Mechanical characterisation of Nb_3Sn cable insulation systems at ambient temperature used for HL-LHC accelerator magnets.

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International Conference on Magnet Technology
Vancouver, Canada | 2019

Abstract

The insulation system is a key component of Nb_3Sn superconducting accelerator magnets under construction for the LHC High Luminosity upgrade (HL-LHC). It needs to ensure the magnet operation at 1.9 K and to guarantee the functionality during the complete service life of the magnet in the accelerator under high mechanical stress and irradiation dose up to 35 MGy. A first set of experimental tests have been performed at room temperature to confirm the stress-strain behaviour, the mechanical strength and the failure mechanisms of the cable insulation system used for the HL-LHC Nb_3Sn accelerator magnets. CERN is performing non-standardised combined compressive shear test, which are considered to be representative for magnet conditions during assembly. The tested samples consist of the same raw insulation material and follow similar specific manufacturing procedures as the ones of the 11 T Nb_3Sn dipole and the MQXF Nb_3Sn quadrupole magnets. In order to represent the different design criteria of these magnets, the sensitivity to the mechanical behaviour of the CTD-101K resin impregnated samples to a varying S2-glass yarn density, sizing and fibre volume fraction is investigated with different types of samples as well as the effect of mica used in the insulation system.

The HL-LHC cable insulation system

Impregnation system

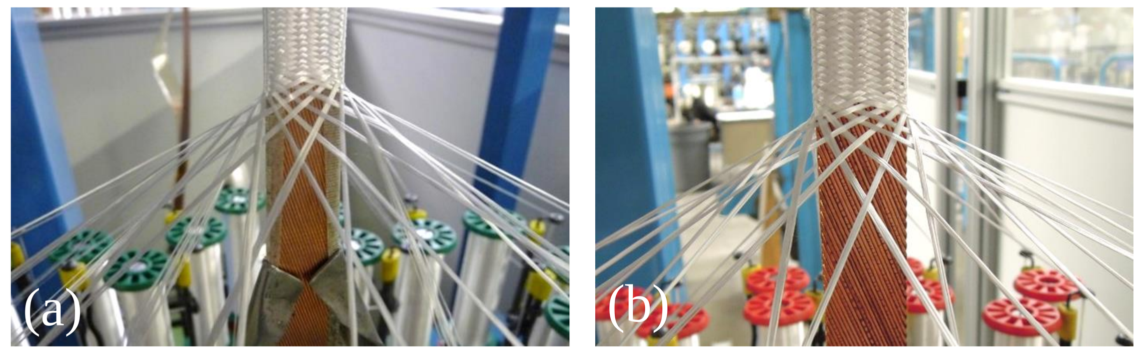
CTD-101K, a Diglycidyl Ether of Bisphenol-A (DGEBA) with anhydride curing agent

11T cable insulation system

42 µm S2 glass and 80 µm mica on a glass fibre grid

MQXF cable insulation system

145 µm S2 glass yarn


Cable braiding of the 11T (a) and the MQXF (b) type of cable, courtesy CERN

Insulation parameter	11T	MQXF
AGY S-2 Glass type	11TEX Grade 636	66TEX Grade 933
Yarn diameter	76 µm	192 µm
№ of spools	32	32
№ of yarns/spool	4	2
Spool yarn count/20mm	18	19
Sizing type (grade)	starch oil (636)	thermal stable inorganic (933)
MICA FIROX 63P24	80 µm	-
Total thickness at 5 MPa	122 µm	145 µm

