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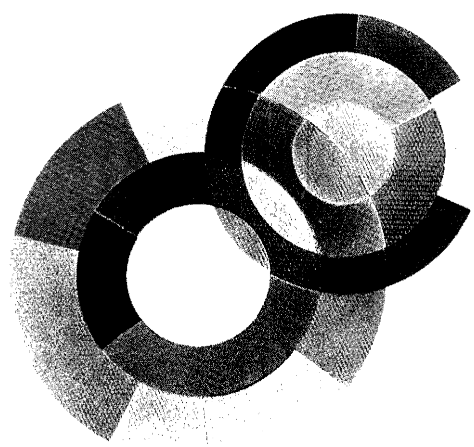

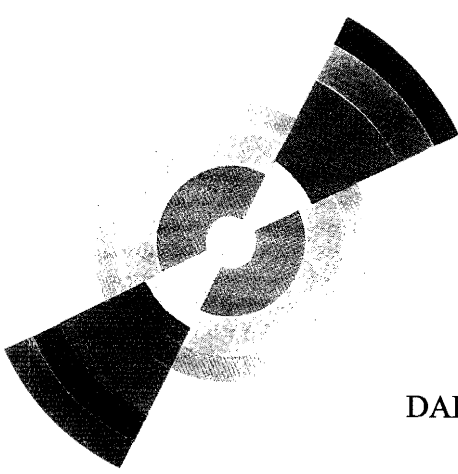

DAPNIA/STCM 99-11 December 1999

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DAPNIA

Presented at the 16th International Conference on Magnet Technology, Tallahassee (USA), September 26-October 02, 1999

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COMMISSARIAT A L'ENERGIE ATOMIQUE

DSM/DAPNIA/STCM

Rapport n° 11
le 15 décembre 1999

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26/09/1999 au 02/10/1999

Shear Test of Glass Reinforced Composite Materials at 4.2 K

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***Abstract*-- Finite element analysis of the 4-T, 12.5-m long, 6-m-bore diameter superconducting solenoid for the CMS experiment at LHC shows that the insulation system is subjected mainly to shear forces during magnet operation at 4.5 K. This paper describes the development of a test procedure to evaluate shear properties of the glass reinforced composite material at 4.2 K. The calculation supporting the new specimen shape and the relation between coil and specimen Finite Element Analysis (FEA) are presented. As an application, this test procedure is used to compare three different surface treatments of the conductor: solvent cleaning, sand blasting and anodic oxidation. Results from these tests are reported. Values up to 110 MPa at 4.2 K have been obtained for the CMS foreseen insulation material, the conductor being treated by anodic oxidation.**

I. INTRODUCTION

The 4-T, 12.5-m long, 6-m-bore diameter CMS superconducting solenoid is wound in 4 layers. The high purity aluminium stabilized conductor is reinforced with aluminium alloy wings. For manufacturing reasons, the solenoid is split in 5 modules. The final design of the CMS solenoid cold mass is presented in [1]. Figure 1 shows a cross-sectional view of the cold mass.

Glass reinforced epoxy resin has been chosen as insulation material for the CMS solenoid. The conductor is first wrapped with glass tapes and is then inserted in the external mandrel, which is made of aluminium alloy. Once the four layers are wound, the magnet is vacuum-impregnated with epoxy resin, module by module. The conductor insulation is 0.5 mm thick, the inter-layer insulation 0.4 mm thick, and the ground insulation 1 mm thick.

The insulation composite material acts first of all as electrical insulation. During a fast discharge, the maximum voltage applied across the coil is 600 V, and is ± 300V with respect to the ground. The test value has been set to 3000 V.
Due to the indirect cooling of the magnet, it is important to ensure a good thermal continuity through the different materials, from the cooling pipes to the Rutherford-type cable. This implies, for the insulation material, a thermal conductivity as good as possible and an accurate bonding between the different elements.
The mechanical load on the insulation material is mainly due to the difference of thermal contraction between glass reinforced epoxy resin and aluminium alloy during cooldown. The Lorentz forces arising during excitation have also some effects on the stress level. FEA of the CMS magnet has shown that the insulation system is subjected mainly to shear forces during magnet operation (see section V). The mechanical shear properties of the insulation material are thus of major importance.

