Mechanical characterisation of Nb3Sn impregnated coils – Compression properties

Initial results

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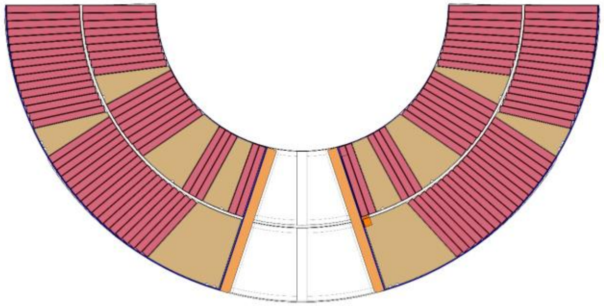
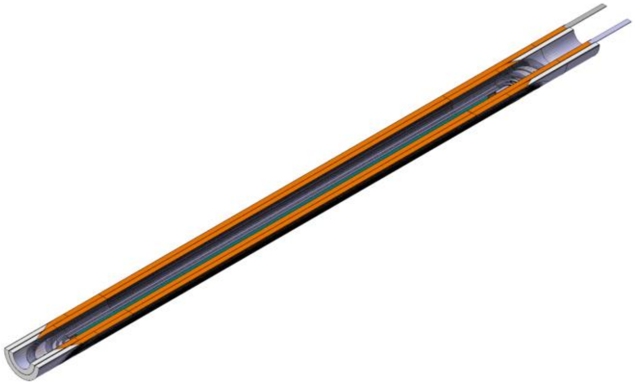
Contents

1. Introduction

- The measurement of the mechanical properties of the 11T magnet coils are necessary for the correct optimisation and control of the stresses induced in the coil during assembly, and operating stage.
- The stress in the coil shall not exceed the non-reversible degradation limit at any point.
- During collaring, coils are compressed within the collar assembly, which leads to high stresses in the mid-plane.
- During powering, Lorentz forces tend to compress the coil against the mid-plane. For this reason, the collars and pole shall keep a level or azimuthal compression, known as pre-stress, with the aim of maintaining the contact between the coil and the collar and poles.



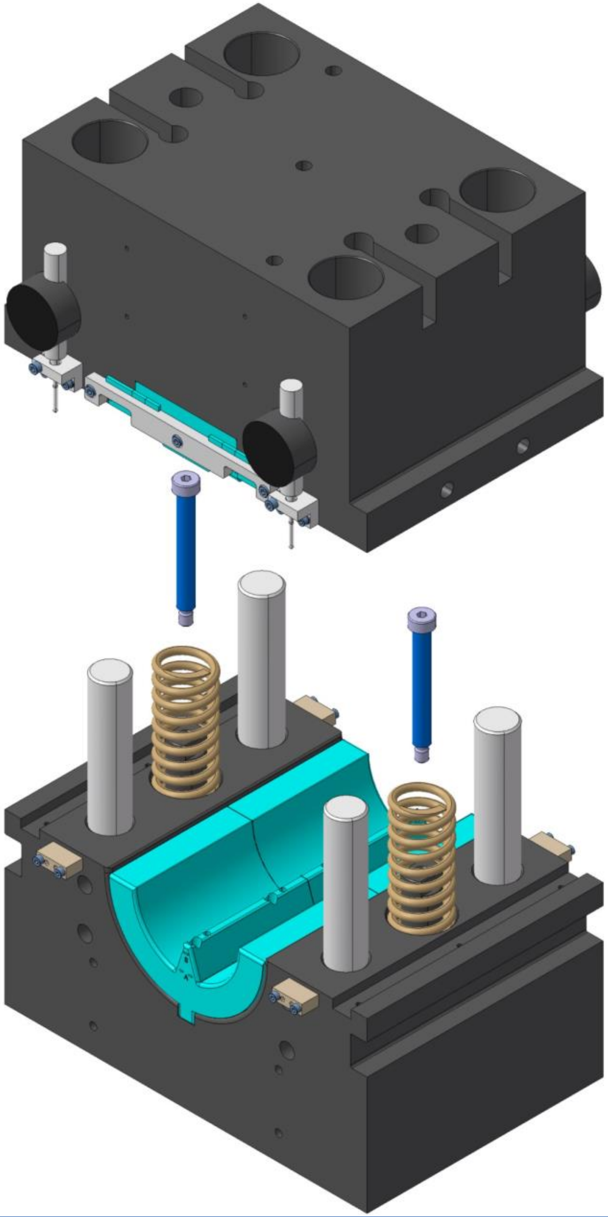


1. Introduction

In order to measure the compression properties of the 11T coils, a series of modifications of an existing press (used to measure MQXC coils) have been implemented.

Main Objectives:

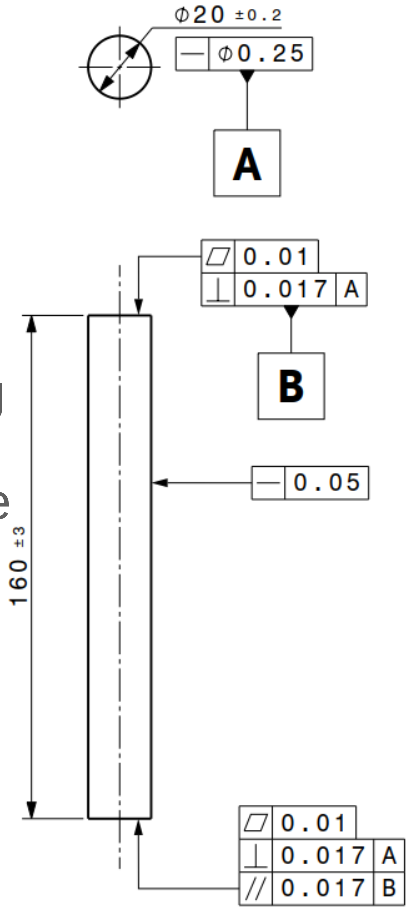
- Characterisation of the mechanical behaviour in the azimuthal direction. Measurement of the stiffness of the composite structure.
- Back-calculation of the equivalent stiffness of a cable block.
- Validation of 10 stack measurements, FE and analytical models.
- Determination of the nominal size of the coil to reach the required azimuthal pre-stress.
- Experimental verification of the shim sizes.



2. Experimental – Material properties

Material properties

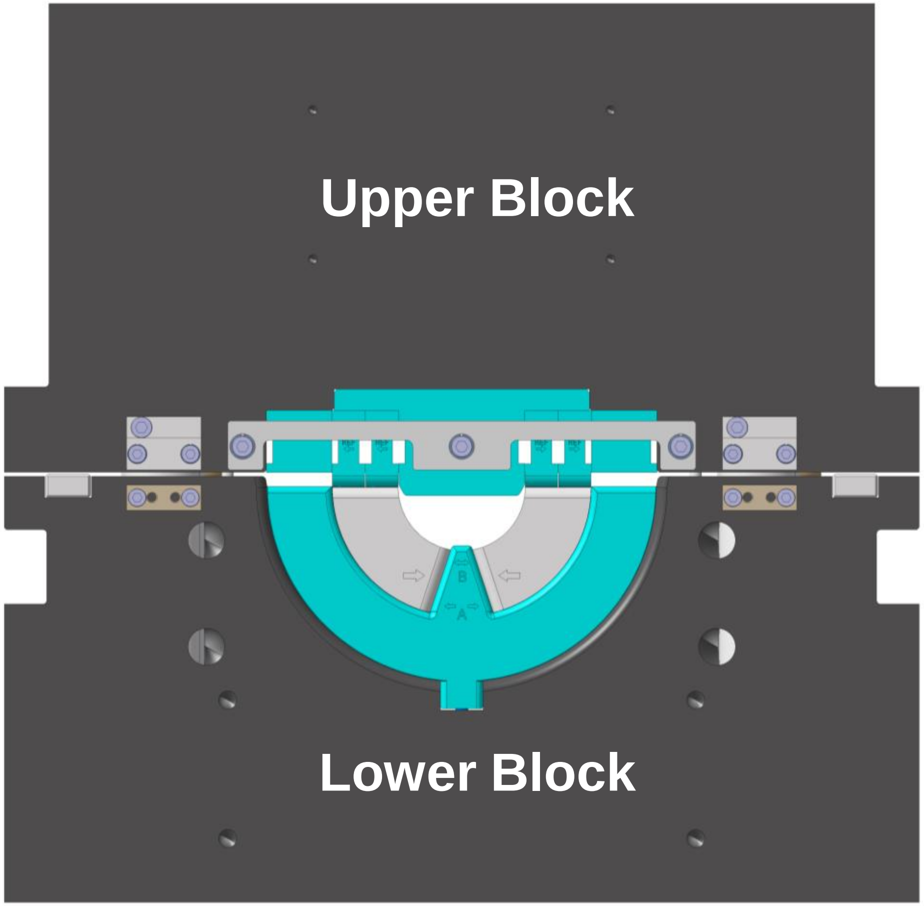
- Characterisation of the Young's modulus in compression of the two materials used for the different parts of the E-modulus press: **1.4104** and **EN AW-6082 T651**
- Tests carried out in a tensile-compression testing machine, equipped with a 200 kN load cell and video-extensometer, according to **ASTM E9**. Determination of Young's modulus based on a straight line fitted to the data in a given stress range by the method of least squares calculated, according to **ASTM E111**.
- Five samples per each material.

