

# Effect of transverse stress applied during reaction heat treatment on the stiffness of Nb<sub>3</sub>Sn Rutherford cable stacks

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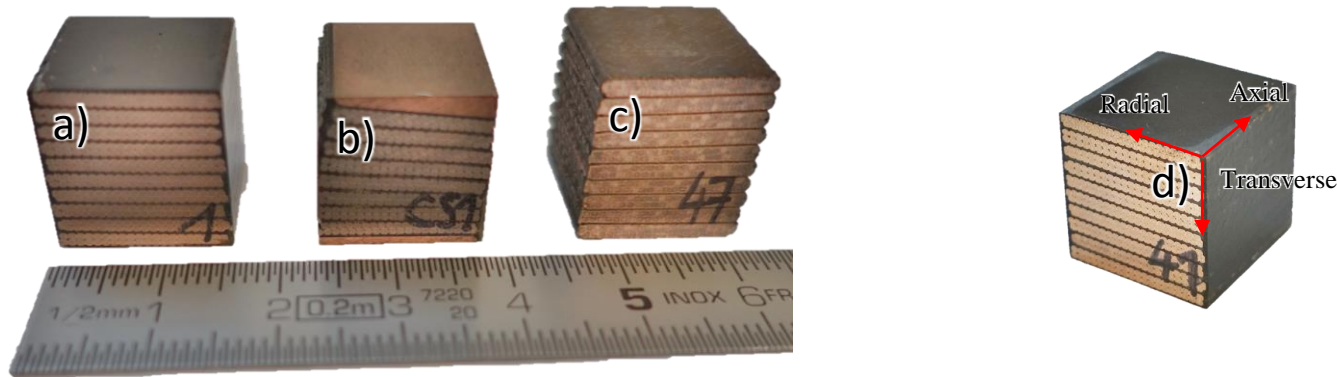


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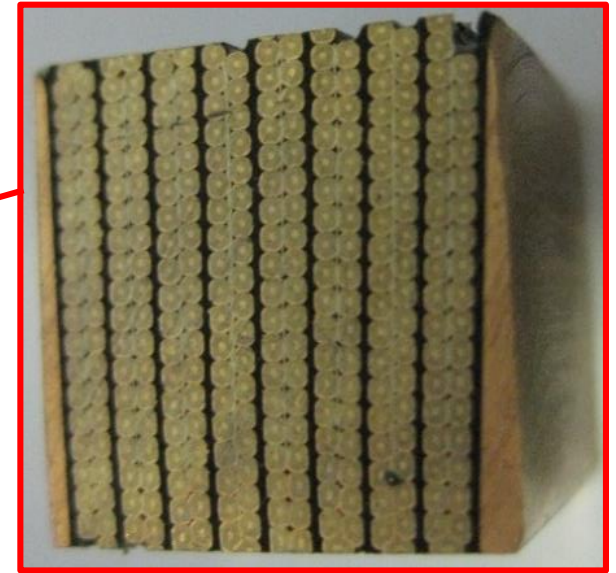
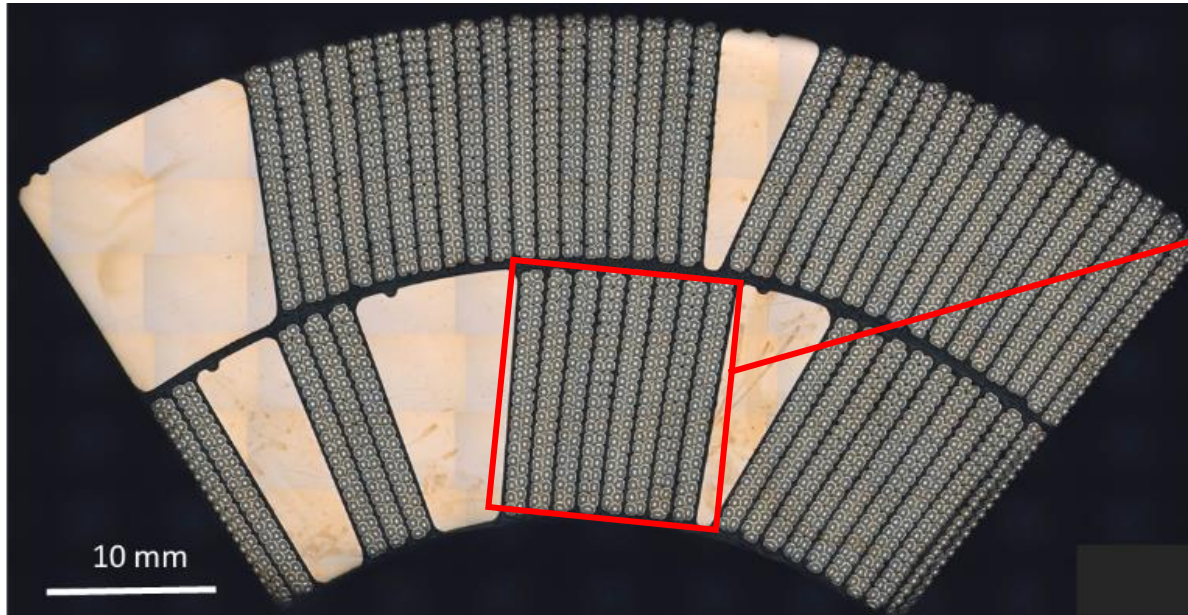
# The samples

- All samples are made of Nb<sub>3</sub>Sn 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.



