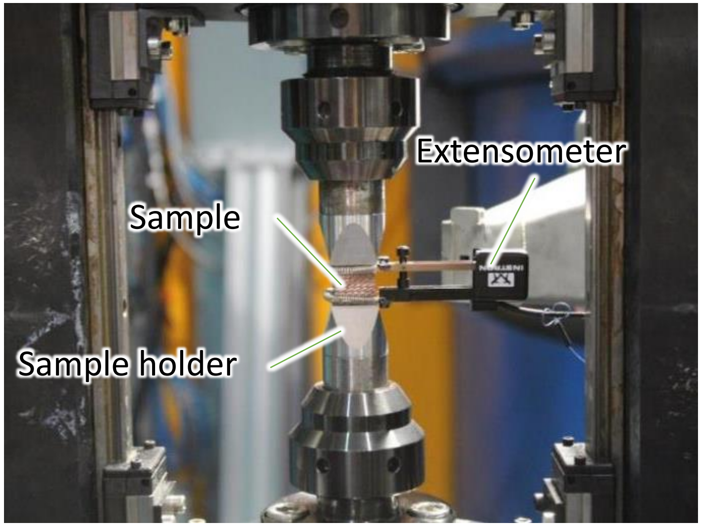
Reference measurement Ti-6Al-4V

- Set-up at CERN
  - Load measured with calibrated load cells (Burster type 8526)
  - Strain measured with clip on extensometer (Epsilon 3442-006M-010-LT Class B-1 6mm gauge length)

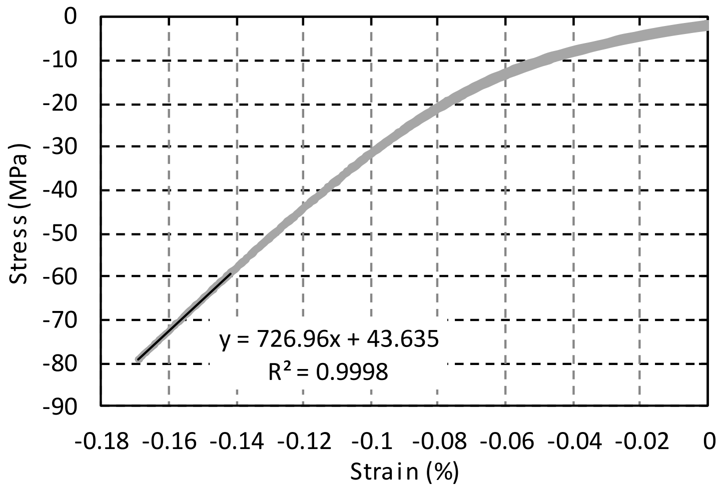
- Validation measurement:
  - Cubic Ti-6Al-4V sample
  - Determined E modulus: 117.4 GPa
  - Literature E modulus: 115 GPa [1]

[1] IEEE Trans. Appl. Supercond., 27(4), (2017), 4003007

Two setups used for stress-strain measurements in compression



Sample with clip-on extensometer with 12 mm gauge length installed in the load frame at StressSpec.

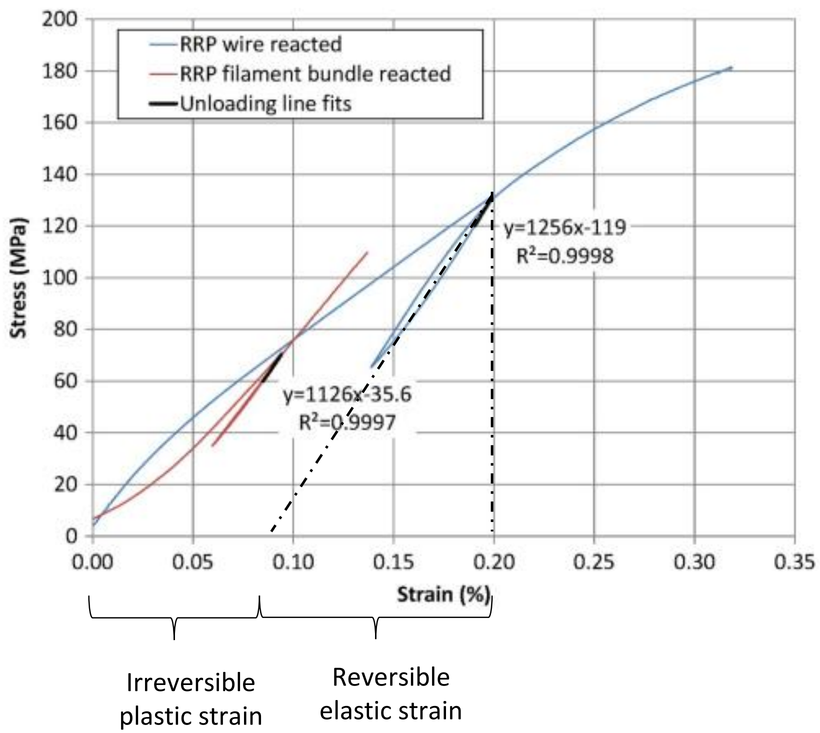


Reference measurement Al7075

- Setup at MLZ StressSpec beam line
- Load measured with calibrated load cells (HBM Typ 03, 50 kN)
- Strain measured with clip on extensometer (Instron 2620-602 12 mm gauge length)
- Validation measurement:
  - Cubic Al7075 sample
  - Determined E modulus: 72.7 GPa
  - Lit: 71.7 GPa [2]

[2] Metals Handbook, Vol.2 ASM International 10th Ed. 1990.