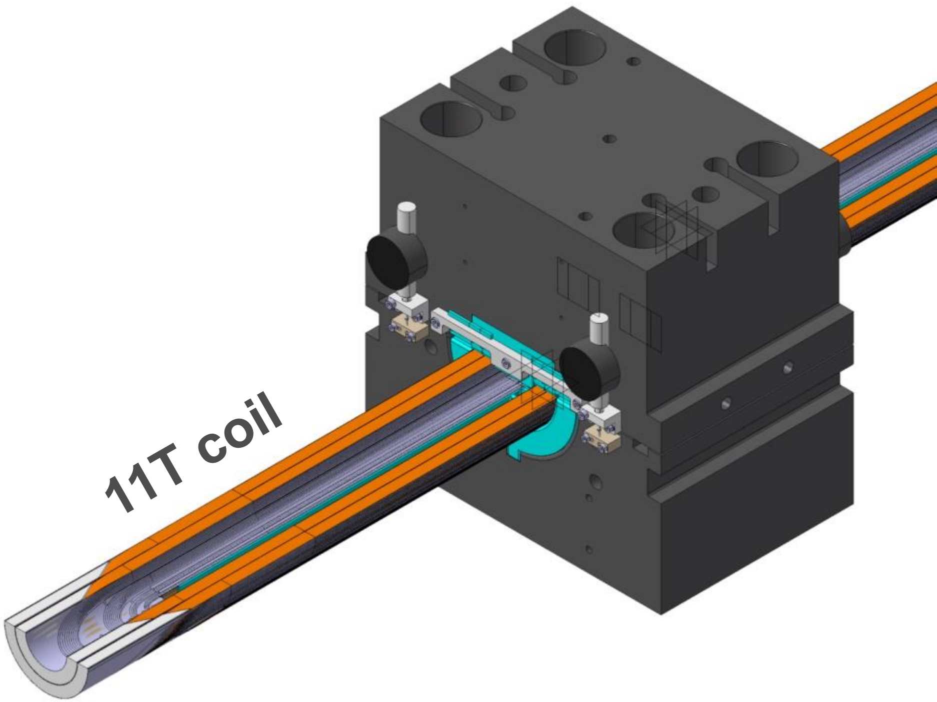


[1]Standard, A. S. T. M. "E9-09." Standard Test Methods of Compression Testing of Metallic Materials at Room Temperature. ASTM International (2009).
[2]Standard, A. S. T. M. "E111–04. ", Standard Test Method for Young's Modulus, Tangent Modulus, and Chord Modulus. ASTM International (2010).

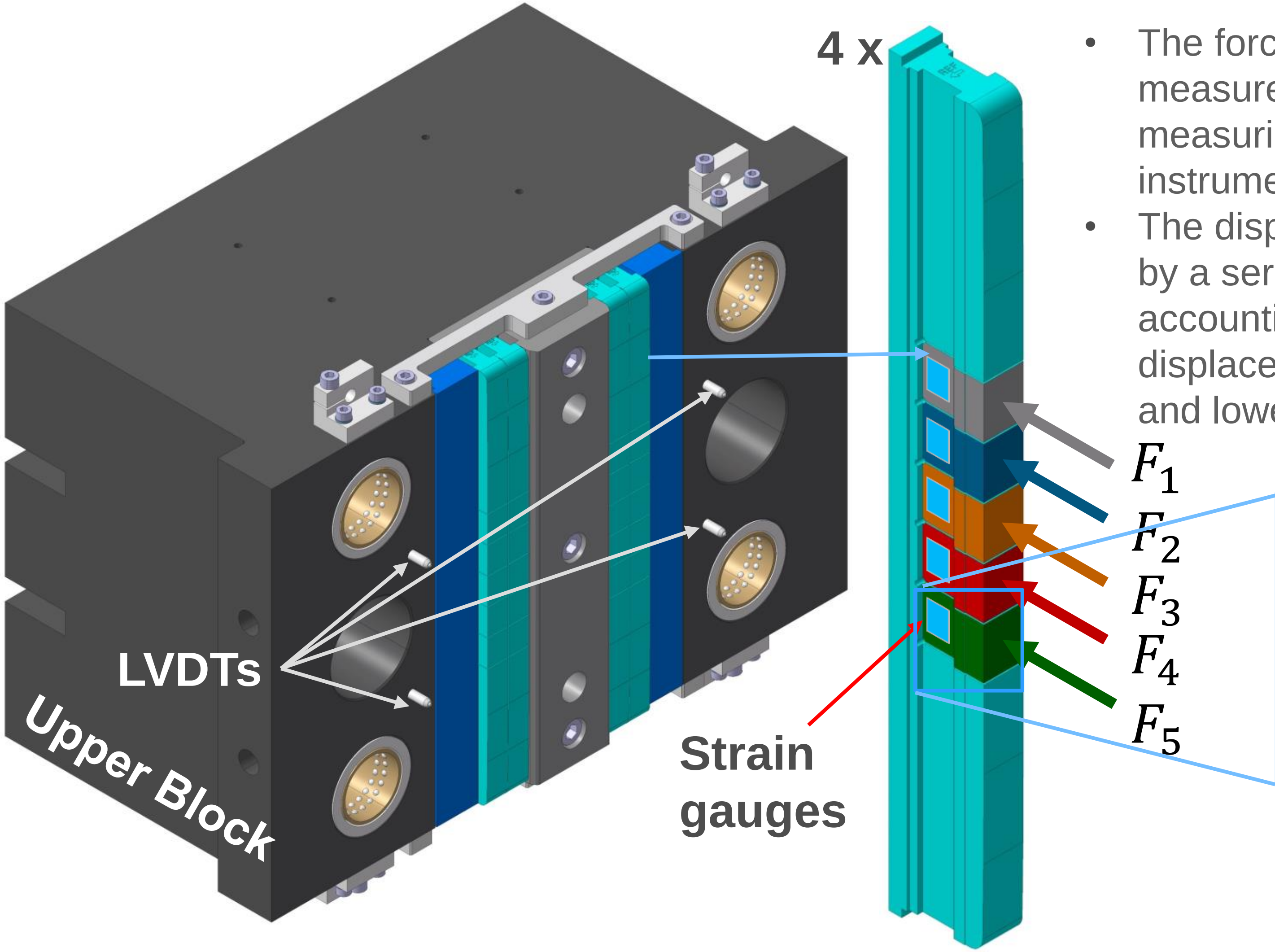
2. Experimental – E-modulus press

E-modulus press – Principles





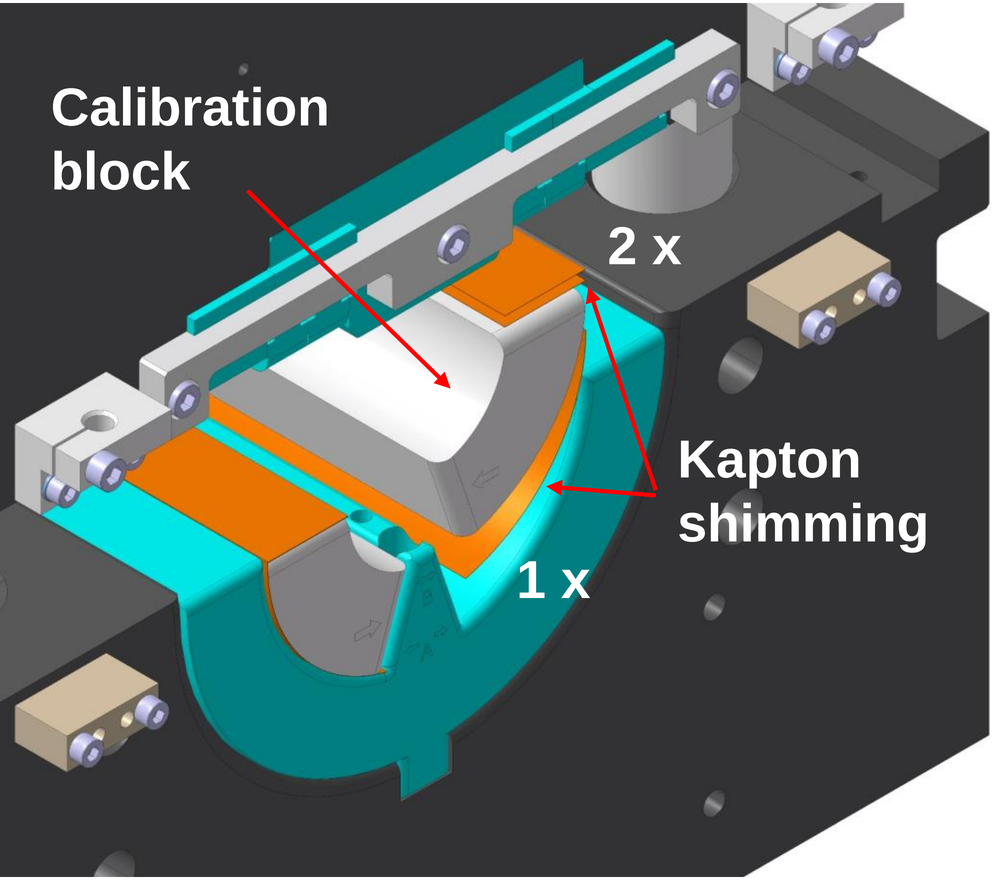
2. Experimental – E-modulus press



- The force induced in the coil is measured by four segmented measuring bars, symmetrically instrumented by strain gauges.
- The displacement is measured by a series of LVDTs accounting for the relative displacement between the top and lower blocks of the press.

$$F_i = \int_A p \, dA$$

2. Experimental – E-modulus press



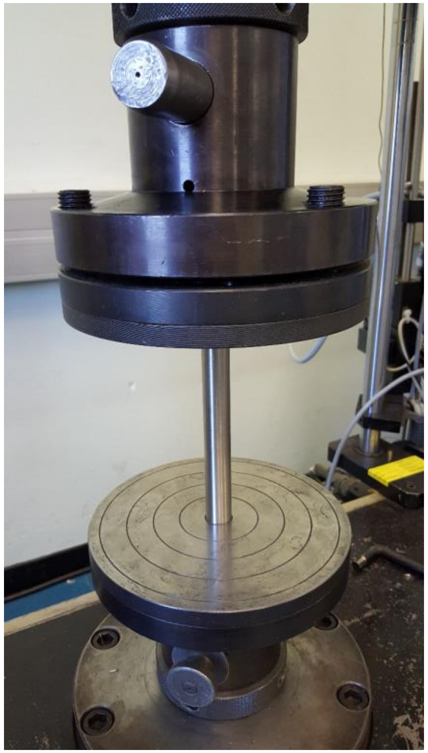
Experimental Test

- Place Kapton shimming.
- Place calibration/test specimens on the Main Pole.
- Adjustment of the upper block until it is almost in contact with the calibration/test blocks.
- Compression until reaching target values on the force measured by the measuring bars. An initial compression cycle is carried out in order to accommodate the blocks.
- The compression rate along the region of interest is 0.6 ± 0.02 mm·min^{-1}.

2. Experimental – E-modulus press

Compliance correction

- Contrary to a standard compression test[1], boundary conditions of the calibration/test blocks, and configuration of the E-modulus press prevent the theoretical curve to be analytically obtained.
- Theoretical curves, to be compared to measurements, are exported from an FE 3D model.

