

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics*Large Hadron Collider Project***LHC Project Report 613****THERMAL CONDUCTIVITY
OF STRUCTURAL GLASS/FIBRE EPOXY COMPOSITE
AS A FUNCTION OF FIBRE ORIENTATION**

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Abstract

The LHC, the new superconducting particle accelerator presently under construction at CERN, makes use of some 1200 dipole magnets for orbit bending and 500 quadrupole magnets for focusing/defocusing of the circulating high-energy proton beams. Two or three column-type support posts sustain each cryomagnet. The choice of a convenient material for these supports is critical, because of the required high positioning accuracy of the magnets in their cryostats and stringent thermal budget requirements imposed by the LHC cryogenic system. A glass-fibre/epoxy resin composite has been chosen for its good combination of high stiffness and low thermal conductivity over the 2-293 K temperature range. Plies of long glass-fibres are stacked optimally yielding the best mechanical behaviour. However, heat leaks from the supports are influenced by the thermal characteristics of the composite, which in turn depend on the orientation of the fibres. To study the dependence of the thermal conductivity on fibre's orientation, we performed high precision thermal conductivity measurements of various samples of glass-fibre/epoxy resin composite. The results of the thermal conductivity measurements are compared with integral measurements on support posts for LHC cryomagnets and with mixing models.

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Thermal conductivity of structural glass-fibre/epoxy composite as a function of fibre orientation

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The LHC, the new superconducting particle accelerator presently under construction at CERN, makes use of some 1200 dipole magnets for orbit bending and 500 quadrupole magnets for focusing/defocusing of the circulating high-energy proton beams. Two or three column-type support posts sustain each cryomagnet. The choice of a convenient material for these supports is critical, because of the required high positioning accuracy of the magnets in their cryostats and stringent thermal budget requirements imposed by the LHC cryogenic system. A glass-fibre/epoxy resin composite has been chosen for its good combination of high stiffness and low thermal conductivity over the 2-293 K temperature range. Plies of long glass-fibres are stacked optimally yielding the best mechanical behaviour. However, heat leaks from the supports are influenced by the thermal characteristics of the composite, which in turn depend on the orientation of the fibres. To study the dependence of the thermal conductivity on fibre's orientation, we performed high precision thermal conductivity measurements of various samples of glass-fibre/epoxy resin composite. The results of the thermal conductivity measurements are compared with integral measurements on support posts for LHC cryomagnets and with mixing models.

INTRODUCTION

Supports are crucial elements in cryogenic structures: they must guarantee both a sufficient mechanical performance and low conduction heat in-leaks. A thermo-mechanical optimisation is necessary to fulfil these two conflicting requirements. Composites are well adapted and hence widely used for such applications. LHC cryomagnet supports, manufactured in low-cost glass fibre reinforced epoxy (GFRE), match the requirements of a sufficient mechanical stability during transport, installation and operation of the cryomagnets and allow at the same time a heat in-leak at 2 K as low as 40 mW per support [1].

Each support post is designed to carry heavy loads, up to 12 tons, and to keep a high positioning accuracy. The lay-up of the long glass-fibres plies has been optimised to fit these mechanical requirements. On the other hand, very little data on the thermo-mechanical conductivity of such structural composites exists, rendering a correct thermal optimisation difficult. A test bench for precise measurement of $k(T)$ for insulators has therefore been constructed and calibrated. Here we describe the set-up and present first results for pure resin and composites with different fibre orientations. Samples of the materials used for two types of support posts, series ones (subsequently referenced as A) and pre-series ones (subsequently referenced as B) are manufactured.

Table 1 presents the main characteristics of the composites.

Measured data are compared with literature [2,3] and with measurements on LHC support posts. Finally, models of the thermal conductivity are constructed to check their agreement with data.

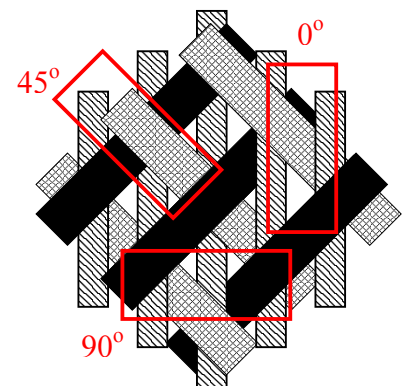


Figure 1 Structure of A-type layer and cupons cut-out.

Type	Epoxy resin	Glass fibre	Fibre vol. (Vf)	Layer	% of fibres per orientation per layer	Stacking
A	823RTM Cytec Fiberite	E	0.46	Triaxial fabric (see Fig.1)	49% (0°) 51% ($\pm 45^\circ$)	4 layers at 0°
B	UF3339 Thiokol	S2	0.5	Biaxial fabric	49%(fill) 51%(warp)	[0/-45/45/-45/0/ 45/-45/45/-45/45]

Table 1 : Main properties of A and B type composites.