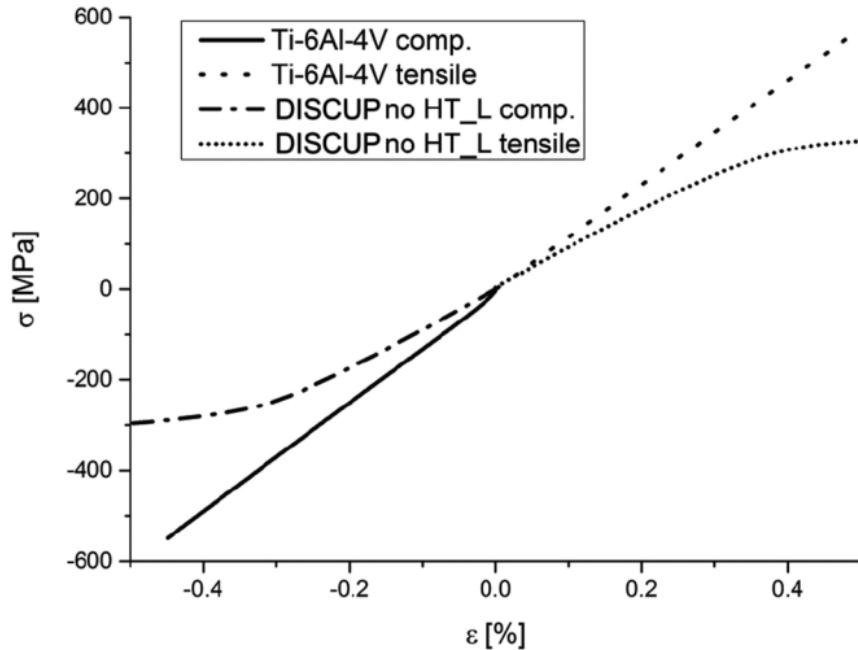
*Nb<sub>3</sub>Sn Rutherford cable sample types: (a) ten-stack, (b) 11 T dipole coil segment and (c) non impregnated ten-stack (d) Sample orientations.*

# 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  $\times$  8mm  $\times$  30mm
- Clip on extensometer with 25 mm gauge length

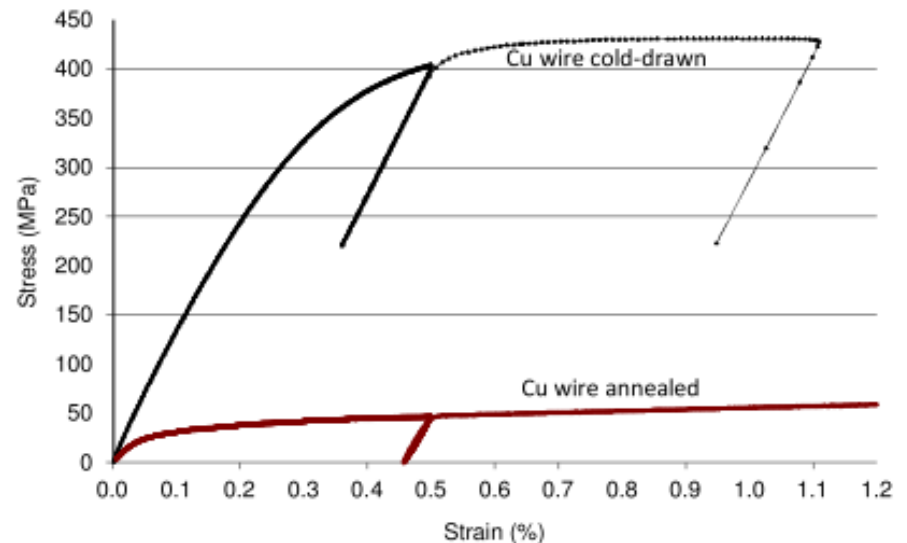
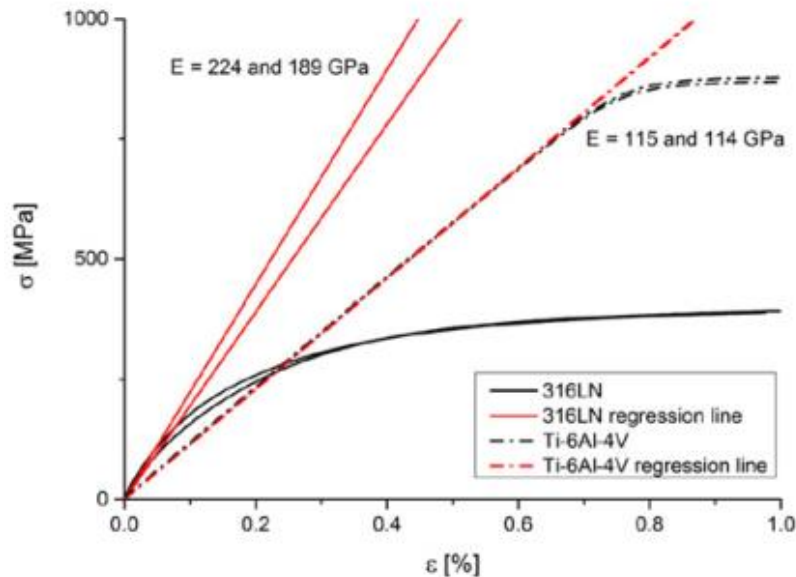
## Compression tests

- Cylinder sample  $\varnothing$  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].*

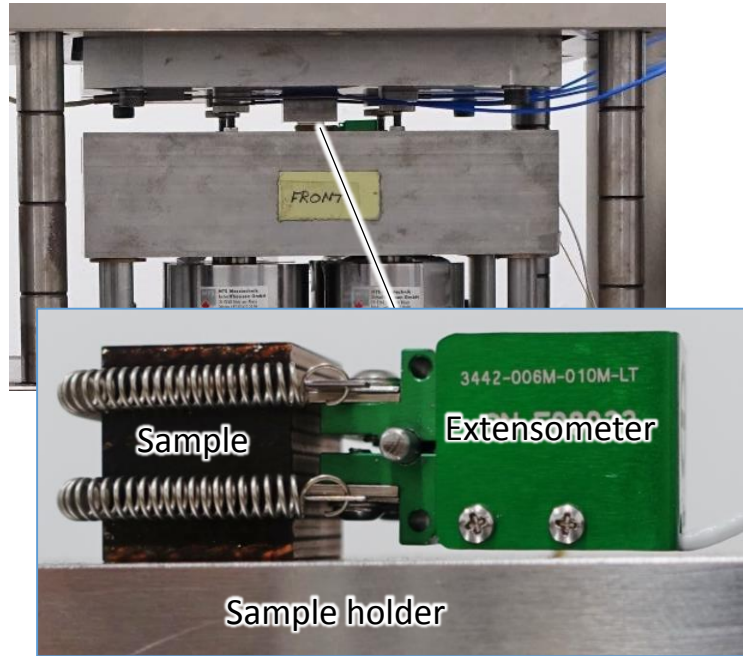
[1] IEEE Trans. Appl. Supercond., 27(4), (2017), 4003007