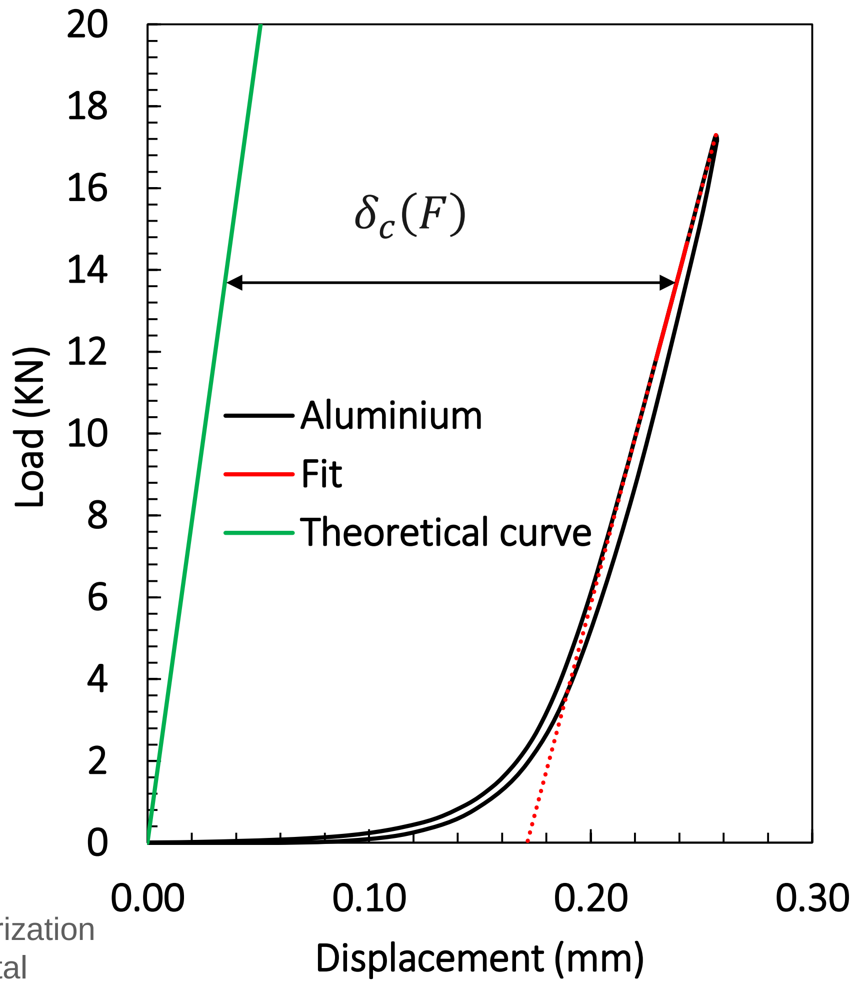


[1]Standard, A. S. T. M. "E9-09." Standard Test Methods of Compression Testing of Metallic Materials at Room Temperature. ASTM International (2009).

2. Experimental – E-modulus press

Compliance correction

- Assuming that the compliance is constant or directly proportional to the force leads to obvious errors.
- Compliance shall be considered as a non-linear function of the Force.
- Correction function to be computed as the difference between the measured curve and the theoretical curve[1].

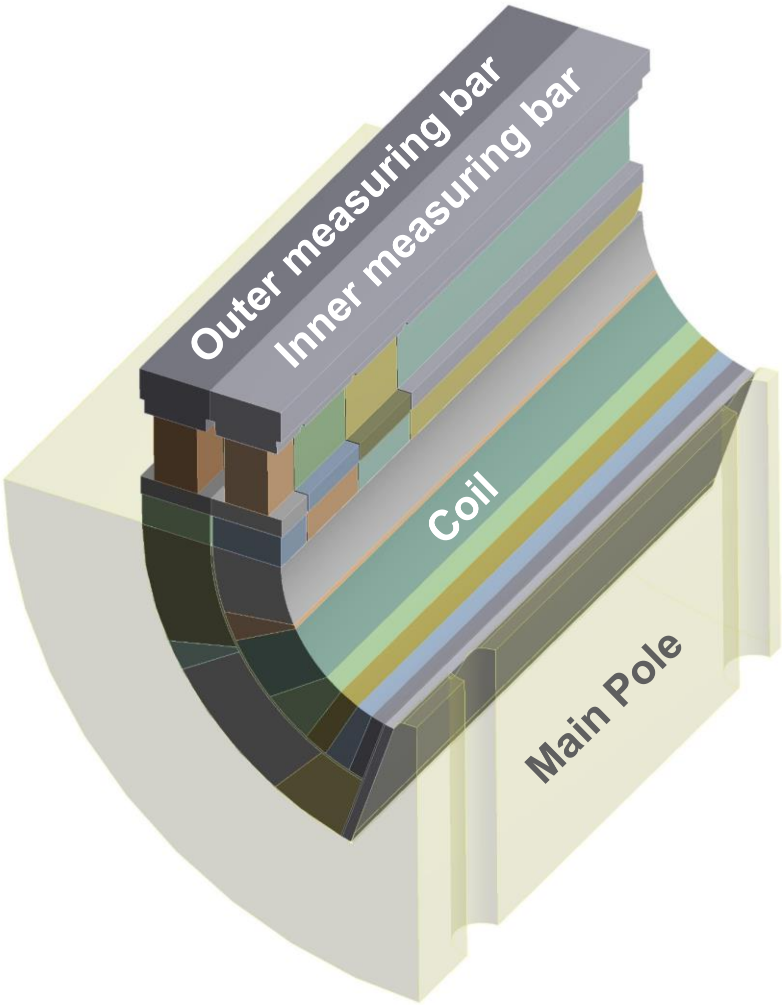


[1]Kalidindi, S. R., A. Abusafieh, and E. El-Danaf. "Accurate characterization of machine compliance for simple compression testing." Experimental mechanics 37.2 (1997): 210-215.

2. Experimental – E-modulus press

FE models

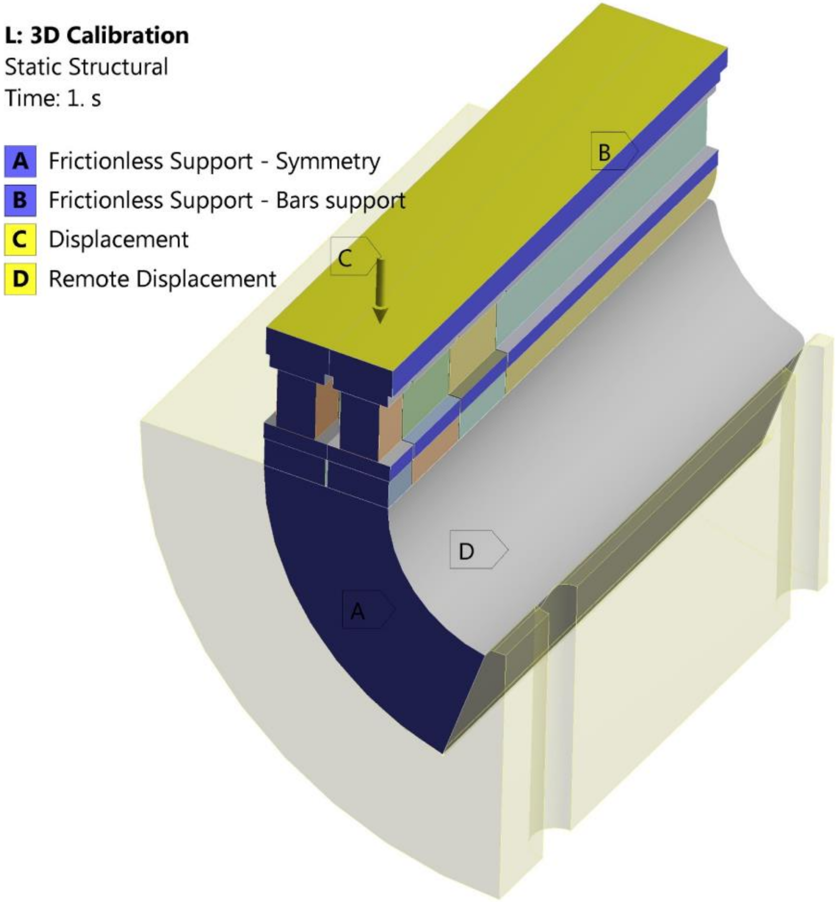
- The models consists of four main parts: coil, inner measuring bar, outer measuring bar and main pole.
- The model was conceived as multi-body, meshed with 3-D elements (SOLID186).
- The stiffness behaviour of bars and coil was set to flexible, while the main pole behaviour was considered as rigid.
- Isotropic elasticity has been considered for flexible bodies.

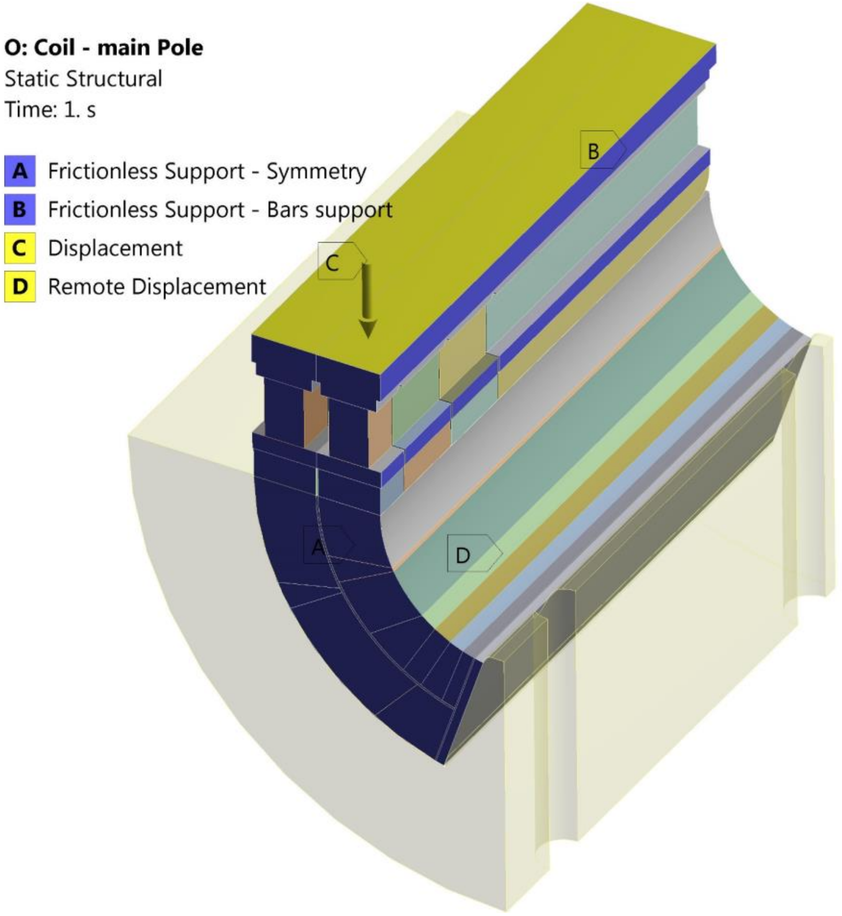


* Wedges material properties from: Scheuerlein, Christian, et al. "Mechanical Properties of the HL-LHC 11 T Nb 3 Sn Magnet Constituent Materials." *IEEE Transactions on Applied Superconductivity* 27.4 (2017): 1-7.