Elastic modulus of RRP type Nb_3Sn wire

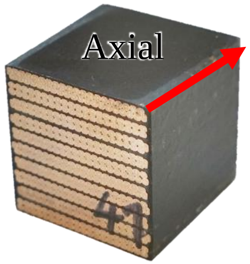


Stress-strain curves measured at room temperature on a reacted RRP wire and its extracted filaments. [3]

- Test performed with a tensile test machine "Inspekt table BLUE 05" from Hegwald & Peschke
- Load measured with AST KPA-S load cell with a maximum load of 1 kN
- Strain measured with a MTS clip-on extensometer 632.27F-21 with 25 mm gauge length
- E is defined as the initial linear slope of the unloading curve.
- Determined elastic modulus of the reacted RRP wire: **126 GPa**

[3] IEEE Trans. Appl. Supercond., 25(6), (2015), 8400605

Estimation of the ten stack stiffness in axial direction from the wire and epoxy properties according to the Rule of Mixtures (ROM)



Definition of axial sample orientation

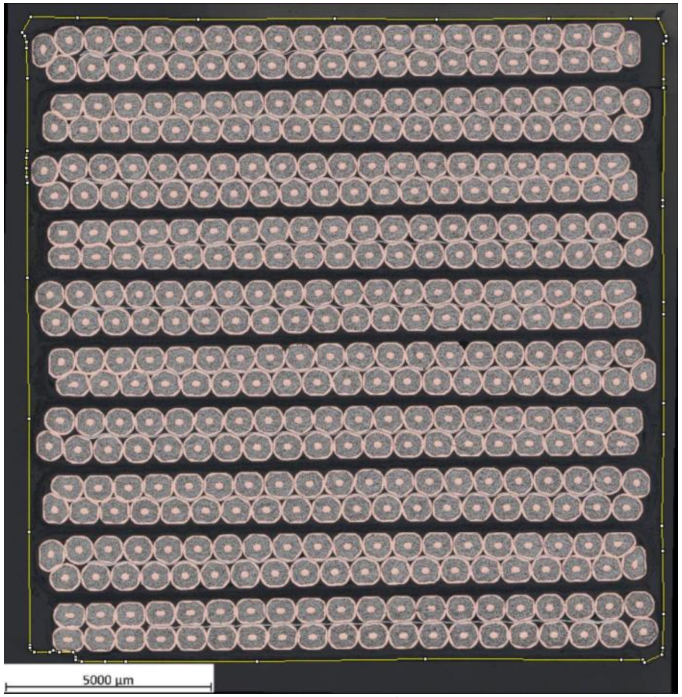
$$E_{\text{composite}} = E_f V_f + E_m V_m \text{ [4]}$$
$$V_i = A_i / A$$

E_f… Young's modulus fibre (strand)
V_f… Volume fraction fibre
E_m… Young's modulus matrix (epoxy impregnation)
V_m… Volume fraction matrix

$$E_f = E_{\text{strand}} = 126 \text{ GPa [3]}$$
$$E_m = E_{\text{CDT }101K} = 3.8 \text{ GPa}$$

Sample	A_{strand}* (mm²)	A_{total}** (mm²)	V_{strand} (%)	$E_{\text{composite}}$ (GPa)
1	175.7	236.6±0.33	74.3	**94.6**
2	175.7	241.3±0.24	72.8	**92.8**
3	175.7	252.4±0.18	69.6	**88.9**