# Test parameters for ten-stack sample compression tests

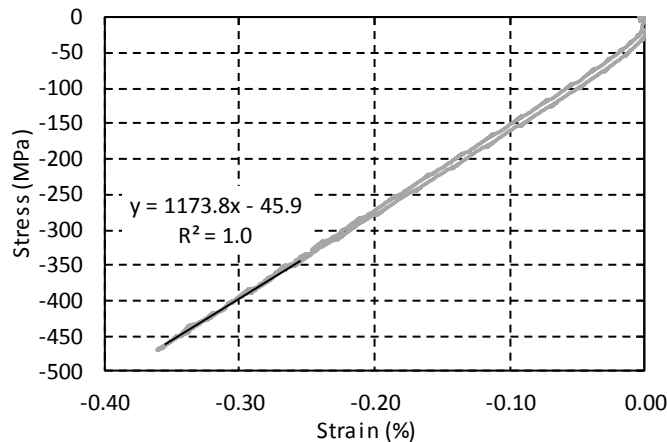
- Two different setups have been used for compressive stress-strain measurements.
- The sample strain in load direction was directly measured with calibrated clip-on extensometers.
- Load plateaus were kept constant for one hour/
- Load rate between plateaus was 50 N/s.
- Stiffness is defined as the 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.



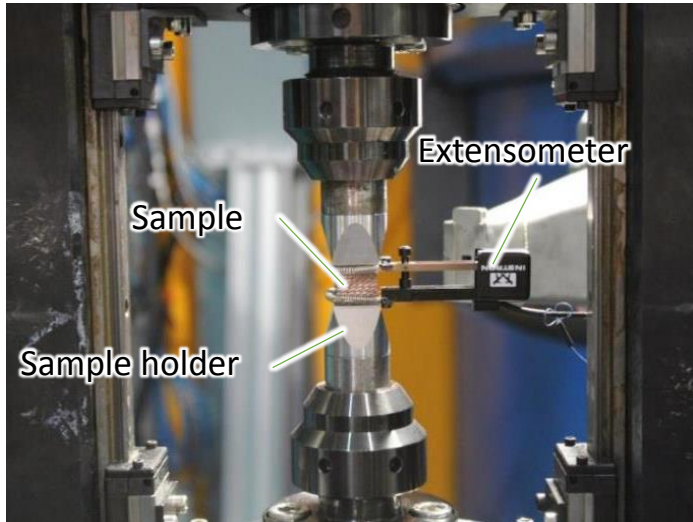
Reference measurement Ti-6Al-4V

- 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]

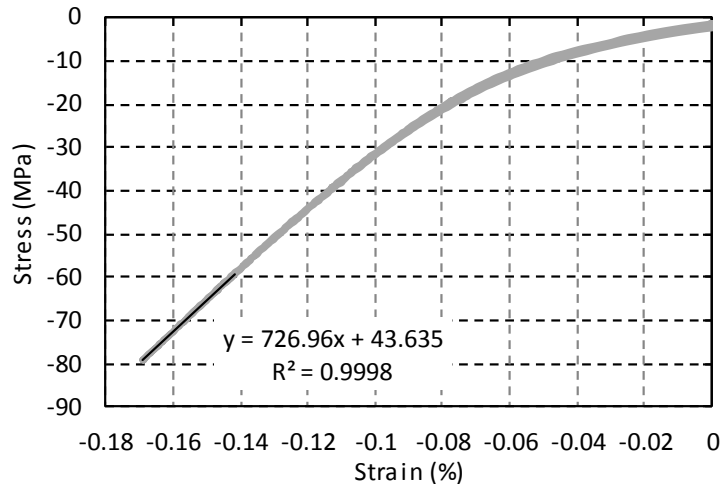
[1] IEEE Trans. Appl. Supercond., 27(4), (2017), 4003007



# 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.*

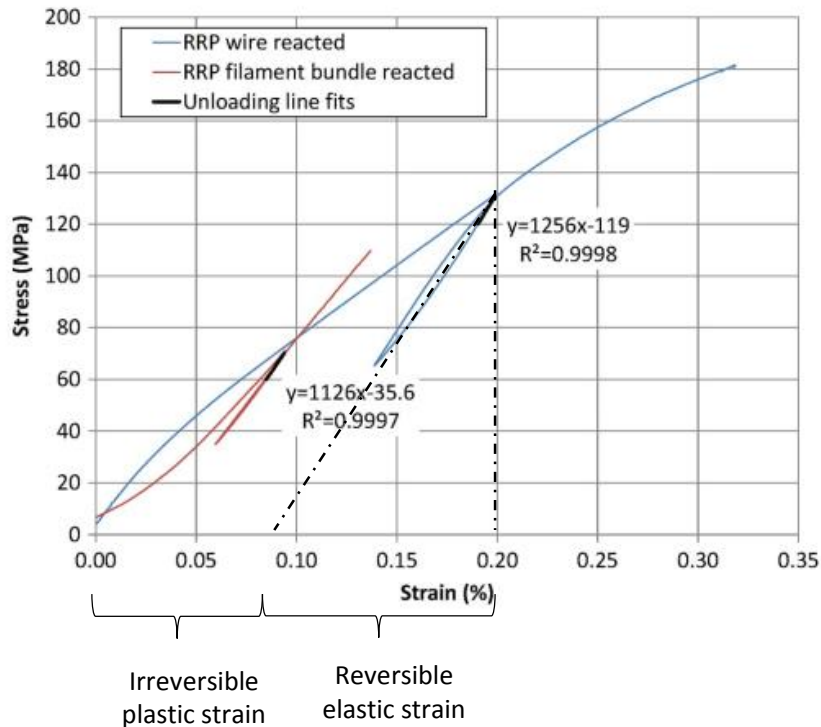


*Reference measurement Al7075*

- 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 $\text{Nb}_3\text{Sn}$ 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)

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

$$V_i = A_i / A$$

$E_f$ ... Young's modulus fibre (strand)

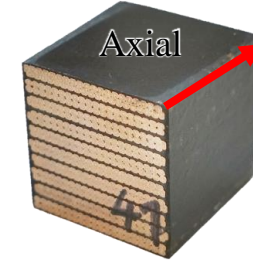
$V_f$ ... Volume fraction fibre

$E_m$ ... Young's modulus matrix (epoxy impregnation)