2. Experimental – E-modulus press

FE models – Boundary conditions

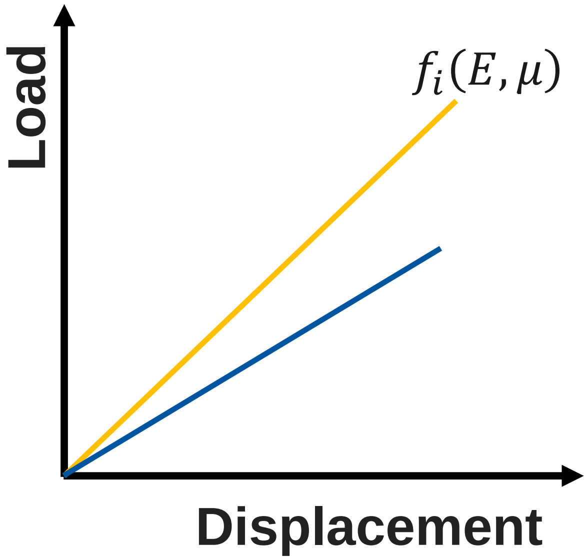


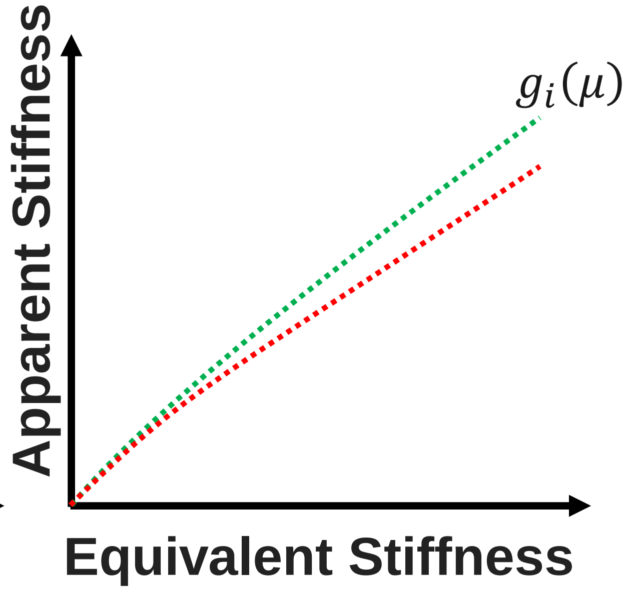


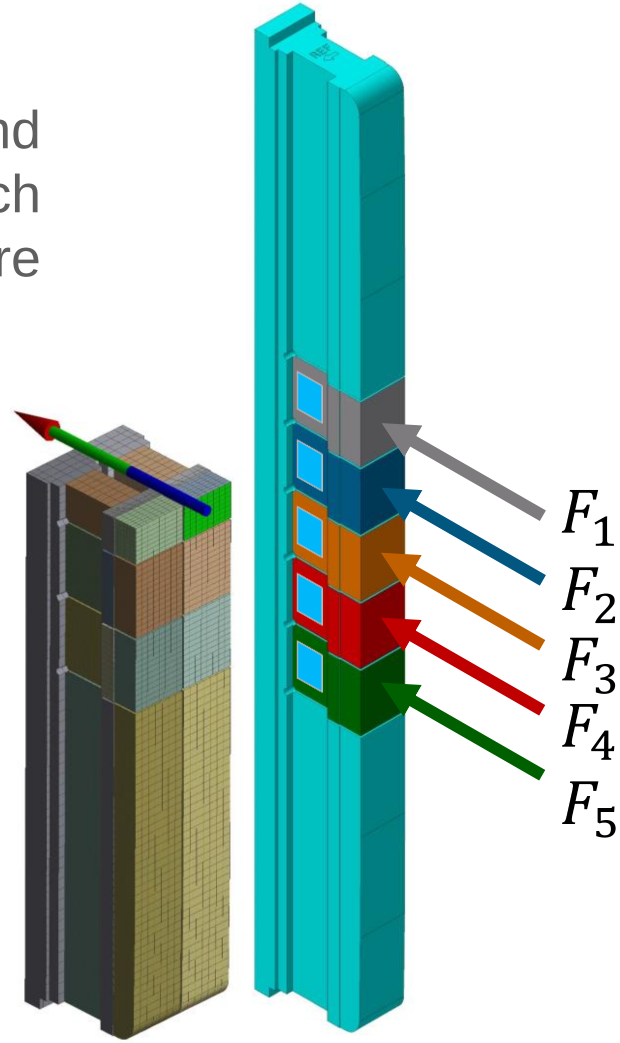
2. Experimental – E-modulus press

FE models – Analysis of results

From the FE model, reaction forces and displacements from the interface between each segment and the mid-plane of the block are exported.



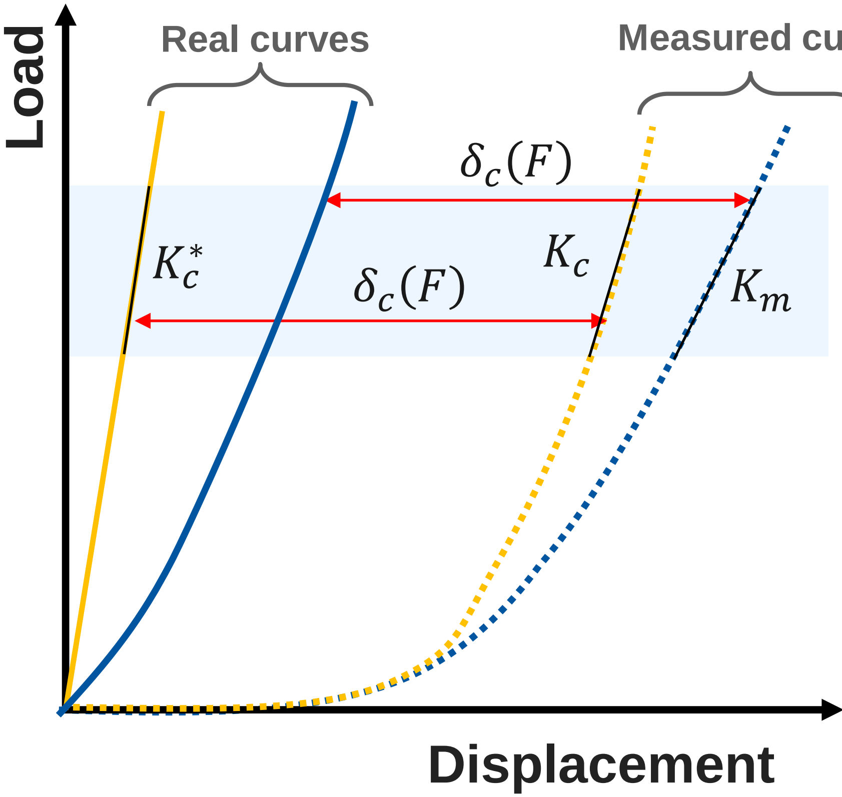


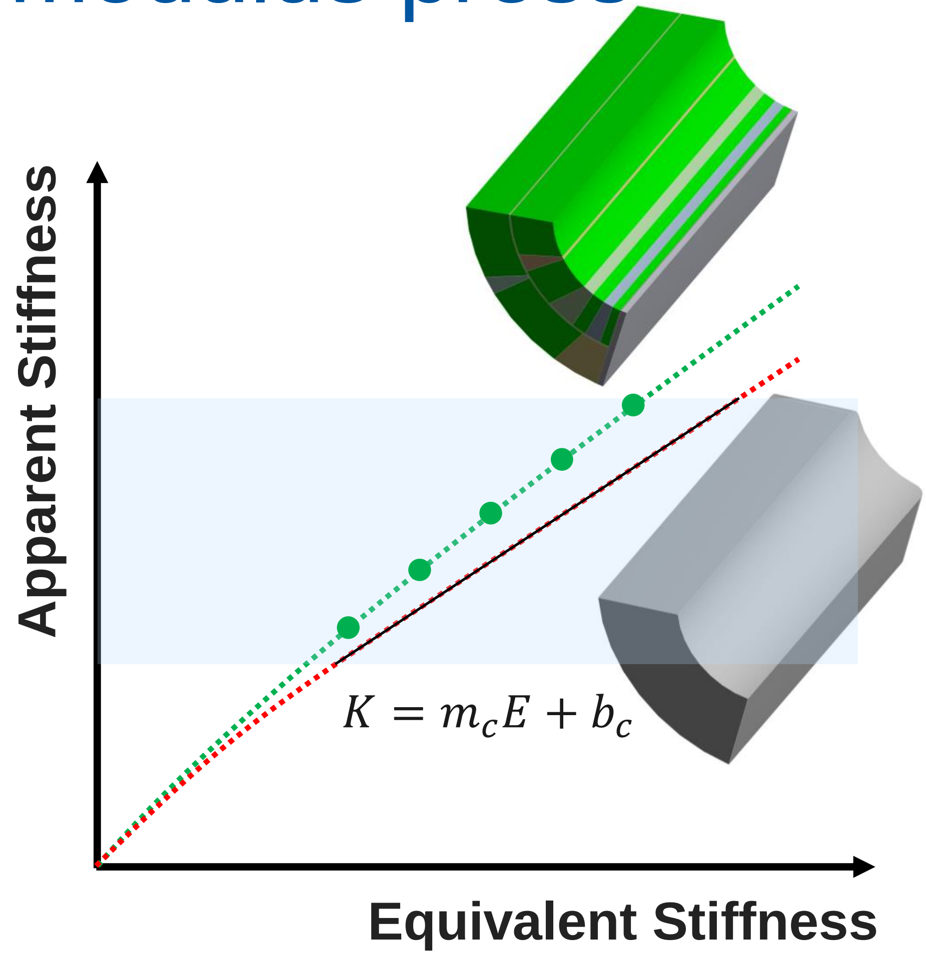


$$f_i \rightarrow [\bar{F}, \bar{\delta}] \qquad \bar{F}_i = \frac{\sum F_i}{n} \qquad \bar{\delta}_i = \frac{\sum \delta_i}{n}$$