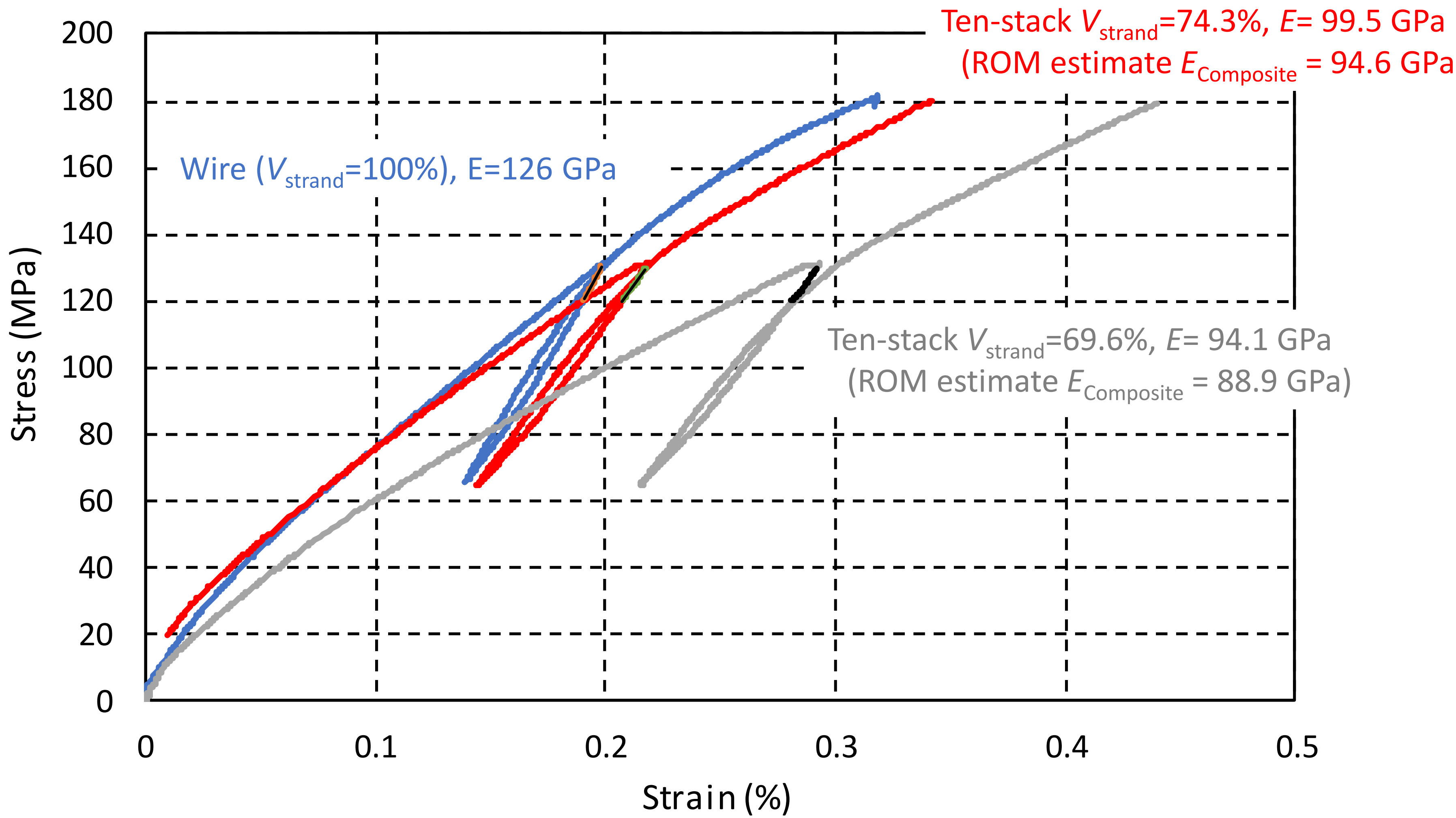
* Determined with image analysis with a Zeiss Axio Imager optical microscope. Courtesy M. Crouvizier, EN-MME
** Determined with contact measurement



Metallographic cross section of ten stack samples for the determination of the epoxy volume fraction by digital image analysis. Courtesy M. Crouvizier, EN-MME

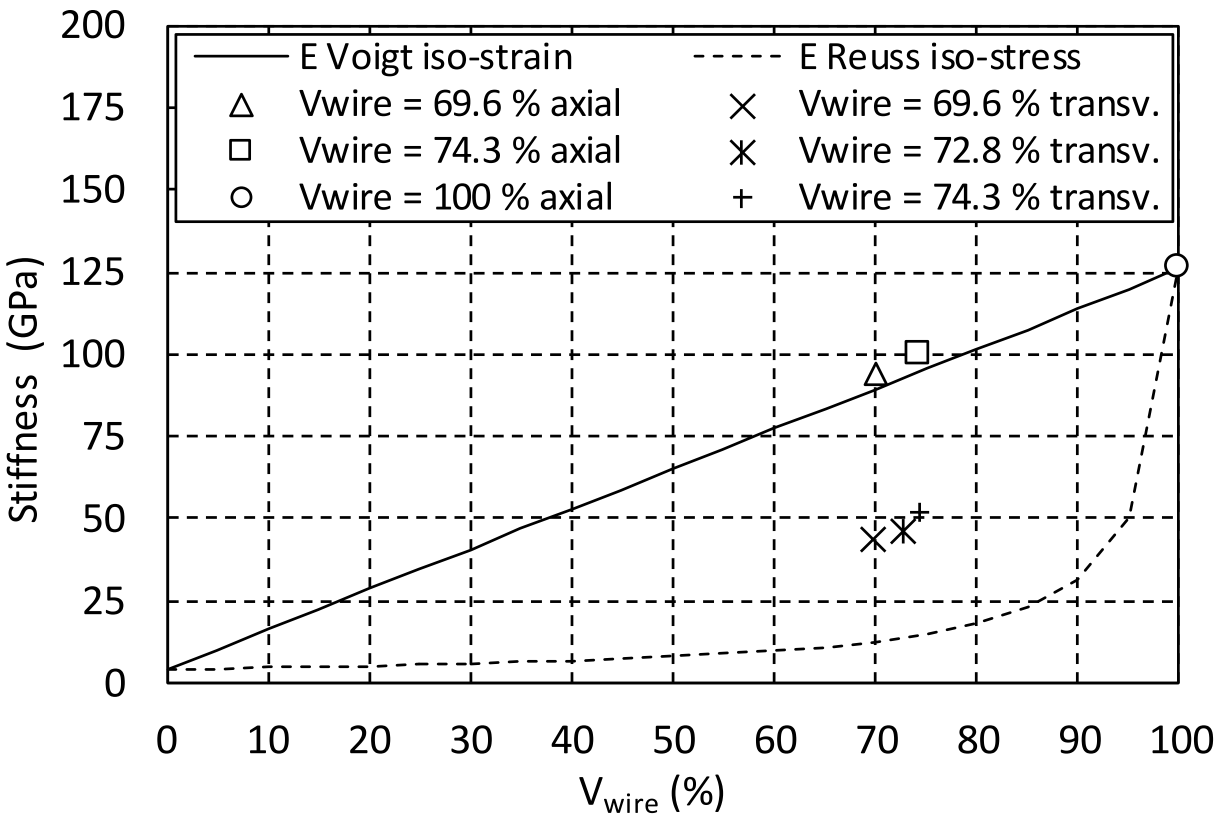
[3] IEEE Trans. Appl. Supercond., 25(6), (2015), 8400605
[4] Mechanics of composite materials, Taylor and Francis, 1999