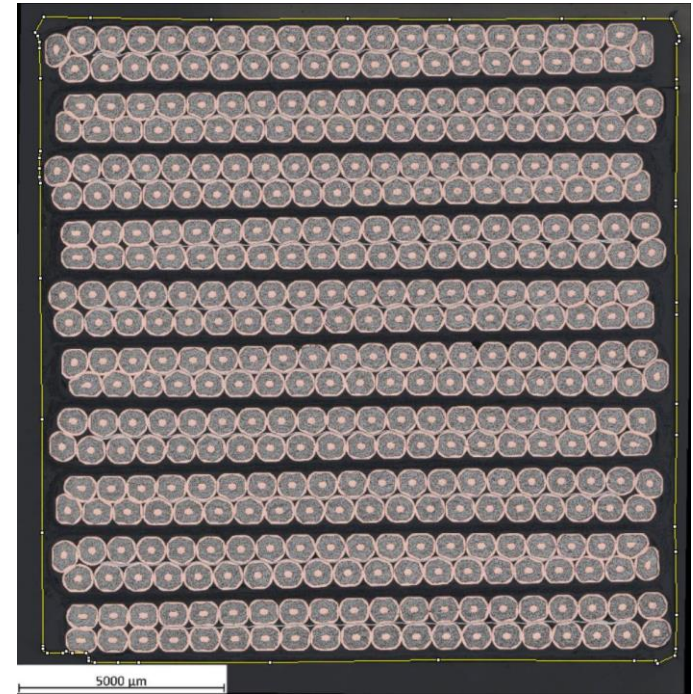
$V_m$ ... Volume fraction matrix

$$E_f = E_{\text{strand}} = 126 \text{ GPa} \quad [3]$$

$$E_m = E_{\text{CDT } 101K} = 3.8 \text{ GPa}$$



Definition of axial sample orientation



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

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

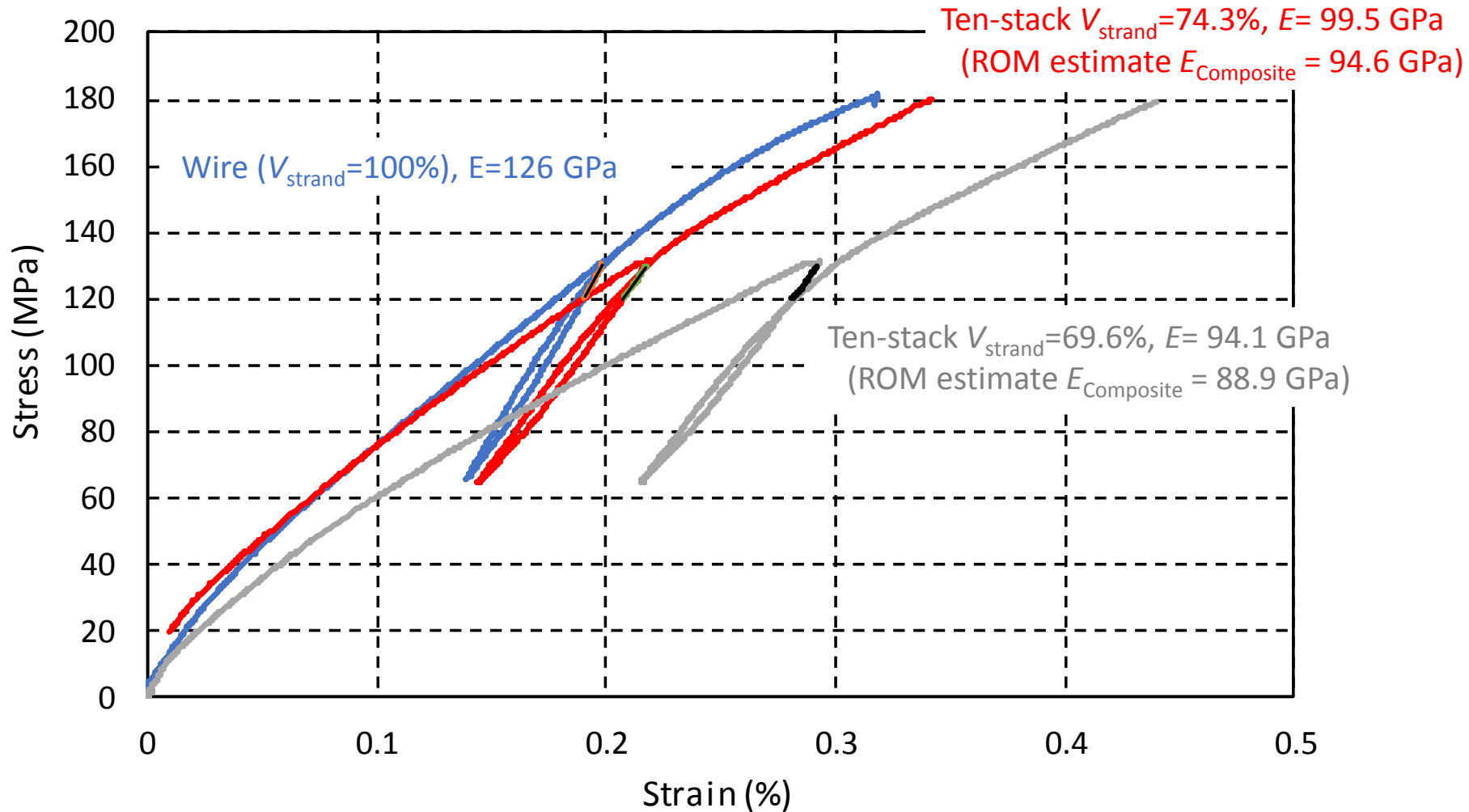
\* Determined with image analysis with a Zeiss Axio Imager optical microscope. Courtesy M. Crouvizier, EN-MME