2. Experimental – E-modulus press

Correction function

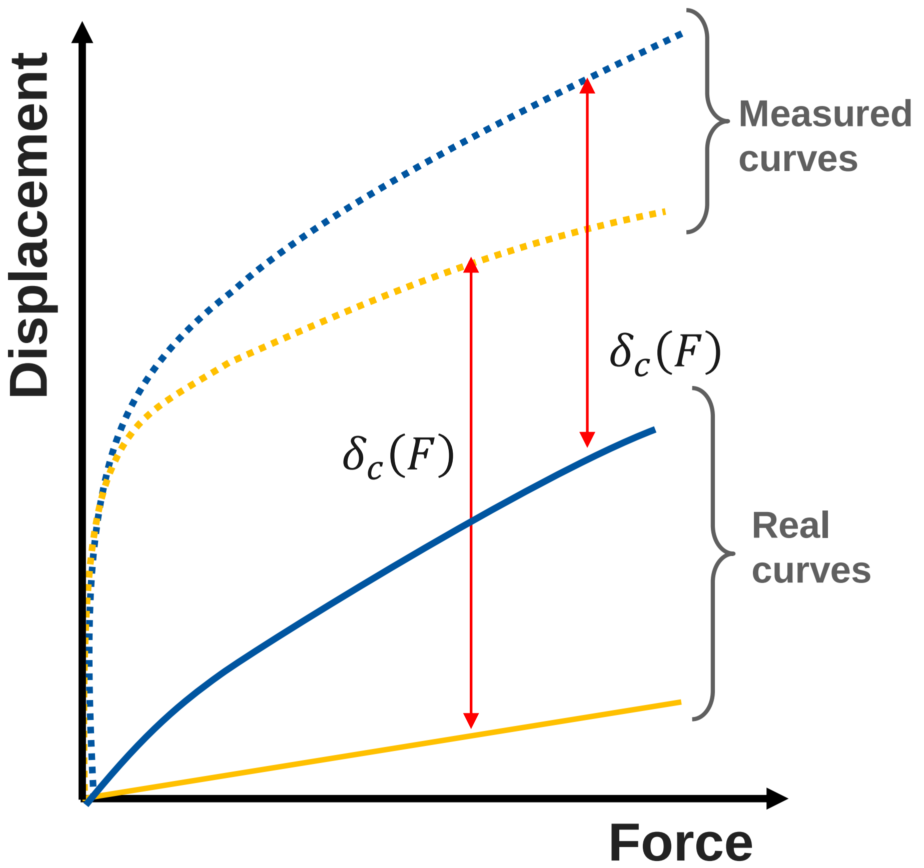


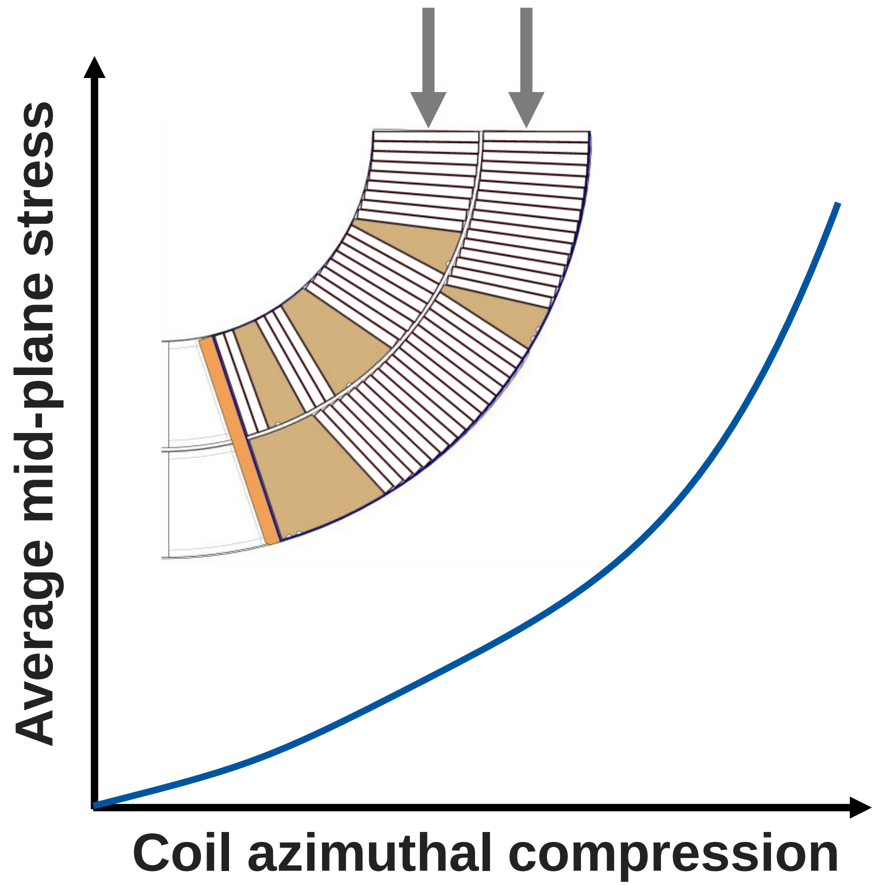


$$E_{corrected} = \frac{1}{m_c(\mu)}\left[\left(\frac{1}{K_m} - \frac{1}{K_c} + \frac{1}{K_c^*(\mu)}\right)^{-1} - b_c(\mu)\right]$$