Comparison between stiffness in axial direction in tension (wire, V_{strand}=100%) and compression (ten-stack)



Comparison of stress-strain curves of Nb_3Sn wire (axial tension) and ten-stack samples (axial compression).

Stiffness comparison between experiment and rule of mixture estimation



Stiffness estimation of the axial and transverse compression with stiffness dependence on V_{wire} and comparison with experiment.

- Iso-strain condition

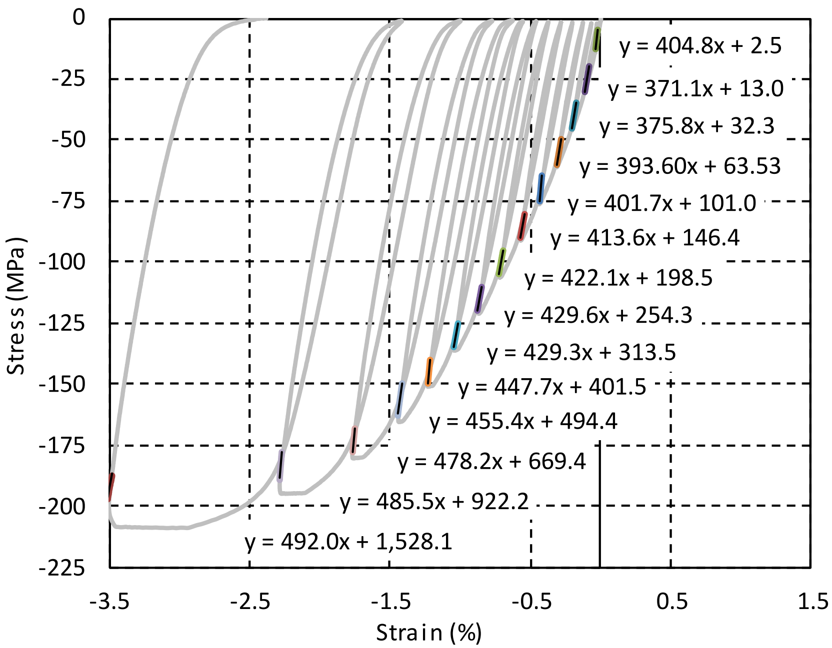
$$E_{\text{Voigt}} = E_f V_f + E_m V_m \text{ [4]}$$

- Iso-stress condition

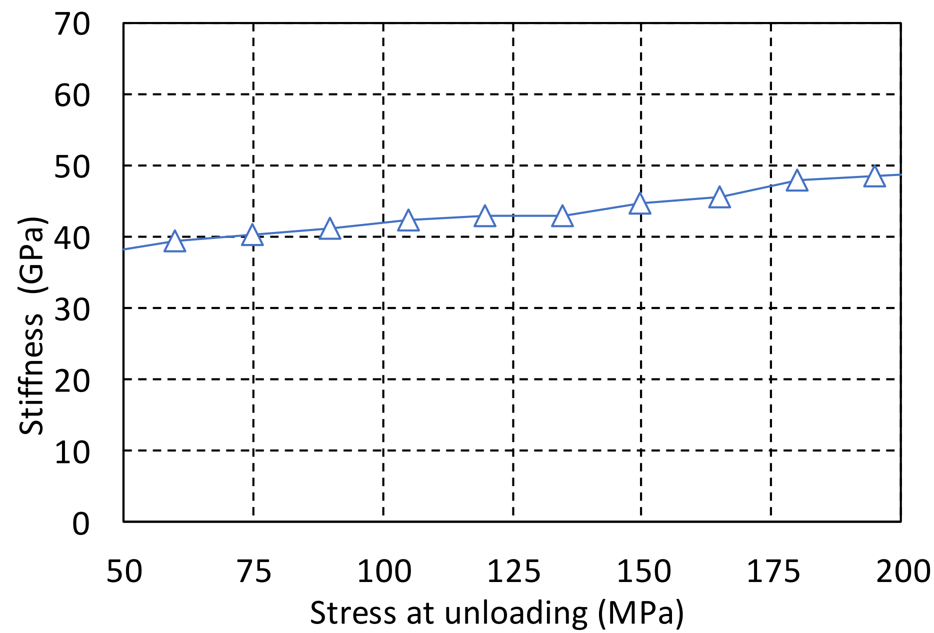
$$E_{\text{Reuss}} = \frac{E_f E_m}{E_f V_m + E_m V_f} \text{ [4]}$$

Effect of unloading stress on ten-stack stiffness in transverse direction– first loading

- The ten-stack stiffness increases with increasing unloading stress.
- A creep behaviour is observed when the transversal load exceeds about 125 MPa.