*11 TEX defines 11 gram per 1000m

Load on the cable insulation system in the magnet

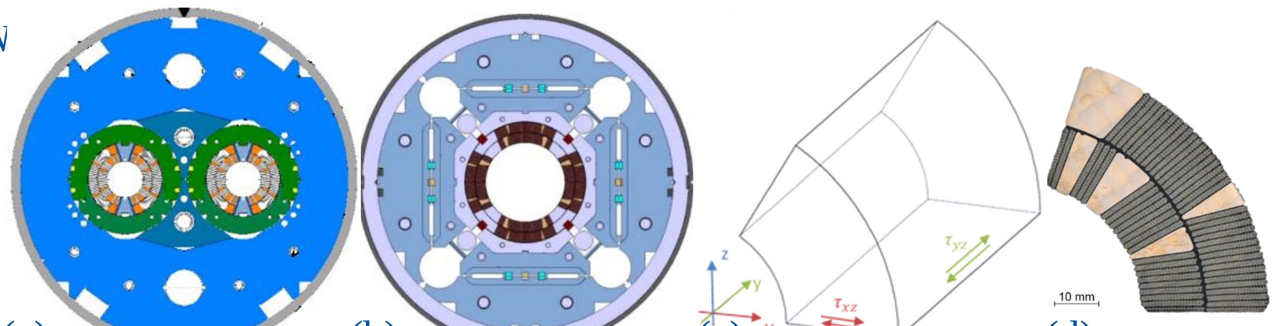
11T dipole magnet (5.5m):

- Manufacturing: Radial shear (red) and transversal compressive stress during pole insertion and magnet pre-loading
- Operation: Axial induced shear stress (green) due to thermal contraction difference between conductor and insulation system

MQXF quadrupole magnet (7.5m):

- Manufacturing: Transversal and radial compressive load during bladder loading
- Operation: Axial induced shear stress (green) due to thermal contraction difference between conductor and insulation system

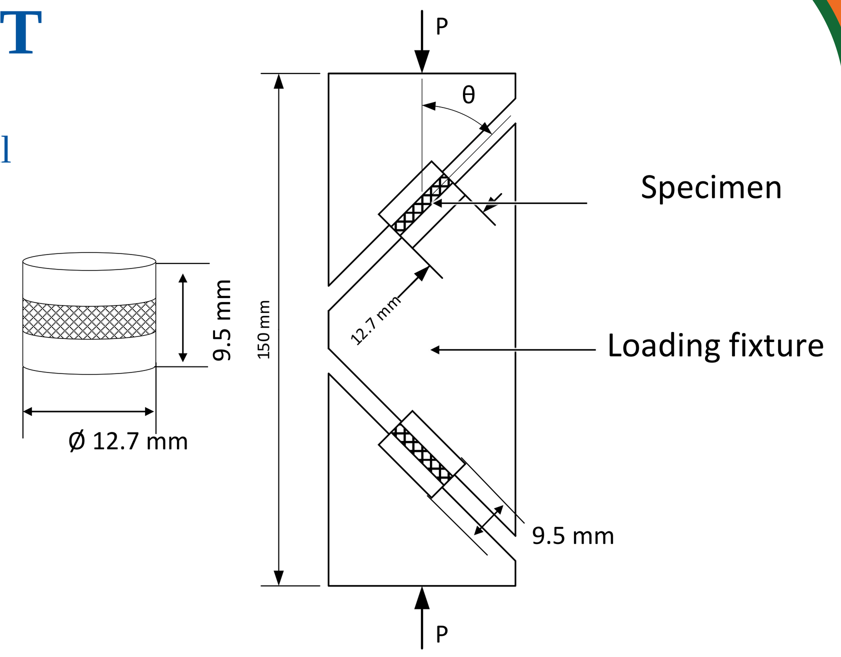

7.5m long MQXF coil.


(a) (b) (c) (d)

Cross section of an 11T (a), MQXF (b) magnet and shear stress definition in a sector coil (c) and microscopy of a cross section of a coil segment (d), courtesy CERN.

Shear compression test

- Test enables the determination of the mechanical strength under shear compressive load of a material
- Ratio between shear and compressive stress is set by the fixture angle $\tau = \cot\theta \cdot \sigma$
- Shear stress and compressive stress are equal at the fixture angle of 45°
- Stress at failure is determined by the maximum load, recorded with a load cell
- The test station enables tests at ambient temperature and at 77 K
- No lateral forces are applied on the test machine due to the multi part test tooling
- The alignment between sample and sample holder is done by stainless steel shims (0.01 mm)
- The test requires just a very small quantity of material compared to standardized mechanical tests



Schematic of sample and test fixture.