2. Experimental – E-modulus press

Correction function – Mid-plane stress vs. Coil size

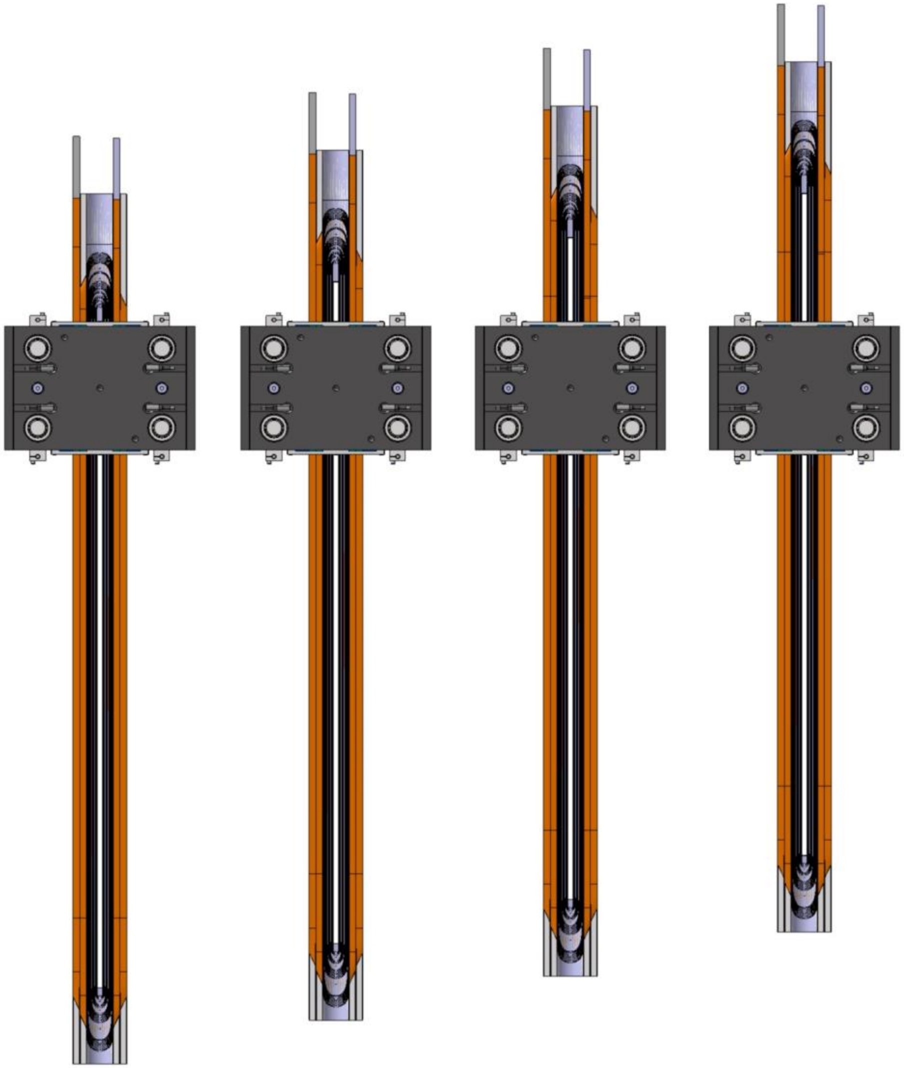




2. Experimental – E-modulus press

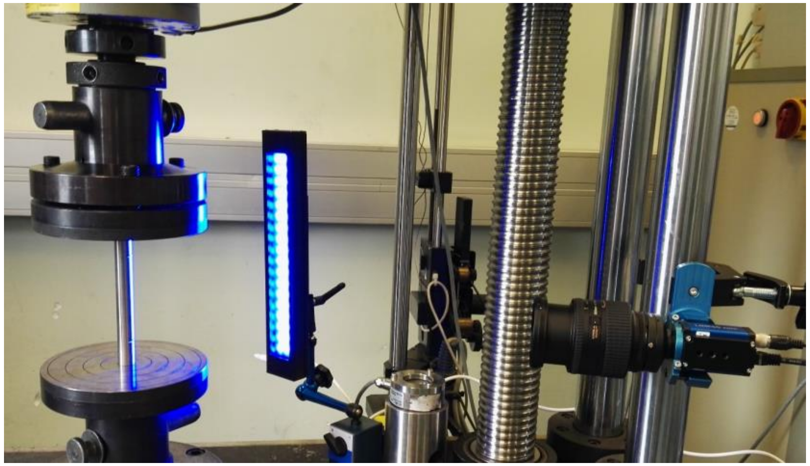
Testing – Measuring a coil

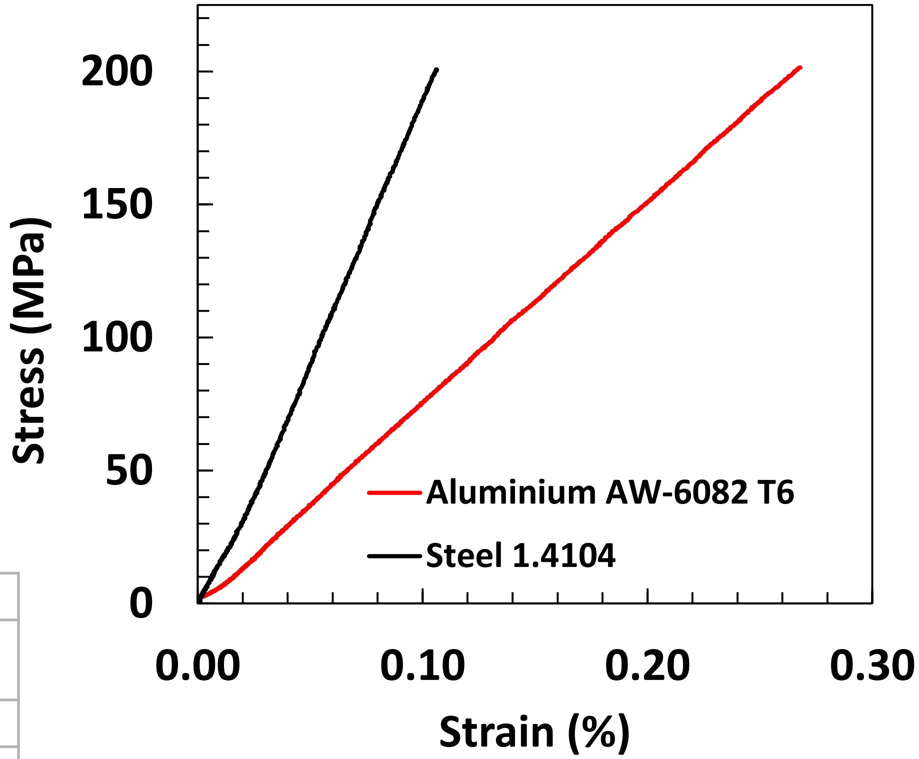
1. Test of calibration blocks (Steel coils have been chosen for this purpose). Three consecutive measurements are taken.
2. Test of coil. Three consecutive measurements are taken for each position. Measurements are taken every 100 mm along the axis of the coil.
3. After measuring the coil, the calibration blocks are measured again, three times consecutively. The final calibration curve is taken as the average of all measurements of calibration blocks.



3. Results and discussion

Material properties





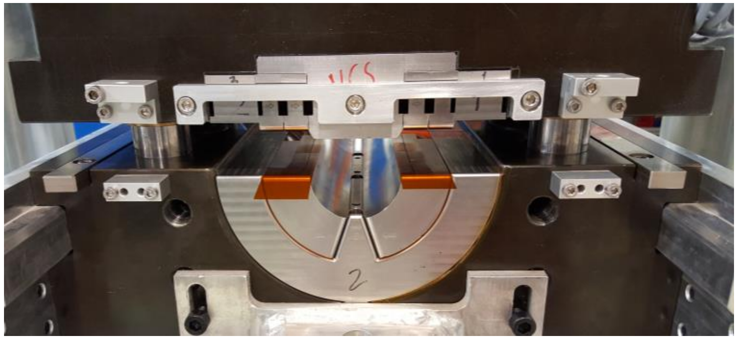
	Young's Modulus* - Loading (GPa)	
Material	**Average**	**SD**
Aluminium AW-6082 T6	75.9	1.4
Steel 1.4104	206.3	4.8

*Young's modulus based on a straight line fitted to the data between 60 and 80 MPa during the loading phase by the method of least squares, calculated according to **ASTM E111.**
Measurements by M. Crouvizier. EDMS 1802283

3. Results and discussion

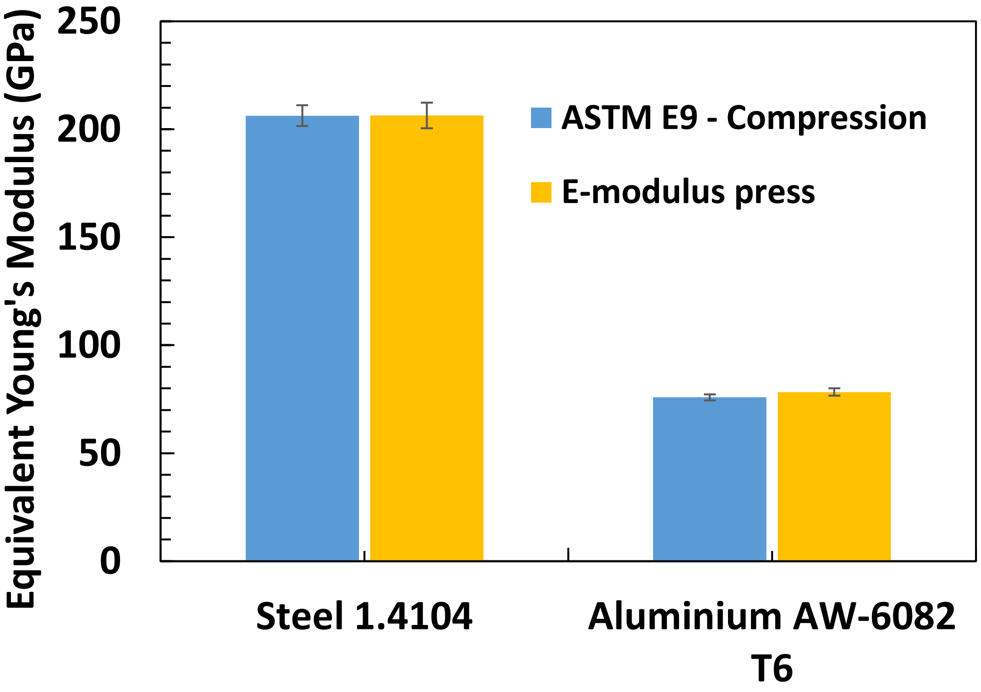
Validation and Repeatability

E-modulus press results based on 30 measurements of each type of calibration block (i.e. steel and aluminium).



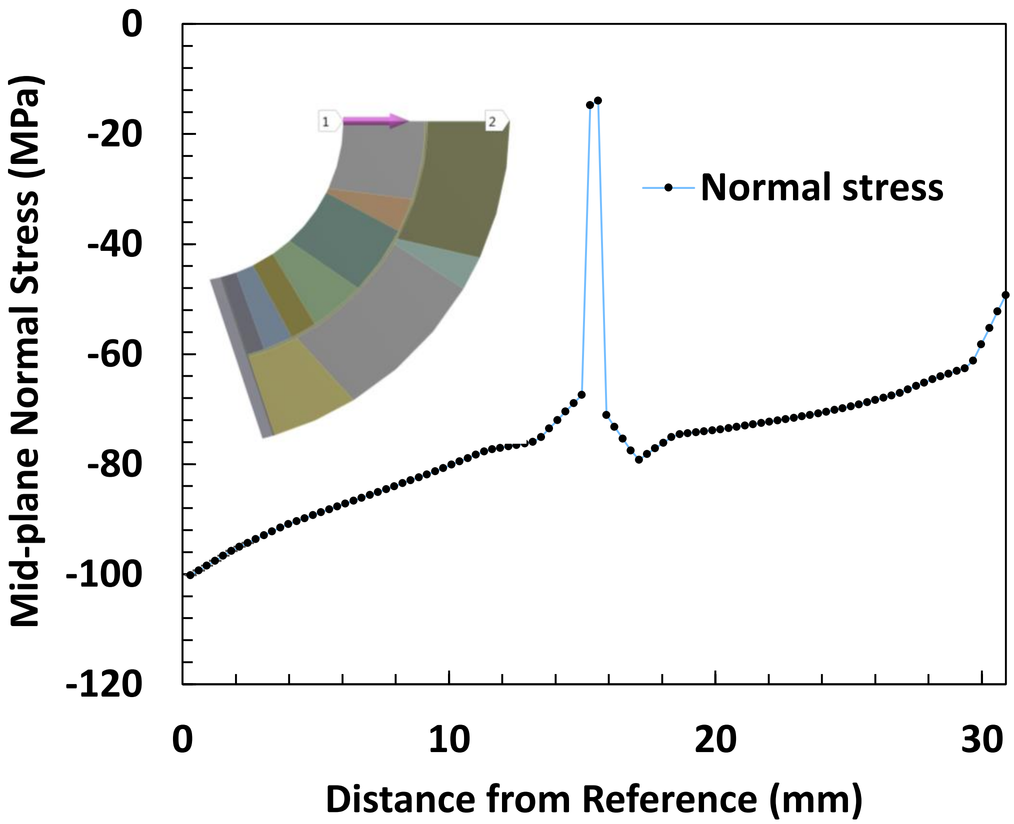
Material	Method	Measured equivalent Young's Modulus - Averaged (GPa)	
		Average	SD
Steel 1.4104	E-modulus press	206.4	6.0
Aluminium AW-6082 T6	E-modulus press	78.3	1.7
Steel 1.4104	ASTM E9 - Compression	206.3	4.8
Aluminium AW-6082 T6	ASTM E9 - Compression	75.9	1.4

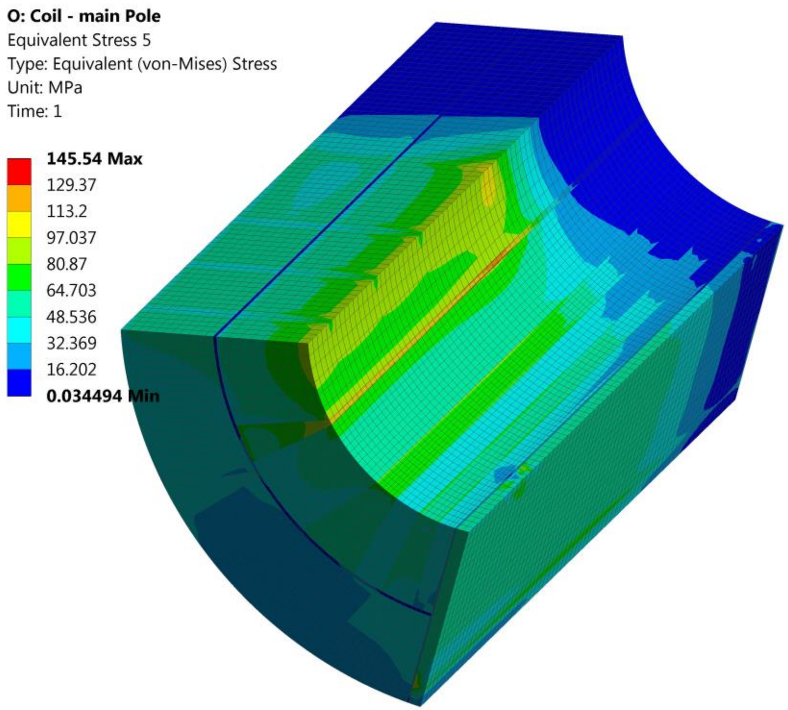
*Young's modulus based on a straight line fitted to the data between 60 and 80 MPa during the loading phase by the method of least squares. (Boundary conditions considered as $\mu = 0.2$)