SET-UP

Thermal conductivity is measured in a “4-wires” scheme, where a known heat flux is applied to the sample and the resulting temperature difference is measured directly in the sample’s body to avoid errors due to contact resistance at the extremities (see Figure 2). The test-bench, miniaturised to hold into the neck of a Dewar, consists in a long tube, ending with a small chamber, which contains the sample holder. The sample holder hangs from a copper disk in contact with the surrounding cryogenic liquid, via an appropriate thermal impedance separating the temperature of the sample holder’s base from that of the cryogen bath. The 50x8x4mm sample is cooled by its upper extremity via the sample-holder’s base, while heat is applied at its lower extremity. The extremities of a thermocouple in differential mode are inserted into the sample. A TVO carbon-glass thermometer monitors the base temperature. Any thermal by-pass of the sample leads to an overestimation of the thermal conductivity; hence, contact resistance between the sample and the thermocouple is minimized, as are conductive losses across the wires. Wire’s number, length and material are carefully dimensioned, wires are heat-sunked at the base. In principle, with an appropriate choice of thermal impedance to the heat sink, the test-bench can operate at any temperature between 5K and 300K, but as the temperature is increased, radiative losses to the vacuum vessel start to by-pass the sample, and a radiation screen, cooled by the base, becomes mandatory. In spite of all these precautions, very low temperature differences have to be maintained across the sample.

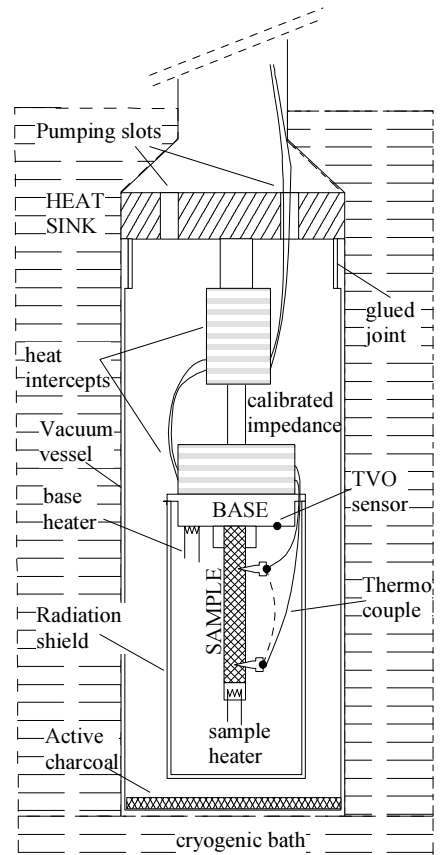


Figure 2 Schema of the test-bench

Calibration with a certified graphite sample from NIST [4] has permitted to estimate the error on $k(T)$ as limited to +5%.

MEASUREMENT RESULTS

Samples of A-type have been cut in different orientations of the composite. Pure resin samples are also included in the test program. Samples of B-type are only cut at a 0° orientation. Figure 3 shows the measured thermal conductivity values.

As expected, pure resin displays the lowest conductivity. Within the A-type samples, the highest conductivity is obtained for the highest fibre’s content in the longitudinal direction. Sample B has a 30% larger conductivity than sample A. The thermal conductivity is approximately proportional to the longitudinal fibre’s contents. Literature on conductivity of composite as a function of fibre content and orientation is sparse ([5,6] and references therein). On figure 2, we compare our results with published data obtained for a similar fibre’s content. A qualitative agreement is obtained. Data are also in agreement (within 10%) with conductivity measurements performed on two complete support posts manufactured in composites A and B, previously measured on a dedicated test-bench [1].

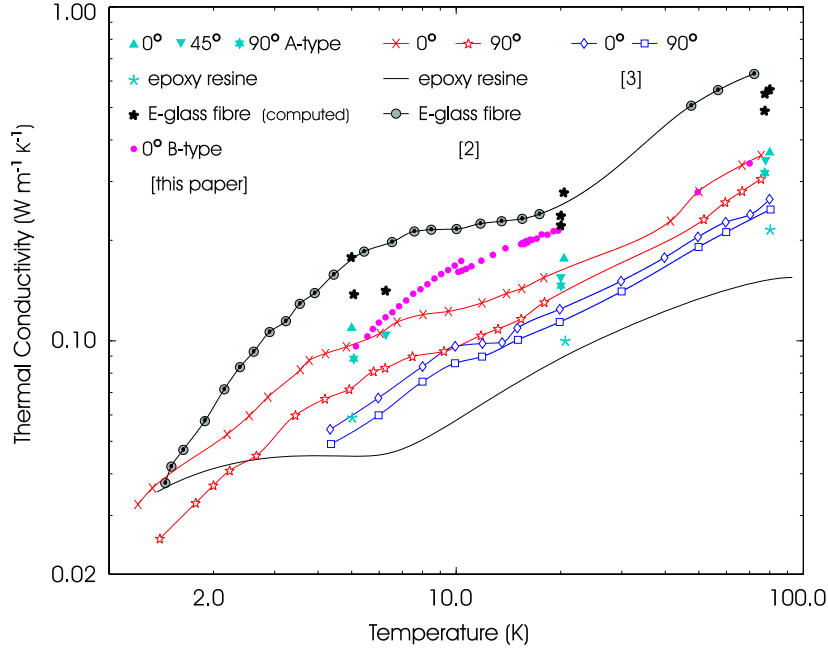


Figure 3 Comparison between our measurements and literature.