Stainless steel sample holder of the shear compressive test.

$$\tau = \frac{P\cos\theta}{A}$$

$$\sigma = \frac{P\sin\theta}{A}$$

τ … Shear stress
σ … Compressive stress
P … Applied load
θ … Fixture angle
A … Sample cross section area

Conclusions

Test outcome:

- An **inter laminar failure** mode was observed in **11 T** samples **with mica** (FIROX 63P24)
- The **shear compressive strength** of the insulation system **with mica** is about **20 MPa** at ambient temperature
- The **inter laminar strength** at ambient temperature of samples **without mica** is **higher** than the bonding strength of the glue **(15 MPa)**

Outlook:

- Improvement of the bonding between steel disc and composite by surface treatment and glue variation
- Manufacturing of samples with impregnated steel pads
- Continuation of the test campaign with MQXF ply material
- Study the effect of temperature (77 K) and irradiation dose up to 35 MGy
- Comparison to short beam bending test results with samples manufactured from the same material with a similar volume fraction
- Determination of the fibre volume fraction by microscopy and density method
- Investigation of the effect of a varying fibre volume fraction on the shear compressive strength

The samples

Manufacturing procedure:

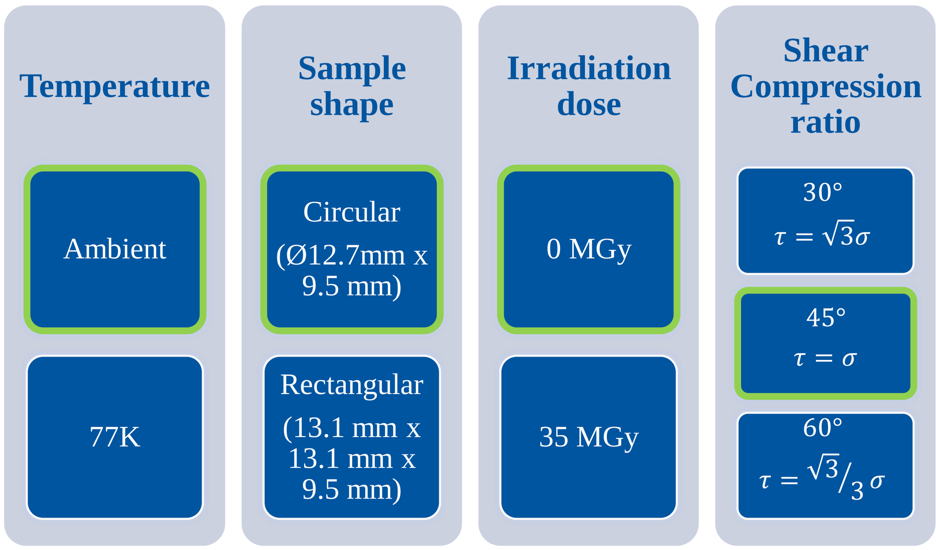
- Glass fibre sleeve extracted from cables used for 11 T and MQXF magnet production was used as ply material
- The glass fibre stacks have been heat treated for 50h at 650°C under argon atmosphere
- Vacuum impregnated with CTD-101K
- Pre-cutting of the composite material
- Cylindrical disk surface treatment, sand blasting and acetone cleaning
- Gluing of composite (Araldite 2015) in special alignment fixture
- Grinding of composite to final dimension of the disk

Overview of the sample characteristic.

Material ID	Description	Composite thickness	Target composite thickness	Theoretical fibre volume fraction
11 T – SC	11 T yarn, single sleeve*	141 µm	84 µm	39 %
11 T – DC	11 T yarn, double sleeve**	233 µm	168 µm	39 %
11 T – M – SC	11 T yarn with mica, single sleeve*	238 µm	244 µm	39 %
11 T – M – DC	11 T yarn with mica, double sleeve**	480 µm	488 µm	39 %
MQXF – SC	MQXF yarn, single sleeve*	366 µm	290 µm	38 %
MQXF - DC	MQXF yarn, double sleeve**	694 µm	580 µm	38 %

*single sleeve provides two layers of glass fibre , **double sleeve provides four layers of glass fibre


Tool for disk alignment and compression during glue curing (a) and paired cylindrical samples (b).