3. Results and discussion

Considerations from FEA



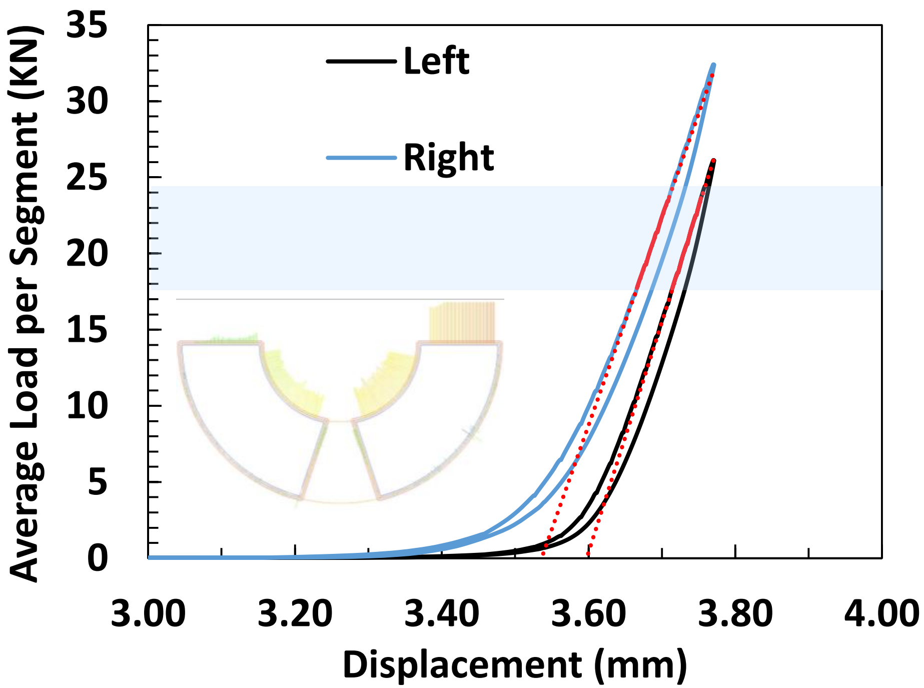


$E_{coil-block} = 30\ GPa;\ \mu = 0.2;$ Displacement $= 0.1$ mm

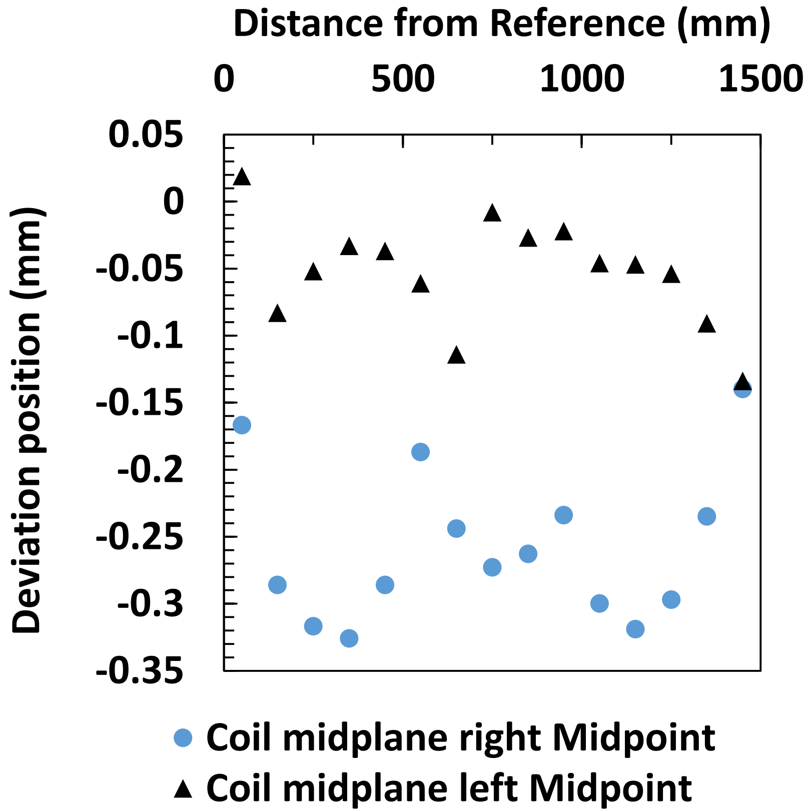
3. Results and discussion

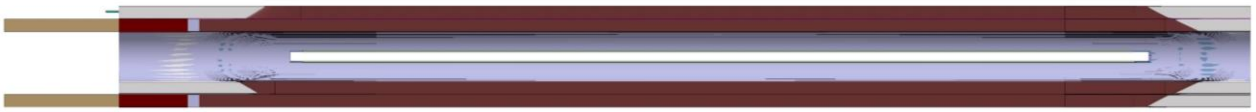
Initial results – Coil 113

Coil oversize



*FaroArm measurements**

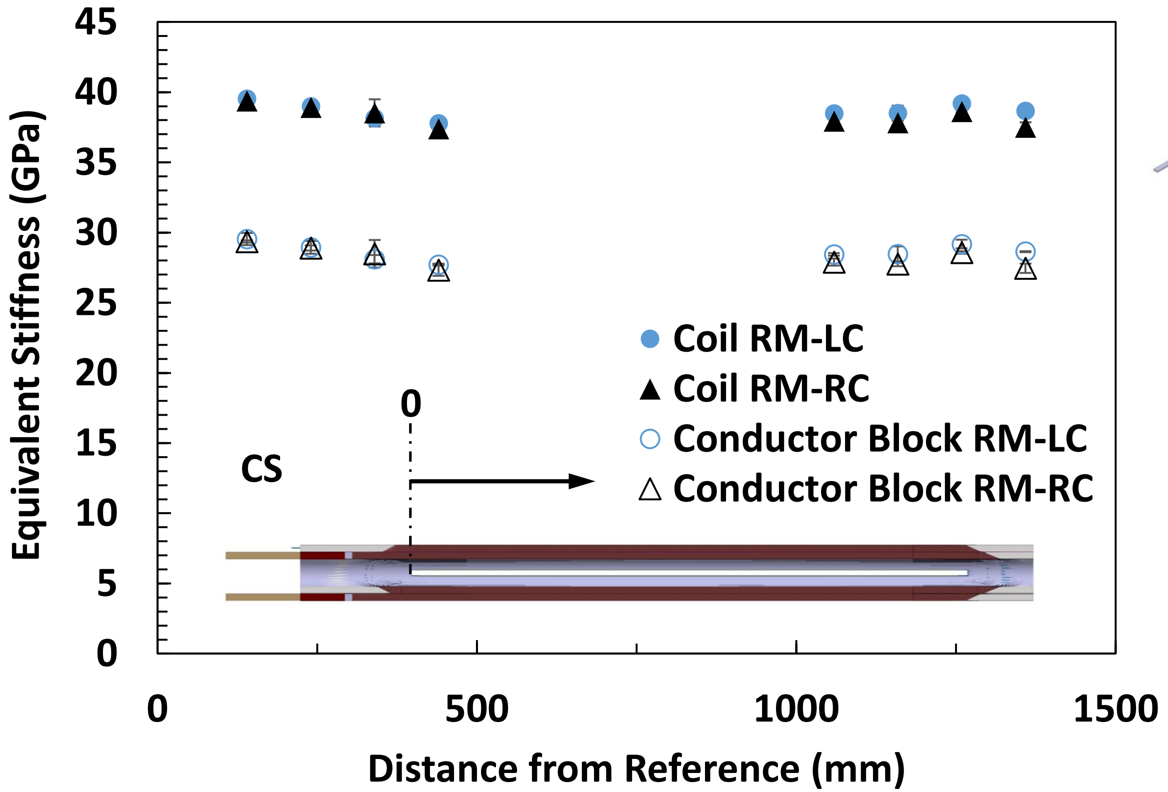




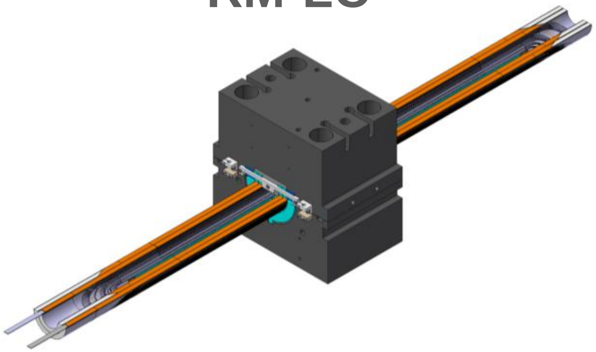
*FaroArm measurements courtesy of J. Ferradás Troitiño