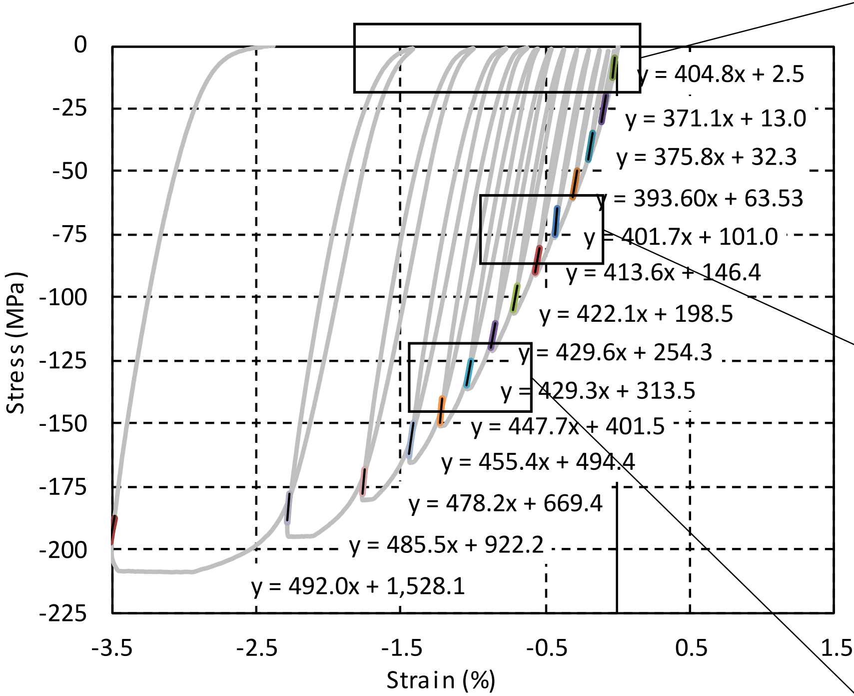


Transverse compressive stress-strain curve of the ten-stack sample (V_{strand}=69.6%).

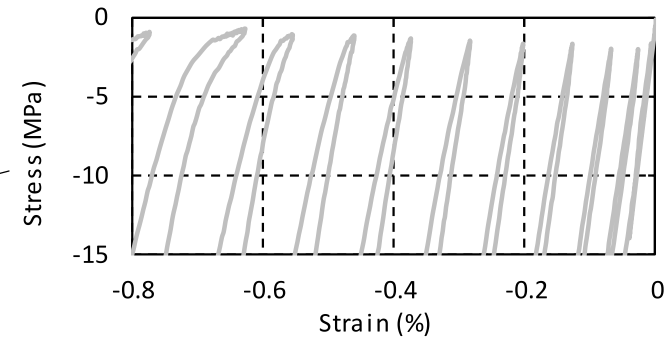


Transverse compressive stiffness at different unloading stress levels of a ten stack.

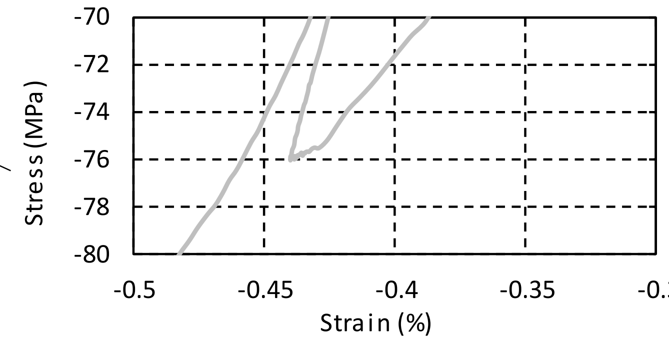
Indications for creep behaviour of a free standing ten-stack



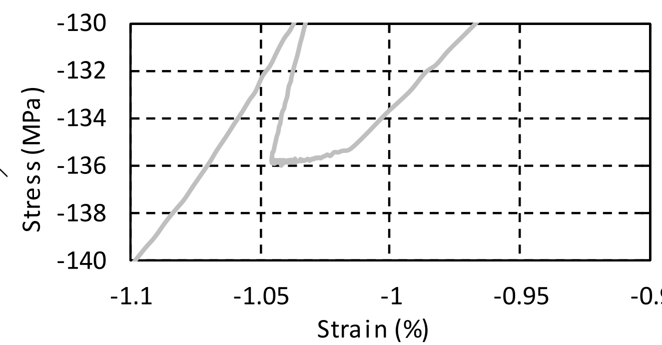
Transverse compressive stress-strain curve of the ten-stack sample (V_{strand}=69.6%).