\*\* Determined with contact measurement

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

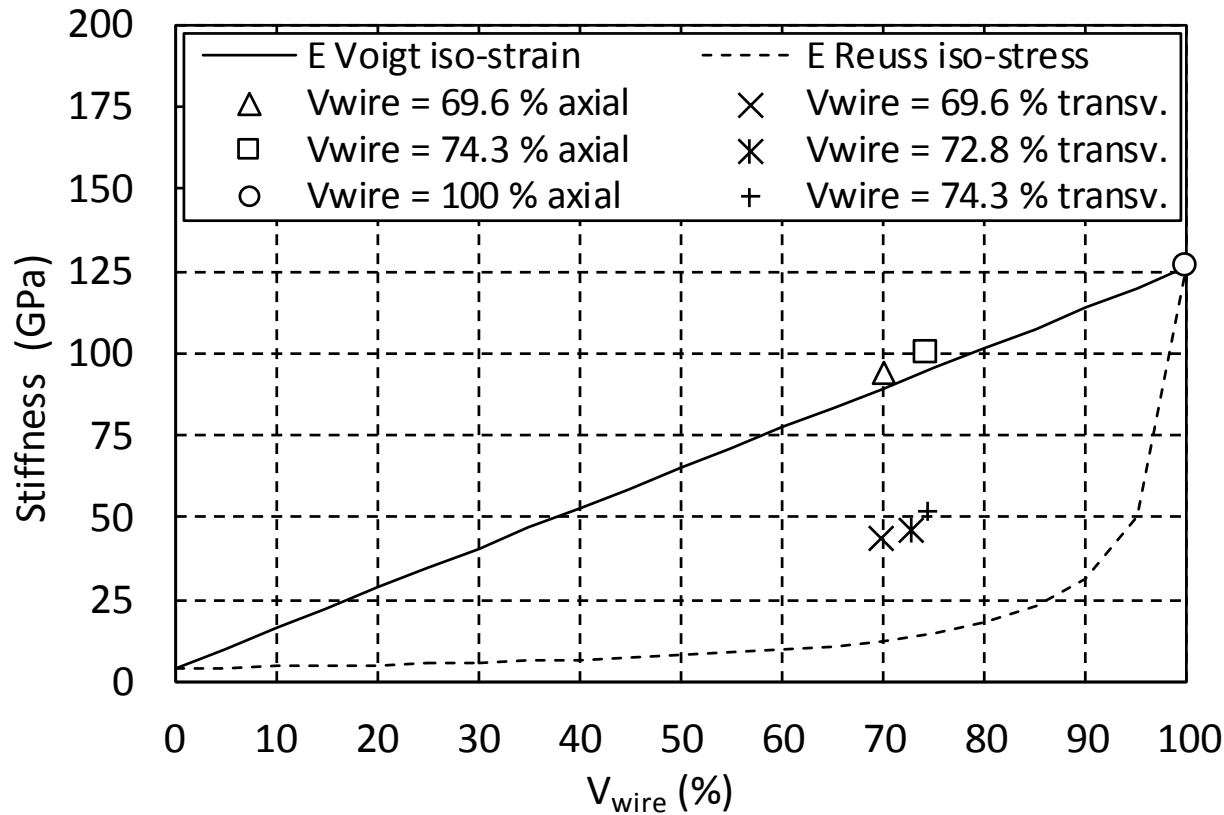
[4] *Mechanics of composite materials*, Taylor and Francis, 1999

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



Comparison of stress-strain curves of  $\text{Nb}_3\text{Sn}$  wire (axial tension) and ten-stack samples (axial compression).

# Stiffness comparison between experiment and rule of mixture estimation



- Iso-strain condition

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

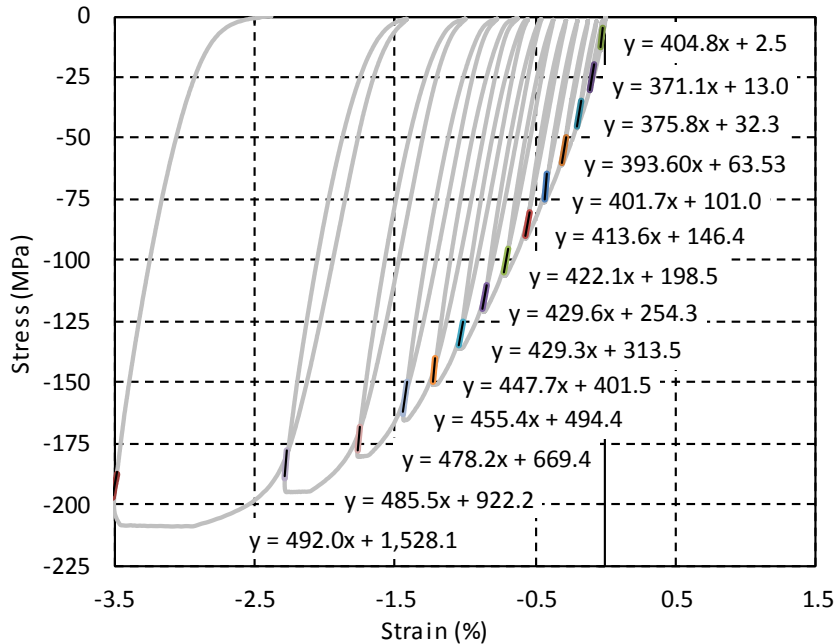
- Iso-stress condition

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

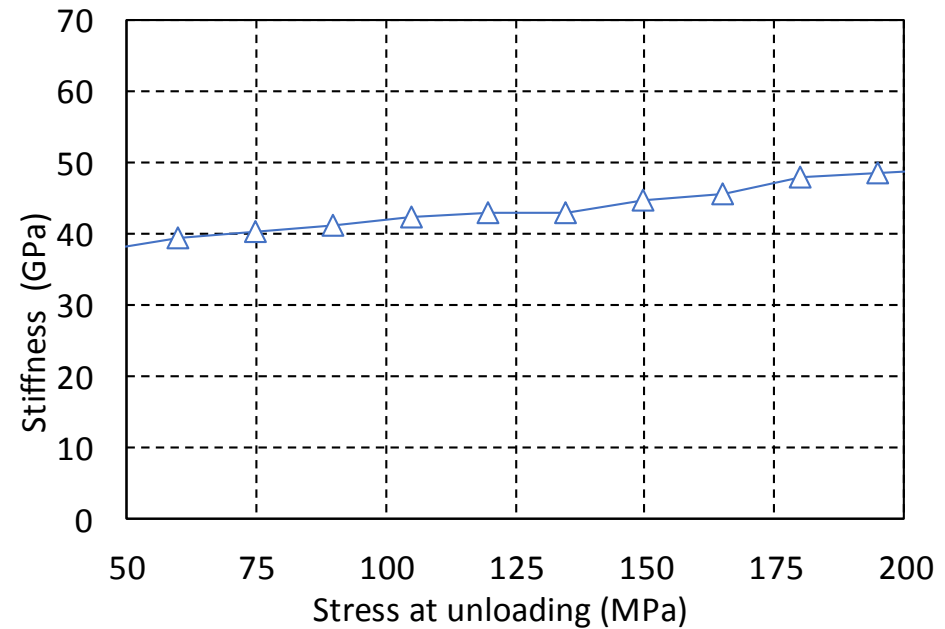
*Stiffness estimation of the axial and transverse compression with stiffness dependence on  $V_{\text{wire}}$  and comparison with experiment.*