A specimen has been developed to check the composite material mechanical properties. The aim was to design a specimen able to load mainly in shear, at the same time, the glass fibre ribbon, the epoxy resin and the bonding between this composite material and aluminium alloy. The specimen should be also easy to manufacture and to test. For these reasons, the single lap joint specimen type has been chosen.

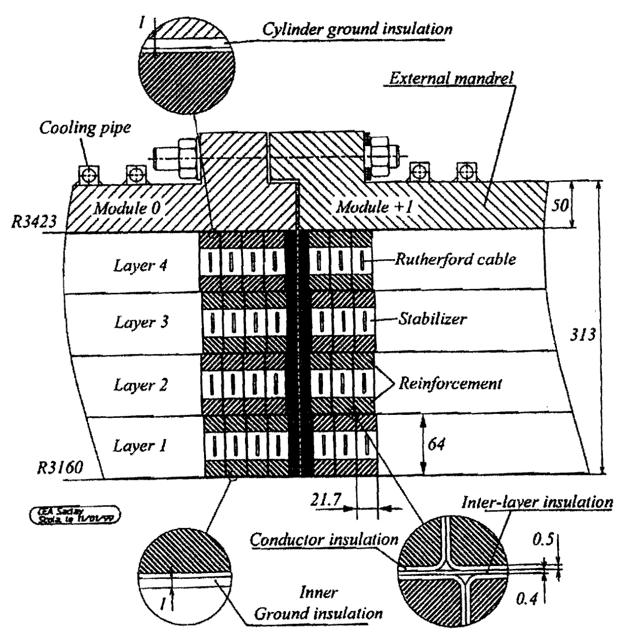

Figure 1 : CMS coil cross-sectional view

II. BACKGROUND

A. Lap-joint Specimen Analysis

The single lap-joint has been studied several times. Volkersen [2] proposed first an analytical stress analysis in 1938. Adams and Peppiatt [3] performed lap-joint FEA. The studied specimens were standard lap-joint with a minimum joint length of l = 12.7 mm (see figure 2).

Manuscript submitted September 27, 1999.
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Figure 3 presents the FEA results of a standard specimen. The stress applied to the FEA model is a unit stress, the stresses are then given by unit stress.
One can see that the stress distribution along the overlap presents strong edge effects. At the same time, the specimen is mainly loaded in shear /tension and not in pure shear.

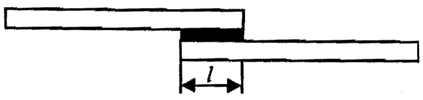

Fig. 2 : Typical single lap-joint specimen

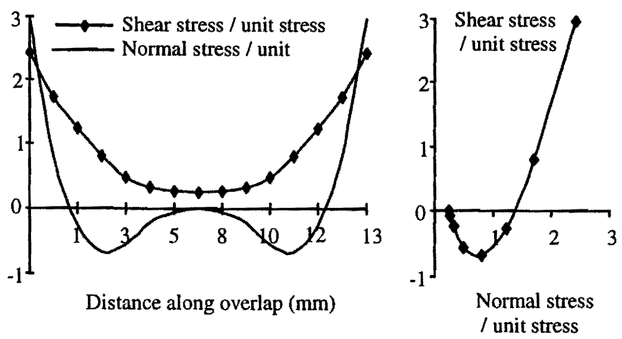

Fig. 3 : Standard specimen stress distribution

B Transverse Tensile and Shear/Tension Strength: Experimental Results

Little is known on the shear properties of glass reinforced epoxy resin at 4.2 K. Table I summarises data from Evans [4] on transverse tensile strength and combined shear/tension strength. These values cannot be directly compared with the shear strength hereafter presented but are fully complementary.