Curve changes in unloading - loading transition after 135 MPa applied load

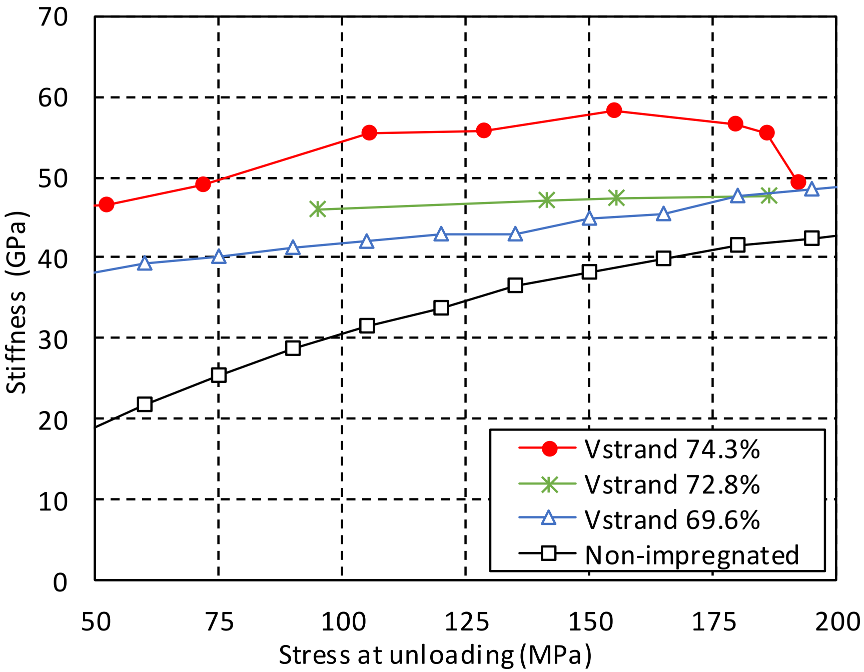


Small displacement at constant load



Increased displacement at constant load

Effect of epoxy volume fraction on transverse ten-stack stiffness (first loading cycle)

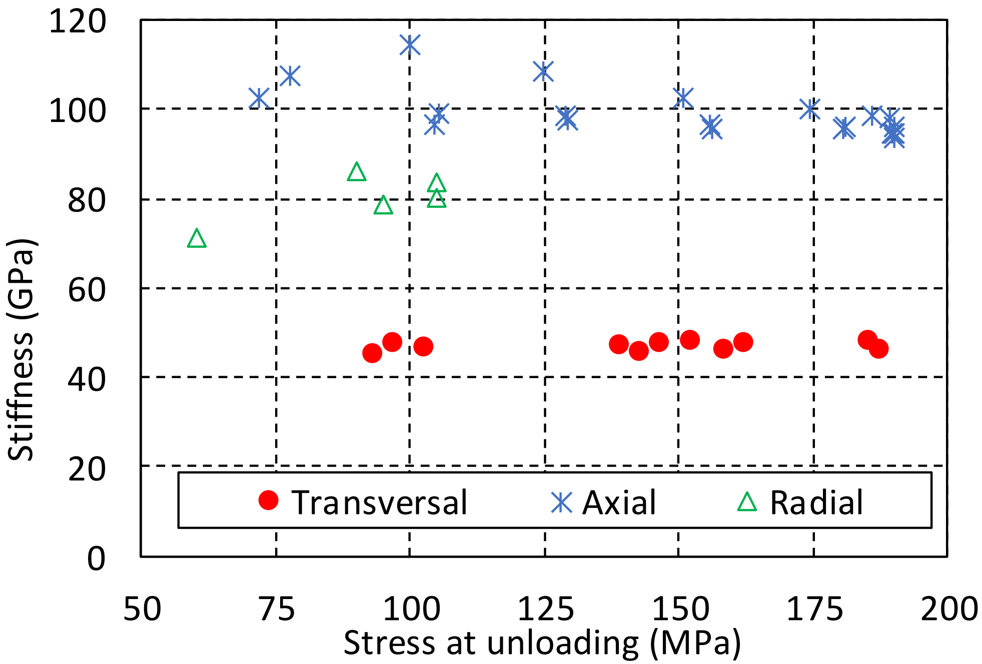


Transverse stiffness of ten-stack samples with different epoxy volume fraction at different unloading levels

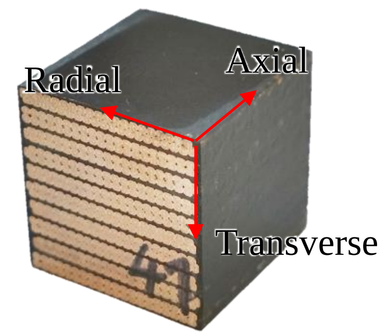
- Samples with three different compaction levels during RHT have been investigated.
- The stiffness increases with increasing unloading stress.
- The stiffness in transverse direction increases with increasing compaction level during RHT and varies between 40 - 60 GPa

Compaction level	HT clearance (mm)	V_{strand} (%)
High	14.6	74.3
Medium	14.8	72.8
Low	15.0	69.6

