CHARACTERISATION OF THE MECHANICAL BEHAVIOUR OF SUPERCONDUCTING CABLES USED IN HIGH FIELD MAGNETS FROM ROOM TEMPERATURE DOWN TO 77K

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Abstract

A comprehensive knowledge of the mechanical properties of the superconducting cable used in high-field magnets is of paramount importance to study and predict the behaviour of the magnet coil from assembly to the operational conditions at cryogenic temperature.

The mechanical characterisation of such materials presents practical challenges associated with the heterogeneity of the materials, the geometry, size and quality of the samples that can be produced out of actual cables. These constraints impose the undertaking of such measurements from a nonstandard approach, and hence the development of tailor-made tooling.

An extensive characterisation campaign for the determination of the mechanical properties of the superconducting cable at room and cryogenic temperature was launched at CERN in order to determine the most relevant mechanical properties of the superconducting cables used in the MQXF and 11T magnets.

This paper describes the design of the tooling developed for this specific application as well as the experimental set-up used for the tests, and discusses the outcomes of the tests performed.

MOTIVATION OF THE MEASUREMENTS

Superconducting magnets have dramatically increased the reach of particle accelerators, and hence are of paramount importance for modern high energy physics [1]. Current LHC dipoles are able to operate at a nominal field of 8.33 T at 1.9 K, which is the upper practical limit using Nb-Ti conductors[2]. Nevertheless, the need for magnets with higher nominal fields has become a necessity for projects such as High Luminosity LHC (HL-LHC), which aims at increasing the luminosity seen by ATLAS and CMS experiments by a factor of 5[3].

Additionally, following the recommendations of the European Strategy Group for Particle Physics CERN has started a design study for a Future Circular Collider (FCC) with an energy of 100 TeV[4]. A first analysis of the general parameters for such a machine has led to a baseline configuration requiring 16 T dipoles in a 100 km tunnel.

Currently there are only a few candidates that can be realistically considered to succeed Nb-Ti conductors, namely a combination of MgB2 YBCO and BSCCO-2212 and Nb3Sn[5].

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Amongst them and despite the challenges posed by its demanding manufacturing processes and its brittleness Nb3Sn is the more promising candidate[6].

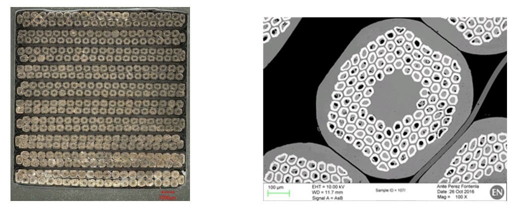

Figure 1: Cross section and micrography of a Nb3Sn Cable.

The mechanical properties and strain tolerance of strands and cables constitute a large chapter in superconducting magnet engineering, which is especially true in brittle Nb3Sn. The strain sensitivity of the Nb3Sn superconducting properties makes the prediction of the internal stresses a necessary step when it comes to understanding the performance of Nb3Sn conductors under the magnetic load conditions experienced in a coil, as well as the assembly procedures that guarantee a correct level of preload[6].

In this scenario, there are several possible tools to advance our understanding of the stress distribution inside the magnet components. Embarked mechanical instrumentation in combination with finite element simulations appear to be the best alternative so far[7]. For this reason, the development of robust constitutive material models are key for improving coil model predictions. The data from literature is scarce and non-existent in some cases, and the properties can vary considerably as a function of the cable constituents and the manufacturing processes. Therefore there is a need for an extensive characterisation campaign allowing the collection of the necessary experimental data.

EXPERIMENTAL SET-UP

A complete test rig together with a cryostat was developed. The top part of the assembly is composed of a top pusher which includes a spherical seated bearing block, and is installed to the crosshead of a Zwick-Roell Z400 universal testing machine.

The bottom part of the assembly is integrated by a base on top of which a measuring sled is fitted. The measuring sled is integrated by a base, which serves also as a support for four horizontal displacement sensors, and a bearing

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block which supports four vertical displacement sensors. A centering hollow platelet keeps the sample in the correct position.