TABLE I
TRANSVERSE TENSILE AND SHEAR/TENSION STRENGTH (MPa)

	293 K	4.2 K
Transverse tensile strength	85	95
Combined shear/tension strength		
Shear	48	67
Tension	62	88

Properties with specimen compacted at 5 MPa during manufacture

III. SHEAR TEST SPECIMEN OPTIMISATION

Starting from the standard lap-joint specimen, a FEA has been performed to optimise the geometry. Considering the specimen shape and the insulation elasto-brittle properties, a 2D elastic analysis in plane stress conditions has been performed. The cooling-down of the specimen was also taken into account. The aim of the optimisation was to limit the edge effects and load the joint mainly in shear and not in shear/tension.

A fractional factorial design has been performed to adjust the specimen shape (see Fig. 4). Four parameters were studied: the joint length, *l*, the joint thickness, *t*, the groove depth, g, and the specimen thickness, s.
The groove depth reduces mainly the edge effects. Groove depth between 1 mm and 2 mm (with respect to the specimen mid-plane) gives good results. The analysis shows the two main parameters which influence the specimen shear/tension loading: the length of the joint has the main role, and the overall thickness of the specimen. To load the specimen mainly in shear, the joint length must not exceed 5 mm, whereas the overall thickness must be at least 10 mm.
The optimised lap-joint specimen geometry is presented in Fig. 4. The joint length has been set to 5 mm to limit the brittleness of the joint during handling and machining. The specimen thickness is 13 mm and the groove depth is 1.5 mm. The joint thickness is function of the glass tape tested, typically 1 mm for the CMS specimen.
The specimen length is 120 mm, its width is set at 20 mm. The groove is 2 mm wide.

Figure 5 presents the FEA results of the optimised geometry. One can see that the joint is mainly loaded in shear, especially in the middle where the stresses are maximum. The edge effect does not exist any more.

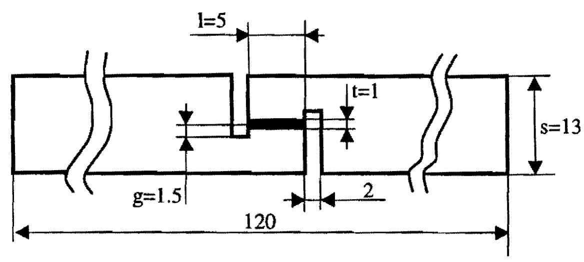

Fig. 4 : optimised lap-joint specimen geometry

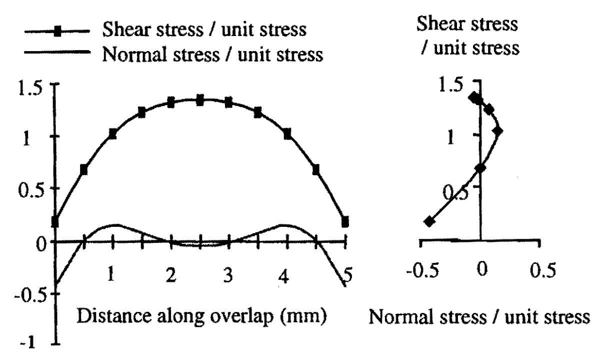

Fig. 5 : Optimised specimen stress distribution

IV. EXPERIMENTAL RESULTS

In order to qualify the insulation process, we have developed a procedure to manufacture and test specimens using the above described geometry. As an application, this procedure has been used to compare three different conductor surface treatments (sand blasting, solvent cleaning and anodic oxidation).

A Sample Preparation

After the surface treatment, two Al alloy 6082 bars are wrapped with glass tape, 50% overlapped. The specimens are then vacuum-impregnated with epoxy resin in a mould under 5 MPa pressure. Upon completion of this operation, the grooves and two holes are machined. The two holes are used to fix the specimen to the tensile machine in the cryostat.

B Test Results

Tensile tests were carried out with a screw-driven machine at room temperature and in liquid helium at 4.2 K. The crosshead displacement speed was set to 0.2 mm/min. The load was measured with a 150 kN cell. All samples were loaded to rupture.
For each surface treatment type, at least three samples have been tested. The results are summarised in Table II. The shear stress values have been calculated by dividing the rupture load by the joint specimen area. No correcting factor coming from specimen FEA has been applied.