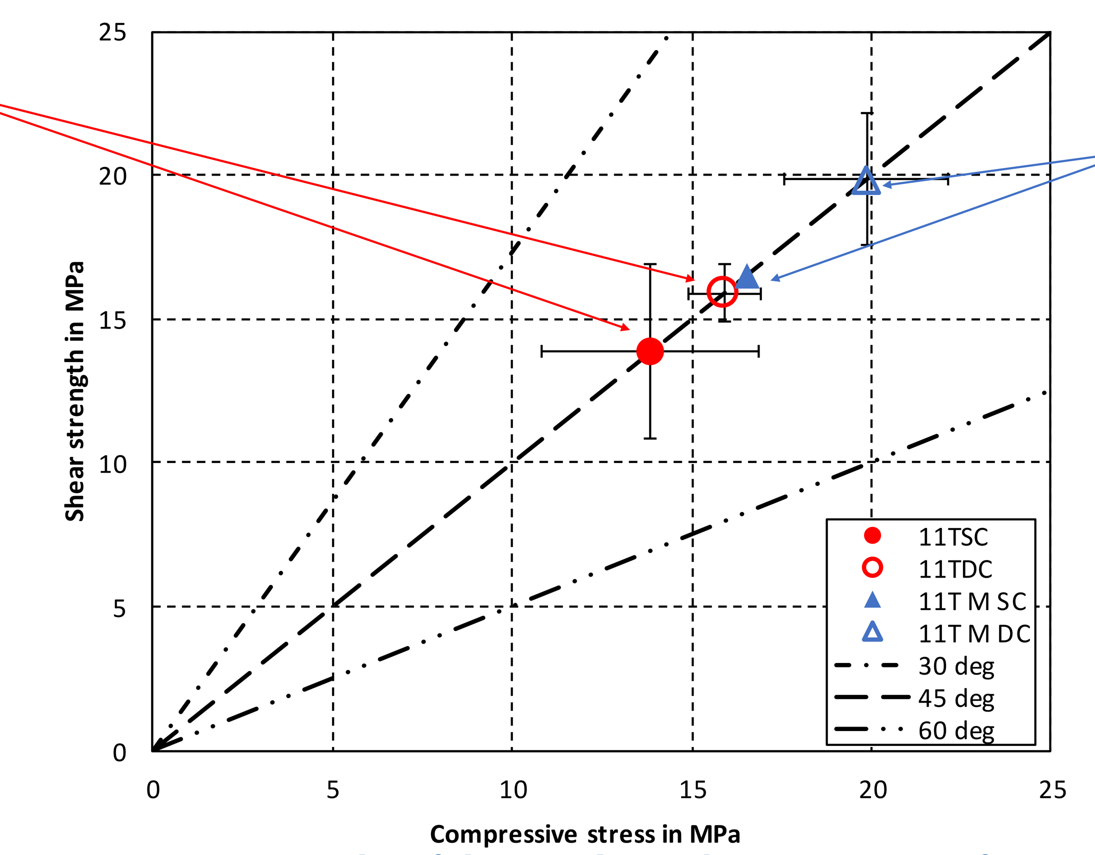
Test matrix with tested path in green.

Test results

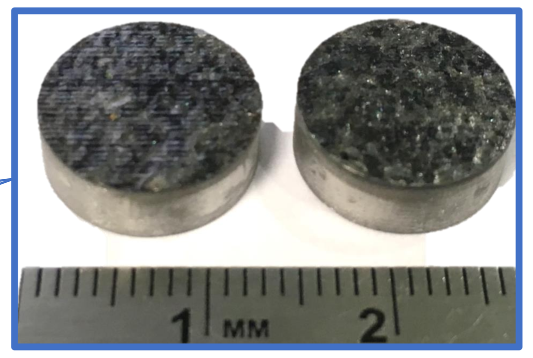

Bonding failure of an insulation system without mica.

11 T glass fibre without mica

- All single sleeve samples (11TSC) failed with a **bonding failure**
- All double sleeve sample (11TDC) failed with a **bonding failure**
- The inter laminar failure is expected to be higher than the bonding strength



Shear-compressive test results of the tested samples in a 45° test fixture at room temperature. The error bar indicates the standard deviation of the test results.


Inter laminar failure of and insulation system with mica.

11 T glass fibre glass with mica

- All single sleeve samples (11TMSC) failed as inter laminar failure
- All double sleeve sample (11TMDC) failed with a inter laminar failure