Effect of load direction on the ten-stack stiffness (first loading cycle)



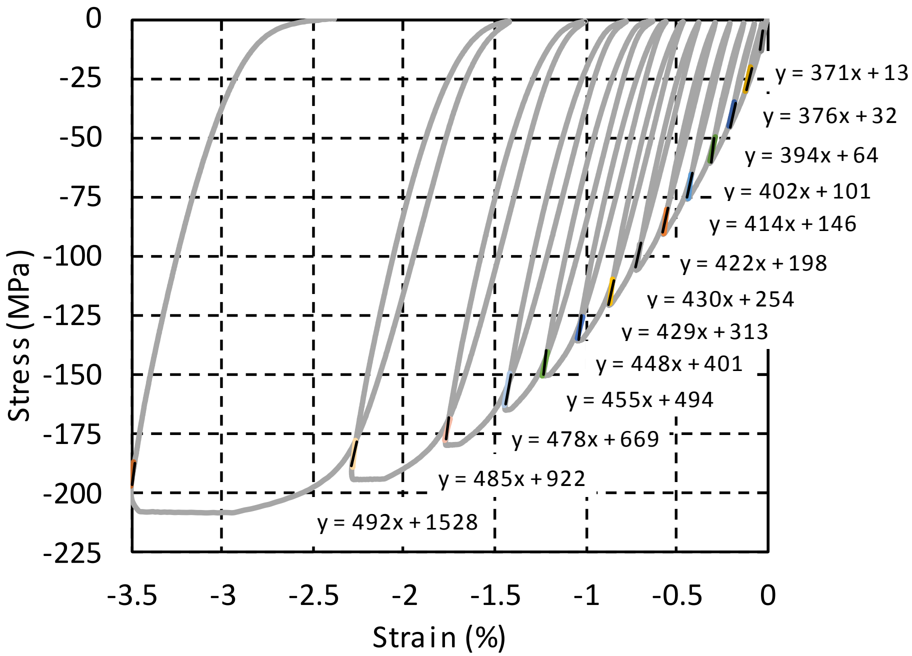
Stiffness in different load directions of a ten stack (V_{strand}=72.8%)



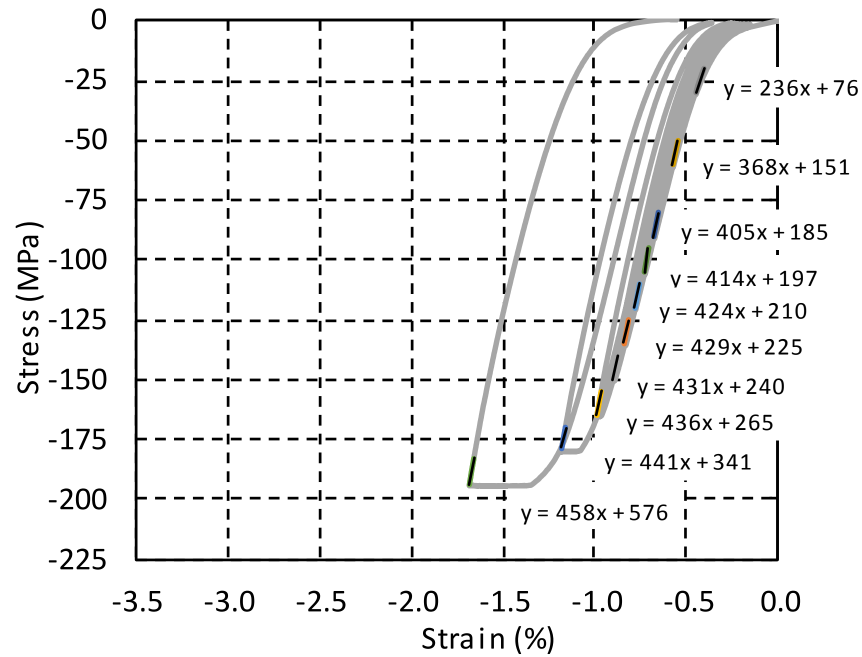
Sample orientation

- Stiffness is strongly dependent to the load direction
- Axial stiffness is 2 × transverse stiffness
- Radial stiffness is 1.3 × transverse stiffness