TABLE II
SHEAR STRENGTH (MPa)

Surface treatment	at 300 K	at 4.2 K
Solvent cleaning	*33 ± 14 (43%)*	
Sand blasting	50 ± 2 (4 %)	99 ± 8 (8%)
Anodic oxidation	55 ± 0.4 (1%)	110 ± 1 (1%)

The conductor treated by anodic oxidation presents the highest value of shear stress, with the lowest scattering.
The sand blasting treatment gives slightly lower values but with a larger scattering. The solvent cleaning treatment must be avoided because of its low properties and non uniformity.
One can note that these values are of same order of magnitude than transverse tensile and shear/tension strength values, measured by Evans [4].
Figure 6 presents the sample after rupture. One can observe a shiny surface after solvent cleaning treatment. The rupture occurs then at the interface between Al alloy and resin. For the two other treatments, the rupture occurs in the insulation composite material.

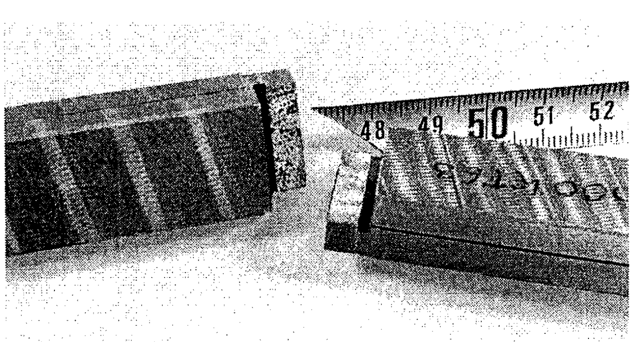

Fig. 6 : Sample after rupture

V. LINK BETWEEN COIL AND SPECIMEN FEA

The specimen has been optimised by using normal and shear stress components for simplicity reasons, whereas the coil FEA uses Mohr-Coulomb criterion for the insulation [5].
The state of stresses of one material can be defined in each of its points by three components called principal stresses. In plane stress conditions, there are only two components σ_I and σ_{II}. In this case, the Mohr diagram is composed with $\sigma_{mean}=(\sigma_I+\sigma_{II})/2$ on the horizontal axis and $\tau_{max}=(\sigma_I-\sigma_{II})/2$ on the vertical axis. The state of stresses of one point is enclosed in the Mohr circle [centre (σ_{mean}, 0); radius = τ_{max}]. The state of stresses of one piece is then represented by several Mohr circles. Figure 7 gives the Mohr circles of the CMS coil insulation most loaded points [5].

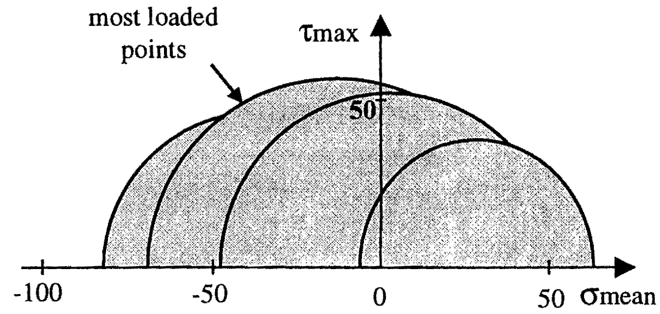

Fig. 7 : Coil insulation Mohr circles

For engineering reasons, these Mohr circles must be compared to the piece material properties. According to the Mohr-Coulomb criterion, the Mohr circles must lay within an experimental failure envelope. To know the complete failure envelope, several tests are necessary. For example, a set of tests using compression, tension and shear specimen could give a good representation of the failure envelope (see Fig. 8). The CMS insulation material being mainly loaded in shear, it has been then decided to work on a shear specimen.