# 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.

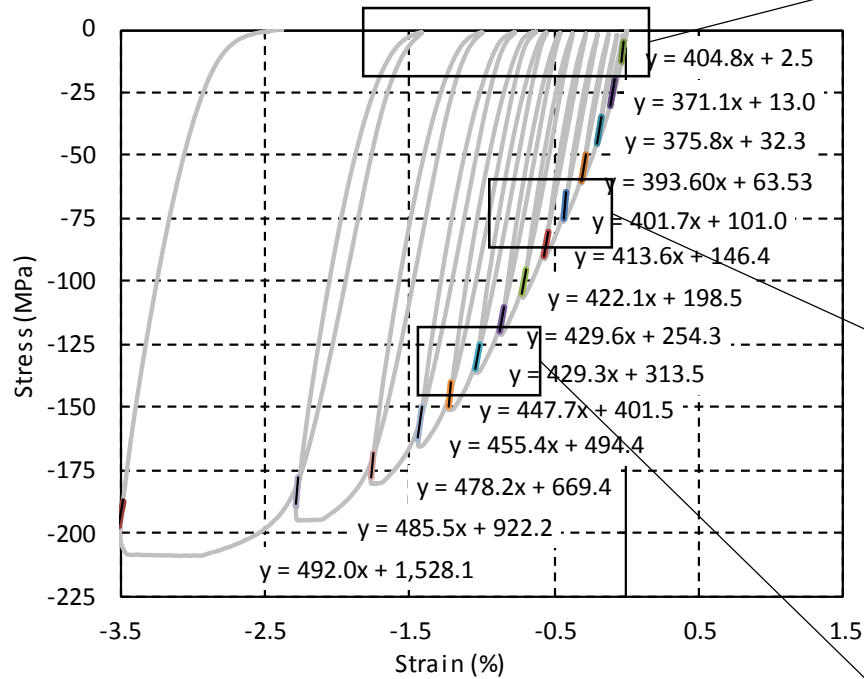


*Transverse compressive stress-strain curve of the ten-stack sample ( $V_{strand}=69.6\%$ ).*

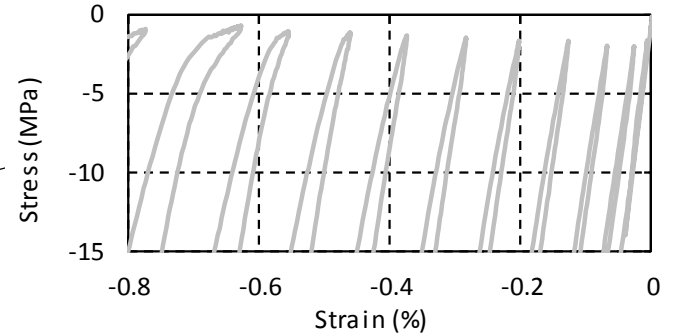


*Transverse compressive stiffness at different unloading stress levels of a ten stack.*

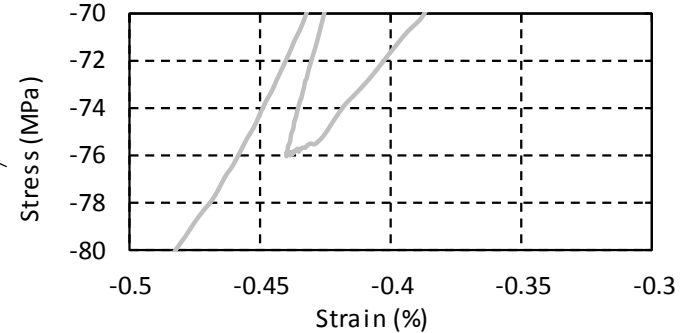
# Indications for creep behaviour of a free standing ten-stack



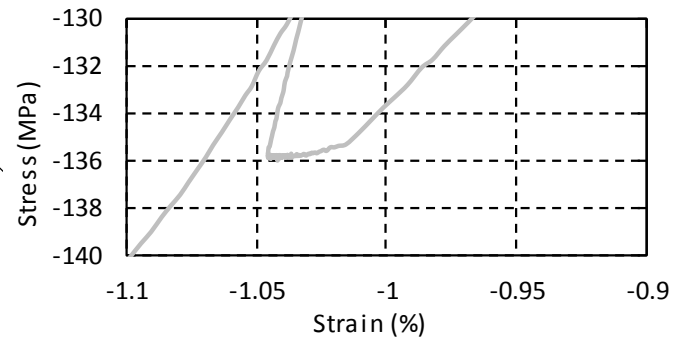
Transverse compressive stress-strain curve of the ten-stack sample ( $V_{strand}=69.6\%$ ).