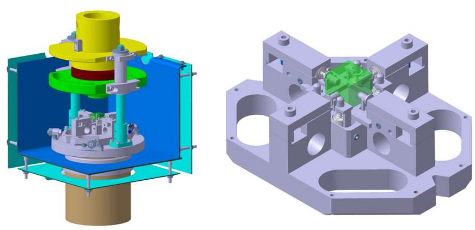

Figure 2: Test rig inside the cryostat and measuring sled.

The four vertical displacement sensors measure the separation between the top pusher and the bottom bearing block, and are used for the determination of the stiffness of the cable. These sensors do not only measure the sample deflection, but the sum of the sample deflection and the compliance of the tooling. For this reason, it was necessary to perform a campaign of tests devoted to determine the tooling compliance

The horizontal displacement sensors are used for determining the Poisson's ratio.

The displacement sensors have a linearity deviation of ± 0.2 %, while the universal testing machine was fitted with a load cell with an accuracy class of 0.05. For the measurement at 77 K the stack is placed in a cryostat filled with liquid nitrogen.

The dimensions of the tested samples are stated in Table 1:

Table 1: Sample Dimensions in mm

Cable Type	Height	Width	Length
11T	15	15	20
MQXF	18.8	18.8	20

VALIDATION CAMPAIGN

Prior to the tests on the cable stacks, a validation campaign was launched with the objectives of evaluating a proper stress distribution between the set-up components and the samples, determining the tooling compliance, and evaluating the accuracy of the system.

Table 2: Scheme of the Validation Campaign

	Room Temperature								77K		
G10 Al Cu	Pressure distribution tests	3 samples	0°, +120°+180° position	Dismount-Clean	LVDT Calibration	3 samples	0°, +120°+180° position	Specific Tests	LVDT Calibration	3 samples	0°, +120°+180° position

The pressure distribution of the contact between the pushers and the sample was determined using different Fujifilm Prescale® sheet types, which showed a homogeneous stress field.

As previously stated, the sensors used to determine the stiffness of the sample do not only measure the sample deflection, but a combination of the sample deflection and the compliance of the tooling. In order to account for this effect, the deflection of the tooling for each sample geometry was measured. For this task, three reference materials with elastic properties within the range of the expected properties of the cable were chosen: G10, Aluminum, and Copper.

The compliance of the tooling was calculated as the difference of the deflection obtained experimentally, and the expected deformation of the sample. The tooling compliance values obtained at 300 K and 77 K for samples with the same geometry than MQXF cables are summarised in the table below:

Table 3: Tooling Deflection for MQXF Sized Samples

Material	Deflection per MPa [μm/MPa]	
	300 K	77 K
G10	0.085	-
Al	0.091	0.081
Cu	0.098	0.086
AVG	0.091	0.083

It is noteworthy that the measured compliance induced by the materials with very different elastic properties only had a 5% difference between the most and least rigid materials.

Once the deflection was determined, a second matrix of tests was performed over the reference materials, obtaining the following results:

Table 4: Validation Campaign Results

300 K	Experimental Value	Reference
G10	12.5±1	13*
Aluminium	73±4	70
Copper	115±6	120
77K	**Experimental Value**	**Reference**
Aluminium	81±4	77
Copper	132±7	138

TEST PROTOCOLS AND DATA ANALYSIS

Several test protocols were developed for each cable type with different purposes. In the case of 11T cables, the elastic modulus of the cables was determined using a test protocol (Test Protocol 1), consisting of four consecutive loading-unloading cycles with a load rate of 3 MPa/s. The loading range started from an applied preload (20 MPa) up to 160 MPa. The upper stress level was chosen because similar to the one applied during the magnet assembly phases, and known to not induce catastrophic damage in the cables.

A variation of the first test protocol was chosen to determine the plastic deformation induced in the samples by additional loading-unloading cycles (Test Protocol 2),

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that consisted in twelve consecutive cycles with the same load range and loading rates as test protocol 1.

The effects of creep on an already permanently deformed sample was tested by loading and unloading 3 times and holding the sample under a load of 160 MPa during one hour (Test Protocol 3).

For MQXF cables, two test protocols were developed. Test protocol 4 aimed at determining the ultimate stress of the cable stacks. For this purpose, the sample was subjected to a monotonic loading at a load rate of 0.2 mm/min up to the fracture of the sample.