Comparison of a first loaded and a reloaded ten-stack sample

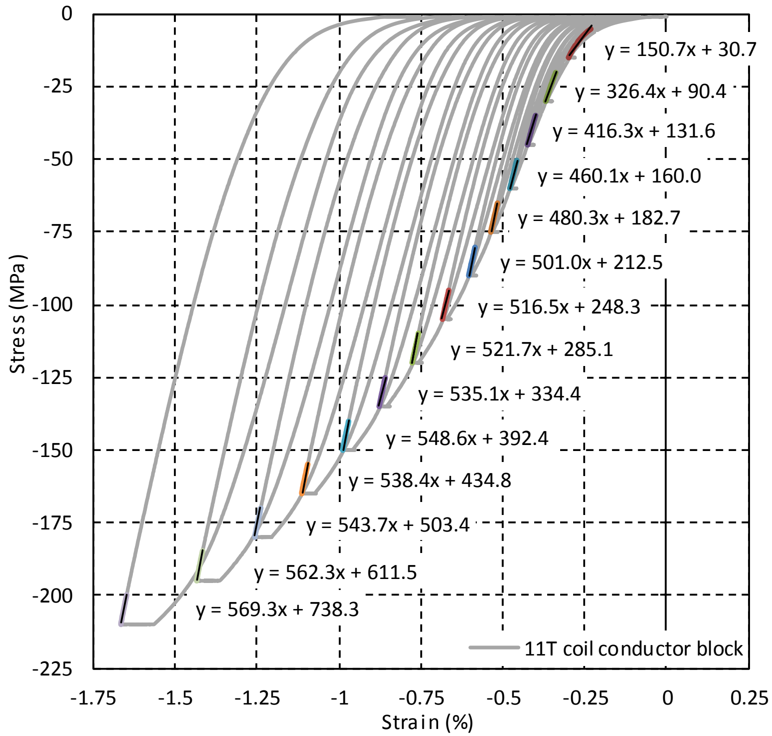


Transverse compressive stress-strain curve of the ten-stack sample (V_{strand}=69.6%) (first loaded).

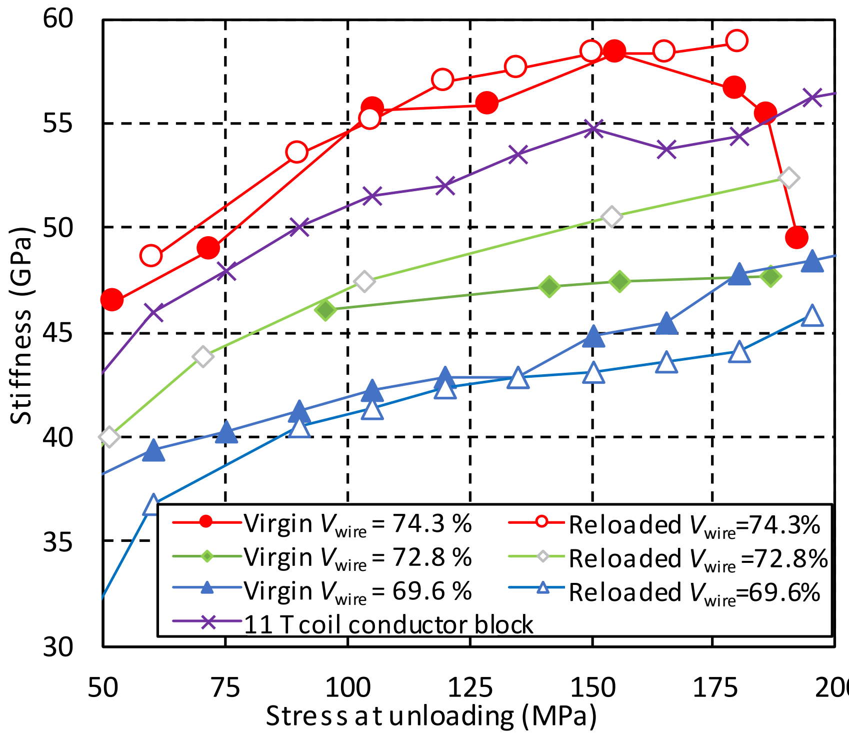


Transverse compressive stress-strain curve of the ten-stack sample (V_{strand}=69.6%) (reloaded).

Comparison of ten-stack and 11 T coil segment stiffness



Transverse compressive stress strain measurement of 11 T dipole coil segment



Transverse compressive stiffness comparison of ten-stacks with different wire volume fraction and 11T coil segemt.

- Stiffness is dependent from the loading level
- Strong creep behaviour starting at 125 MPa

- Stiffness is depended to the unloading stress

Conclusion I

- Good agreement of the stiffness results for identical Nb_3Sn Rutherford cable ten-stack samples measured with two independent test set-ups.

- In axial load direction the ten-stack stiffness can be predicted by the rule of mixtures assuming iso-strain conditions.

- 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 ten-stack samples can represent well the 11 T dipole conductor block.

- 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.

Conclusion II

The ten stack stiffness depends on:

- Epoxy volume fraction (depending on the sample compression during the RHT)
- The unloading stress level
- The load history
- The load direction (axial stiffness is 2 × transverse stiffness, radial stiffness is 1.3 × transverse stiffness).

- The transverse stiffness of 11 T dipole coil block corresponds with that of the ten stack samples with similar epoxy volume fraction.
- A strong creep behaviour is observed when the transversal load exceeds about 125 MPa.

Some open questions and outlook

- How is the load case of free standing ten-stack samples related to the loading of constraint coils in a magnet?
- What is the conductor block stiffness at 4.2 K?
- What is the effect of the load rate?
- What is the effect of creep?

References

[1] C. Scheuerlein, F. Lackner, F. Savary, B. Rehmer, M. Finn, and P. Uhlemann, “Mechanical properties of the HL-LHC 11 Tesla Nb_3Sn magnet constituent materials”, IEEE Trans. Appl. Supercond., vol. 27, no. 4, Jun. 2017, Art. no. 4003007.

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[4] Robert M. Jones, “Mechanics of composite materials”, Second edition, Taylor and Francis, Inc. London 1999