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



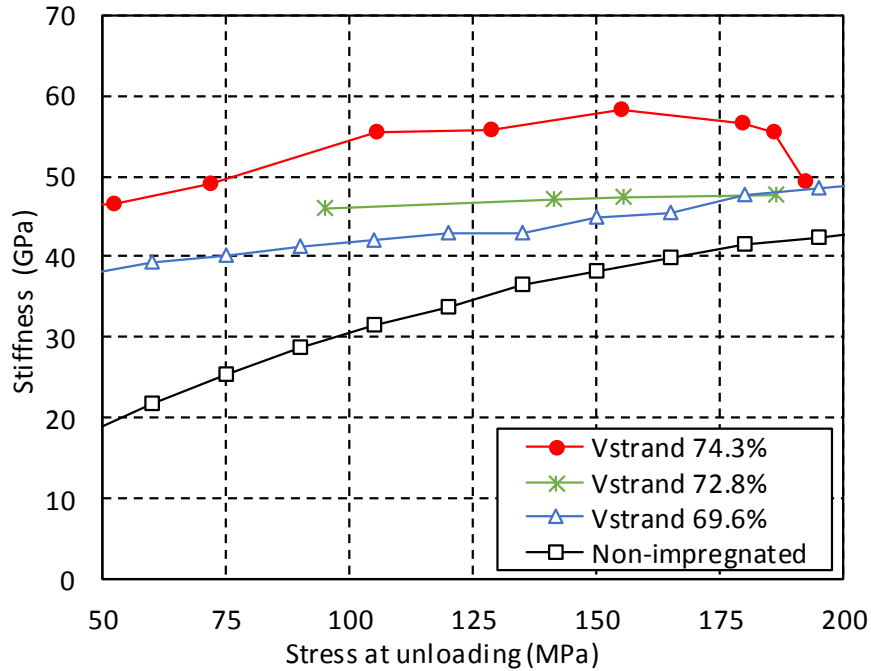
Small displacement at constant load



Increased displacement at constant load



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

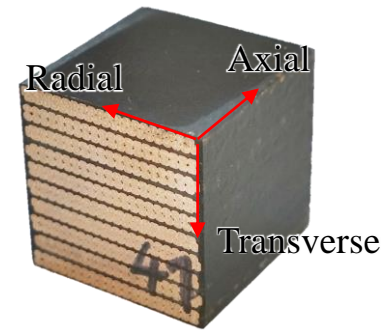
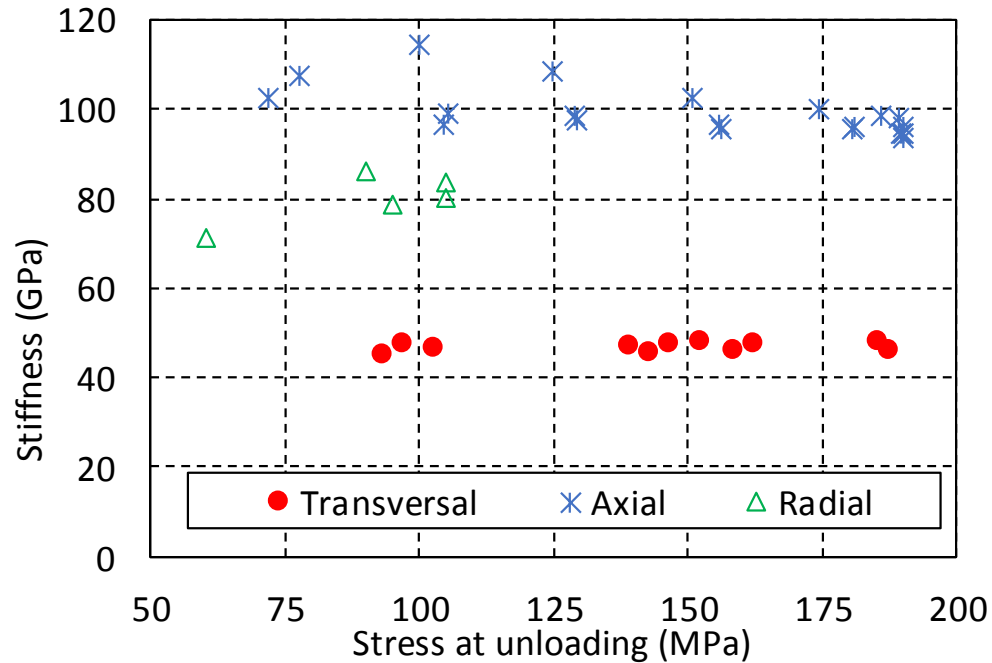


*Transverse stiffness of ten-stack samples with different epoxy volume fraction at different unloading levels*

- 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)

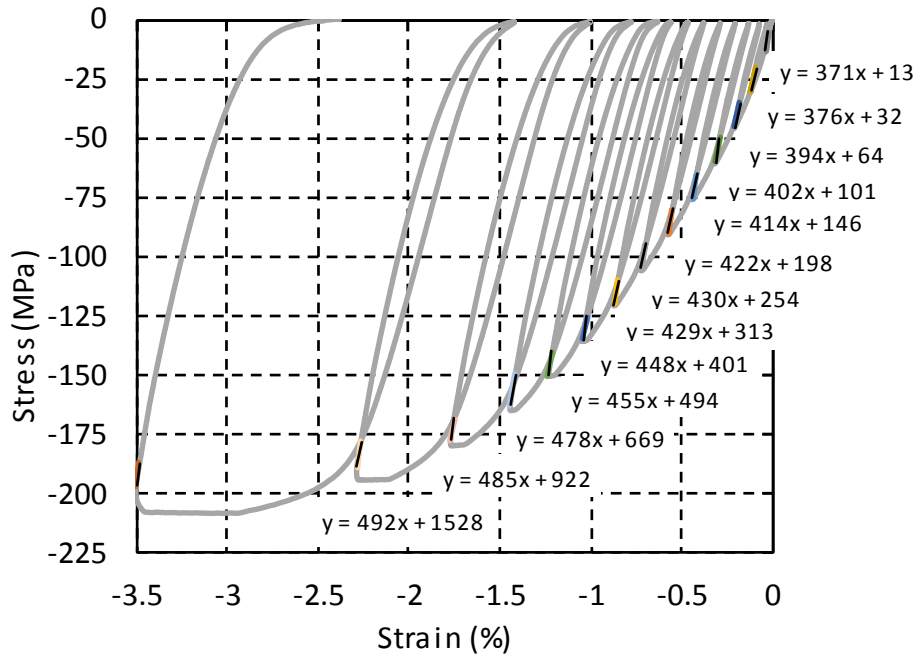


Sample orientation

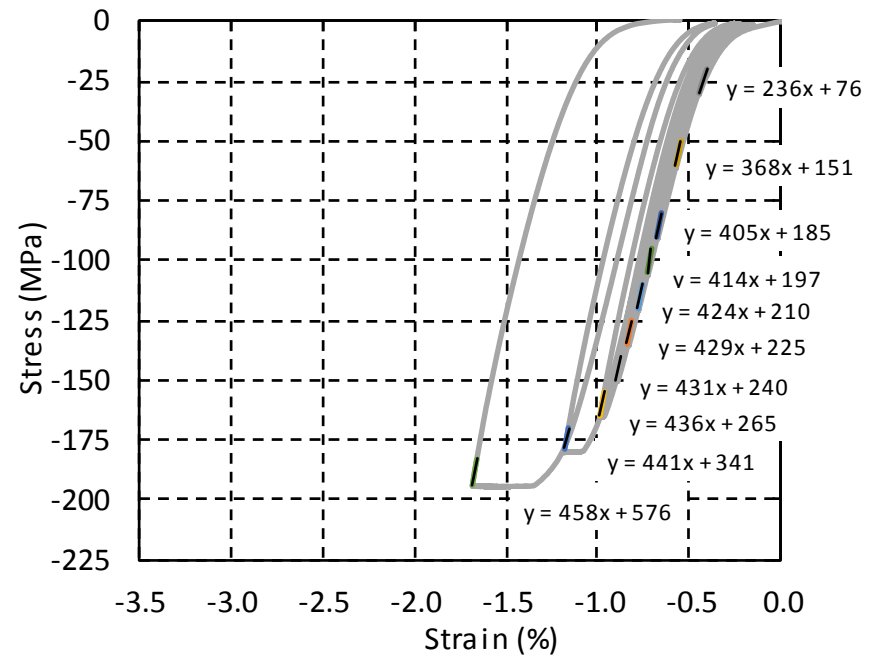
*Stiffness in different load directions of a ten stack  
( $V_{strand}=72.8\%$ )*