Test protocol 5 was developed in order to unveil the plastic deformation left behind by load cycles up to different strain levels as well as the rigidity presented by the sample at the different load steps. For this purpose, and in order to keep the results comparable with those obtained by the first test protocol, the load rate was maintained, and 3 consecutive load-unload cycles were performed up to 50, 100 and 150 MPa

While it does not reflect the complexity of the stress-strain behavior showed by the cable stacks, by convention the secant modulus is stated when quantifying the rigidity of the cables.

FIRST RESULTS

The following commented plots show the most representative results obtained so far at room temperature tests.

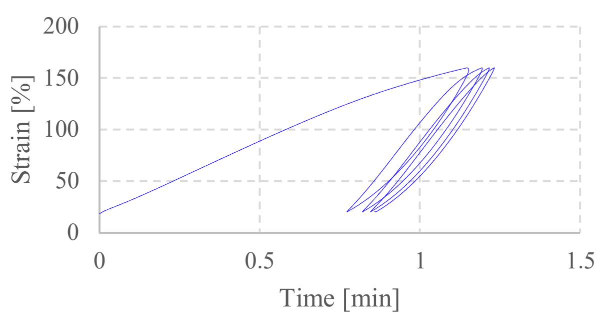

Figure 3: 11T Azimuthal – Test Protocol 1.

Specimens subjected to test protocol 1 presented in general an important plastic deformation after the first loading cycle, up to 0.8%, and showed a secant modulus ranging from 32 to 37 GPa.

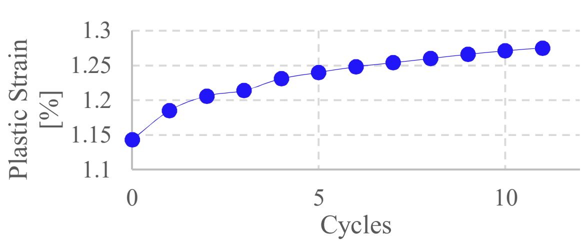

Figure 4: Plastic deformation after load-unload cycles in 11T azimuthal cables.

Test protocol 2 shows that although most of the plastic deformation is induced by the first loading step, subsequent loading cycles continue to deform the cables by a non-negligible amount.

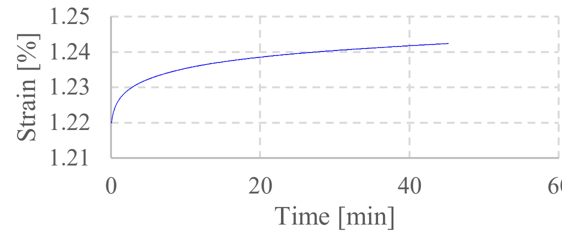

Figure 5: Creep presented by 11T cable.

Test Protocol 3 confirmed the viscoelastic nature of Nb3Sn superconducting cables.

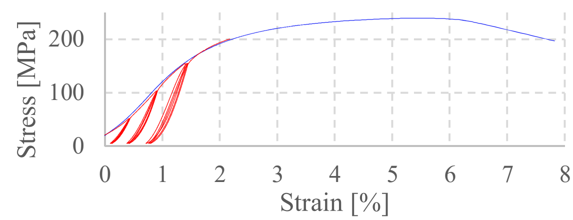

Figure 6: Compression tests over MQXF Samples.

MQXF cables showed an ultimate compressive strength of approximately 250 MPa. In the case of test protocol 5, the material presented a variable secant modulus depending on the loading stage, with its maximum during the 150 MPa loading-unloading cycle.

CONCLUSIONS

The strain sensitivity of the Nb3Sn superconducting properties makes essential an accurate prediction of the coils internal stresses both during the assembly and operation of the magnet. With the aim to improve the knowledge of the cables behaviour for the finite element models, a preliminary characterization campaign was performed. Even though this will serve to gain a first insight of the properties of the materials, several paths should be explored in a close future: translation of the existing experimental data into robust and accurate constitutive models, study of the dependence of the properties on the manufacturing processes, and determination of the mechanical characteristics at cryogenic temperatures.

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