3. Results and discussion

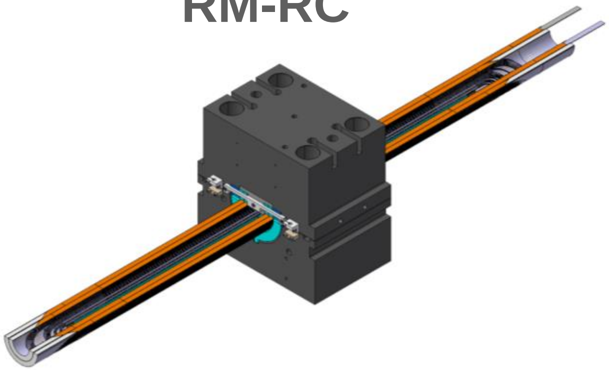
Initial results – Coil 113



RM-LC



RM-RC

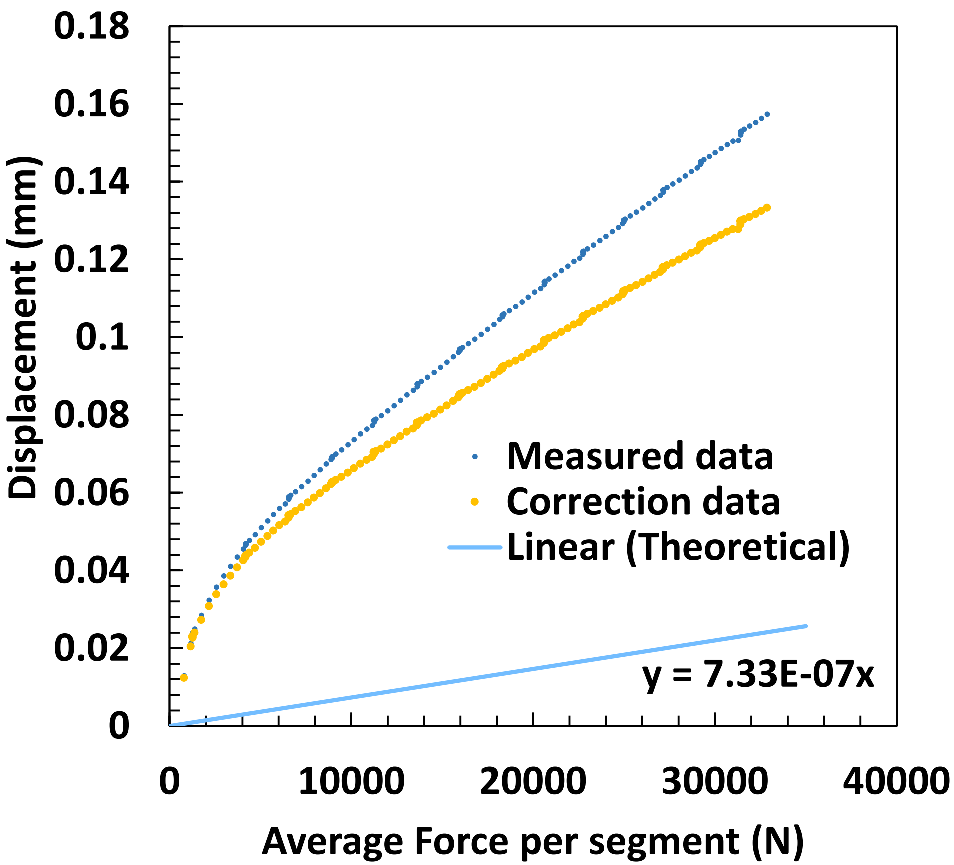


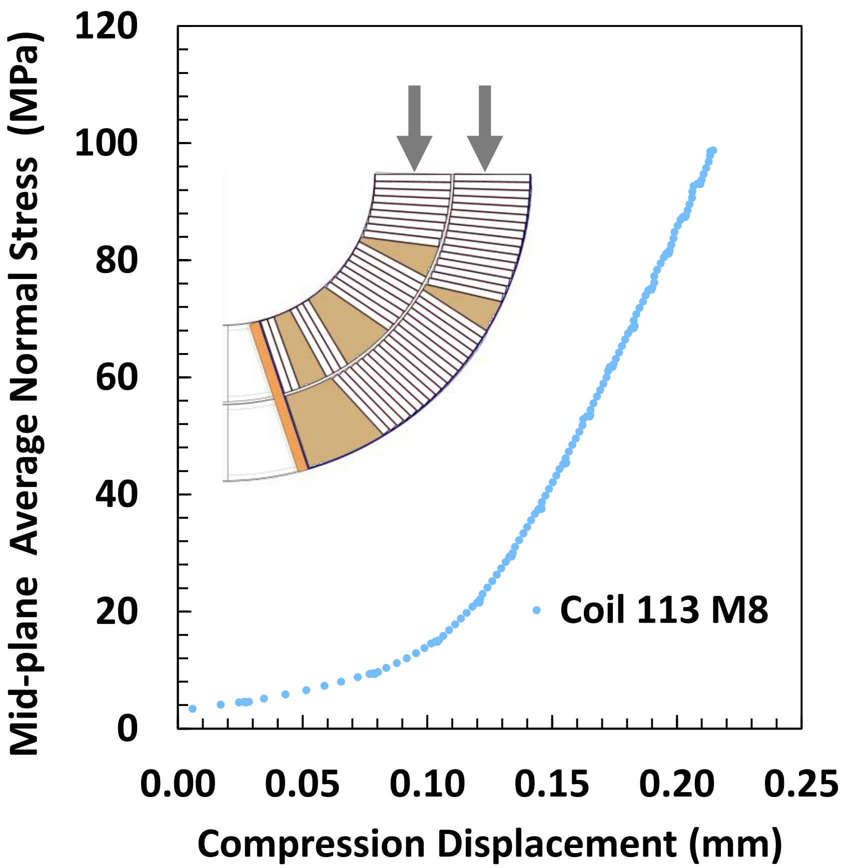
*Equivalent stiffness based on a straight line fitted to the data between 60 and 80 MPa during the loading phase by the method of least squares. (Boundary conditions considered as $\mu = 0.2$)

3. Results and discussion

Initial results – Coil 113

Correction function – Coil 113 M8

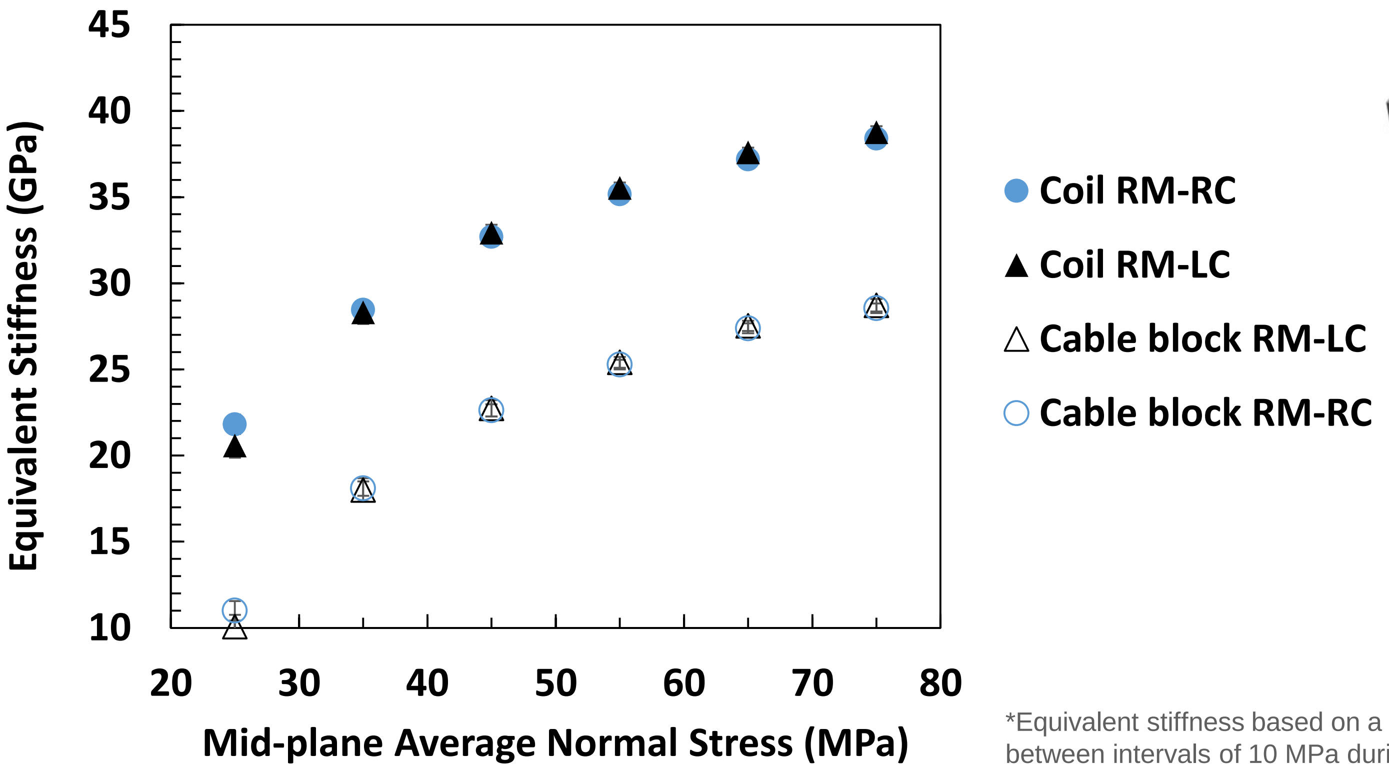


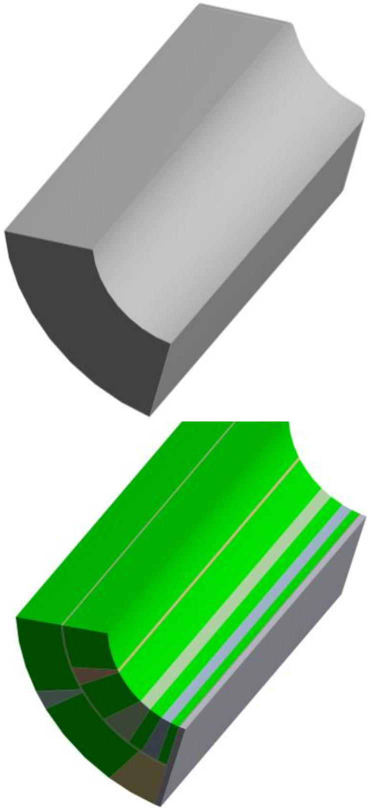


3. Results and discussion

Initial results – Coil 113

Equivalent Stiffness vs Mid-plane Average Normal Stress





*Equivalent stiffness based on a straight line fitted to the data between intervals of 10 MPa during the loading phase by the method of least squares. (Boundary conditions considered as $\mu = 0.2$)

4. Conclusions and considerations

- The **stress-strain compression behaviour** of the overall coil composite structure, and conductor block, is **non-linear** for the analysed region (0-80 Mpa). Moreover, it is clear that this behaviour is not fully described by a Young's modulus value.
- The assumption of linear or bi-linear isotropic hardening material models in FE analyses, might lead to miscalculation of the real stress level.
- The translation of the **coil mid-plane stress vs. coil size** into the analysis of collaring, shall ponder that the measured data is linked to very particular boundary conditions.
- The **average mid-plane stress** level is calculated through the **integrated pressure** over the contact surfaces between the coil mid-plane and segments of the measuring bars, and therefore shall be carefully used when predicting limit peak stresses.
- Future work:
  - Further analysis of results (e.g. stiffness dependence on strain).
  - Development of a common framework for the analysis and comparison of non-linear stress-strain behaviour.
  - Analysis of data in relation to the collaring procedure.
  - Integration of data with analytical analysis[1].
  - Measurement of magnet "heads".

[1]Rudeiros-Fernández, J. L. "Predicting the elastic deformation of the 11 T coil." (2015).

Thanks!