MODELLING

Some references on unidirectional composites (fibres embedded into the resin along a single direction) present measurements and models for the thermal conductivity. However, cryogenic supports should be mechanical parts resisting to complex load sets. Therefore, the optimised composite should be multidirectional, manufactured from layers of various orientations. In consequence, knowing the overall conductivity of multidirectional composites is of prime importance. In order to model it, we may have to consider coupling between the layers and between the differently oriented fibers of each layer.

Unidirectional composites.

Let $\lambda_{||}$ and λ_{\perp} be the conductivities of the material in the fibre's direction and perpendicularly to it, while λ_m and λ_f are resin's and fibre's conductivities. Glass fibre and resin are treated as isotropic materials. V_f denotes the volume fraction of fibres. The longitudinal conductivity is given by a classical mixing law:

$$\lambda_{||} = \lambda_f \cdot V_f + \lambda_m \cdot (1 - V_f) \quad (1)$$

For the computation of the transverse conductivity, several modified mixing laws are available. We consider three of them: Rayleigh's [7], Pilling's [8] and Clayton's [9] laws. In particular, the first one is the analytical solution for the transverse conductivity of a square array of cylinders, while the second is an improvement of the classical mixing law. The three models yield approximatively the same results.

Some authors [5] report a good agreement between measurements and such models for unidirectional composites. However, discrepancies appear at low temperatures, where phonon transmission impedance (Kapitza effect) between fibers and resins becomes non-negligible (see [10,11]).

Multidirectional composites.

One can find in the literature various analytical exact solutions for geometries of limited complexity (see [12]) which provide well tunable models containing coupling effects between fiber layers, while finite element models (FEM) can accurately account for complex geometries, with the disadvantage of needing one mesh for each configuration. We avoided heavy FEM models and chose to construct an analytical model for A-type composite. We turned to a first approach without coupling between layers. The four interleaved layers are considered as thermally independent, and each of them is seen as a stack of three unidirectional layers, which are not thermally interacting. The overall conductivity is the one of the constitutive layers in a parallel heat-transfer mode. The conductivity tensor of a layer is diagonal in its principal frame (in-plane tensor, with its first axis along the fibers' direction). In a different frame, rotated by an angle θ , it becomes:

$$\bar{\lambda}_\theta = P_\theta^{-1} \cdot \bar{\lambda} \cdot P_\theta \quad (2)$$

where P is the rotation matrix. Hence, the conductivity of a 0° layer is $\bar{e}_{0^\circ} \cdot \bar{\lambda}_{0^\circ} \cdot \bar{e}_{0^\circ} = \lambda_{//}$, while the one of a layer rotated by an angle of 45° is equal to $\bar{e}_{0^\circ} \cdot \bar{\lambda}_{45^\circ} \cdot \bar{e}_{0^\circ} = \frac{1}{2}(\lambda_{//} + \lambda_{\perp})$. The overall conductivity is then:

$$\lambda_{eff}^{0^\circ} = \alpha \cdot \lambda_{//} + \frac{1}{2}(1 - \alpha)(\lambda_{//} + \lambda_{\perp}) \quad (3a)$$

where α denotes the ratio between longitudinal and non-longitudinal fibres in a single layer. The longitudinal conductivity is computed applying the linear mixing rule eq.1, the transverse is calculated with any of the three models presented above.

Measurements have been performed for samples cut in the 0° as well as the 45° and 90° directions (see Figure 1). In the two other cases, we can estimate the effective conductivity in the same way, namely:

$$\lambda_{eff}^{90^\circ} = \alpha \cdot \lambda_{\perp} + \frac{1}{2}(1 - \alpha)(\lambda_{//} + \lambda_{\perp}) \quad (3b) \quad \text{and} \quad \lambda_{eff}^{45^\circ} = \frac{1}{2}(\lambda_{//} + \lambda_{\perp}) \quad (3c)$$

Then, the only variable which is not known in this model is λ_f , the thermal conductivity of E-glass fibres. We used this model to compute it and compare the resulting value with [2]. We obtain in this way a different value of λ_f for each orientation of the composite. The three values are in the correct range, as seen on Figure 3, but a systematic trend, i.e. higher 'reconstructed' fibre conductivity for orientations close to 0° , more striking at low temperatures, reminds us that our model is not only neglecting the Kapitza effect mentioned above, but also the coupling between layers.

CONCLUSIONS

Precise thermal conductivity measurements are needed for thermo-mechanical optimisation of cryogenic supports, since they permit tuning of predictive models. We have shown that we are able to perform measurements on a large temperature range and that anisotropic behaviour of reinforced composites can be accurately detected. To allow a best fit of data, the interaction between fibres and resin in the transverse direction has to be calculated, especially below 10K. Further work is necessary to obtain a larger set of data, and then to be able to qualify or construct a convenient model to predict the conductivity of a reinforced composite knowing the characteristics of the constitutive materials.

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