- Stiffness is strongly dependent to the load direction
- Axial stiffness is  $2 \times$  transverse stiffness
- Radial stiffness is  $1.3 \times$  transverse stiffness

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

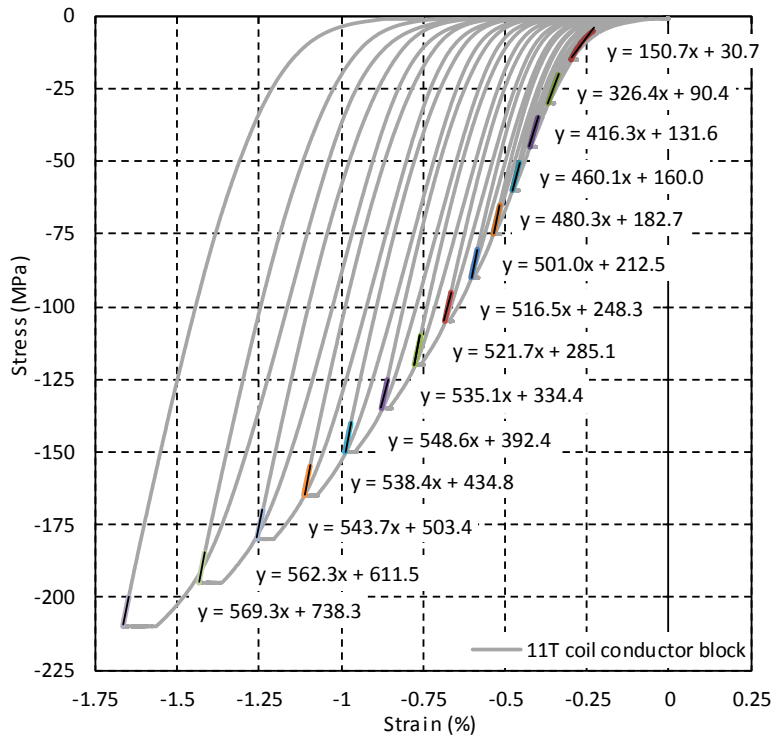


Transverse compressive stress-strain curve of the ten-stack sample ( $V_{strand}=69.6\%$ ) (first loaded).



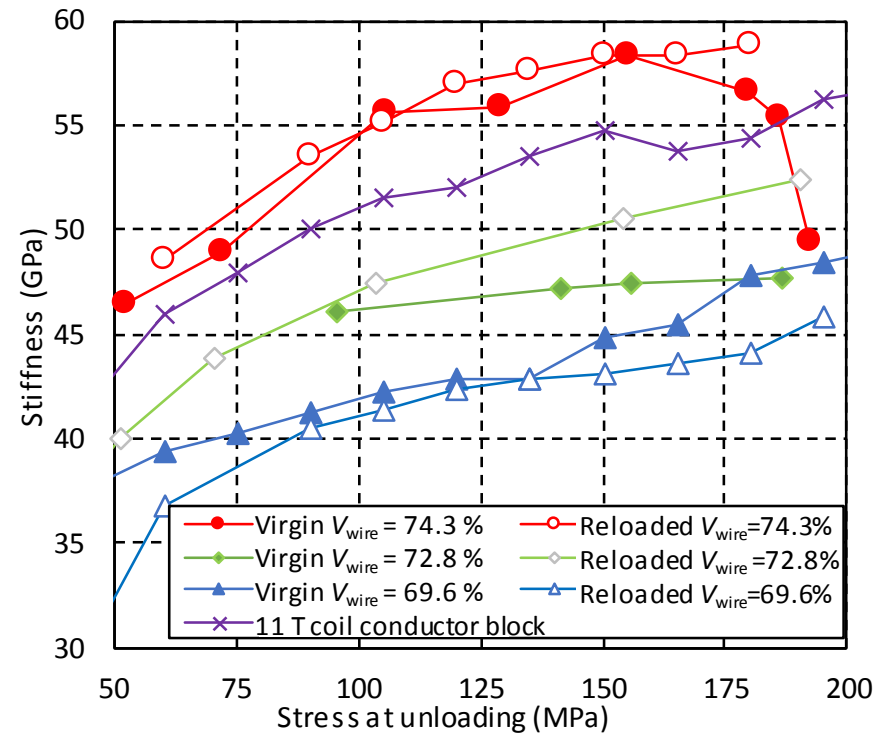
Transverse compressive stress-strain curve of the ten-stack sample ( $V_{strand}=69.6\%$ ) (reloaded).

# Comparison of ten-stack and 11 T coil segment stiffness



*Transverse compressive stress strain measurement of 11 T dipole coil segment*

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



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

- Stiffness is depended to the unloading stress

# Conclusion I

- Good agreement of the stiffness results for identical Nb<sub>3</sub>Sn 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  $2 \times$  transverse stiffness, radial stiffness is  $1.3 \times$  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<sub>3</sub>Sn magnet constituent materials”, IEEE Trans. Appl. Supercond., vol. 27, no. 4, Jun. 2017, Art. no. 4003007.
- [2] Metals Handbook, Vol.2 - Properties and Selection: Nonferrous Alloys and Special-Purpose Materials, ASM International 10th Ed. 1990.
- [3] C. Scheuerlein, B. Fedelich, P. Alknes, G. Arnau, R. Bjoerstad, and B. Bordini, “Elastic anisotropy in multifilament Nb<sub>3</sub>Sn superconducting wires”, IEEE Trans. Appl. Supercond., vol. 25, no. 3, Jun. 2015, Art. no. 8400605.
- [4] Robert M. Jones, “Mechanics of composite materials”, Second edition, Taylor and Francis, Inc. London 1999