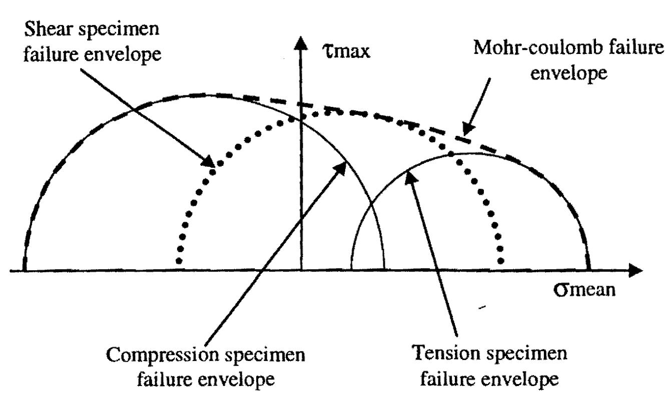

Fig. 8 : Mohr-Coulomb failure envelope

The Mohr diagram of the optimised lap-joint specimen is given in Fig. 9. As discussed in section IV, a minimum value of 100 MPa can be taken for shear failure strength at 4.2 K in the case of anodic oxidation treatment. Using this stress to load the specimen in the FEA, we can draw the shear specimen failure envelope. All the Mohr circles are enclosed in the biggest one, which corresponds to the centre of the joint, where the loads are the largest. This circle can be considered as the specimen failure envelope.

Figure 10 presents on the same graph, the CMS coil insulation stress distribution and the optimised lap-joint specimen experimental failure envelope.
We can see that the Mohr circles of the coil insulation critical points are included in the specimen failure envelope. We should also remind that as discussed previously, the shear specimen failure envelope is only a part of the material failure envelope (see Fig. 8).

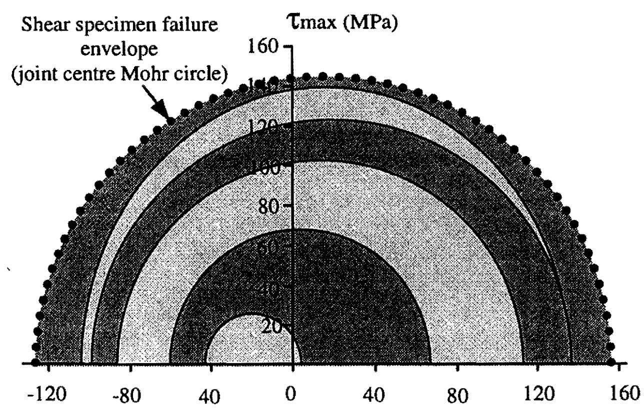

Fig. 9 : Optimised shear specimen Mohr diagram

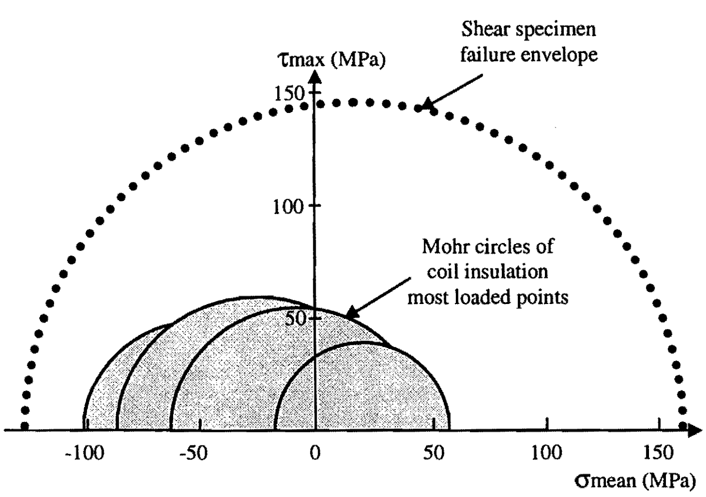

Fig. 10 : Coil insulation Mohr circles and shear specimen failure envelope

VI. CONCLUSIONS

The lap-joint specimen which has been designed has no edge effects and is mainly loaded in shear. After anodic oxidation surface treatment, rupture shear strength larger than 100 MPa has been obtained at 4.2 K.
The comparison between coil FEA [5] and test results in the Mohr diagram shows a significant engineering safety margin.

ACKNOWLEDGMENT

The authors would like to thank A. Forgeas for the specimen preparation and S. Cazaux, G. Lemierre and A. Poupel, for the tests at room and cryogenic temperatures. B. Gallet was deeply involved at the beginning in the specimen development and in the tests. Courtesy to S.Farinon for the CMS coil insulation FEA.

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