CHARACTERIZATION OF THROUGH-THICKNESS THERMAL CONDUCTIVITY OF WIND TURBINE BLADE CFRP MATERIALS USING A STEADY-STATE TECHNIQUE

Evangelos C. Senis[1], Igor O. Golosnoy[2], Janice Dulieu-Barton[1], Ole T. Thomsen[1] and Søren F. Madsen[3]

[1] Faculty of Engineering and the Environment, University of Southampton, United Kingdom
[2] Faculty of Physical Sciences and Engineering, University of Southampton, United Kingdom
[3] Global Lightning Protection Services, Denmark

Email: E.Senis@soton.ac.uk

Keywords: CFRP, Thermal conductivity, Wind turbine blades, Lightning protection

ABSTRACT

The through-thickness thermal conductivity of unidirectional CFRP laminates was examined by means of a steady-state technique based on the Guarded Hot Plate (GHP) method. By establishing the one-dimensional heat flow through the sample and measuring the heat flux the thermal conductivity was determined. To validate the technique, measurements were conducted in two different materials with well-defined values. PTFE and Fused Silica samples were employed as reference materials. Calibration runs showed good correlation with the expected literature values for both of the reference materials. Unidirectional CFRP laminates with a fibre volume content of 57% were manufactured using Vacuum Assisted Liquid Resin Infusion in three different thicknesses to assess the measuring capabilities of the apparatus. Consistent results were obtained for all three laminate thicknesses thus validation the efficiency and accuracy of the technique.

1 INTRODUCTION

The thermal response of CFRP (Carbon Fibre Reinforced Polymers) materials has received significant scientific interest during recent years due to the increasing use of these materials in aerospace and automotive applications, which in turn has created new scientific and technical challenges. Unlike metals and other isotropic materials, the anisotropic properties including thermal conductivity of CFRP, impede their incorporation in applications in which thermal loads can be imposed on the structure. Their poor transverse and through-thickness direction thermal conductivity, compared to the values encountered parallel to the fibre direction, impedes the heat dissipation in the bulk material resulting in local heating and thermal degradation of the composite laminate [1, 2].

The wind turbine industry has only recently started embracing large scale usage of CFRPs in the principal load carrying elements of wind turbine blades. This is to achieve longer and lighter blades, compared with blades made from traditional GFRP (Glass Fibre Reinforced Polymer), allowing for higher rated power output of wind turbines [3]. As the blades become longer an increase in the overall height of the wind turbine needs to be realized to incorporate them into the design, and current wind turbines reaching heights (ground to blade tip in upper position) up to 230m with future trends suggesting even larger machines.

Such tall structures exhibit higher lightning susceptibility and when adding electrically semiconducting materials such as CFRP to the blade structure new challenges are introduced for the wind turbine lightning protection systems since modern multi-MW wind turbines are expected to receive 1-2 lightning strikes each year [4-6]. To minimize the risk of internal flashovers, equipotential bonds between the down conductor and the CFRP sparcaps of the wind turbine blades need to be realized along the length of the blades. In these equipotential bonds electric current is introduced into the structure allowing current flow through the main CFRP laminate/sparcap of the blade. High thermal loads attributed to Joule heating are induced in these electrical connections. Considering the poor electrical conductivity of CFRP in the transverse and through-thickness directions, high temperature gradients can be observed in these directions. Taking into account that the thermal conductivity is also very low (much lower than in the fibre direction) in these directions heat dissipation is constricted, and as a result localized thermal damage can degrade the properties of the equipotential bond/structure that can deteriorate the performance of the lightning protection system as well as the structural integrity.

Similarly to the electrical conductivity, CFRP materials exhibit anisotropic thermal conductivity. Factors such as fibre volume content, laminate layup as well as the properties of constituent materials affect the thermal conduction mechanism. Thus, phonon scattering which is the predominant thermal conduction mechanism in CFRP differs in the carbon fibres and the polymer matrix, since phonons can travel faster through the crystalline structure of carbon fibres compared to the amorphous polymer [7]. A key aspect of wind turbine CFRP sparcaps is that they are usually manufactured using vacuum infusion and they feature additional layers of glass fibres placed between carbon layers as well as glass fibre stitches that help to ease the resin flow. Considering that glass fibres have similar thermal conductivity to epoxy resins, between 0.2-0.3 W/mK, their presence influence the heat conduction in the transverse and through-thickness directions [8].

Several experimental techniques have been developed to determine the thermal conductivity of solids. These techniques can be categorized either as steady-state (Guarded Hot Plate) or transient (laser flash, Transient Hot strip, Hot Disk etc.) [1, 7, 9-14]. Variations or discrepancies can be observed between the values obtained using the two different techniques, and therefore accurate methods need to be developed [15]. A significant advantage of the steady-state techniques is that, unlike transient methods, no additional information about the examined material such as specific heat is required.

The purpose of this study is to characterize the through-thickness thermal conductivity of CFRP used in wind turbine blade applications. To achieve these measurements a novel measuring method was developed.

2 EXPERIMENTAL METHODOLOGY

2.1 Sample preparation

A two-component epoxy system supplied by BASF was used as matrix material. The system consisted of Baxxores® ER 5300 epoxy resin and Baxxodur® EC 5310 curing agent. The components were mixed by weight at a ratio of 100/20 according to the specifications of the manufacturer. Aunidirectional non-crimp carbon fabric, supplied by SAERTEX GmbH & Co, Germany, with Zoltek Panex 35 50K carbon fibres and an areal weight of 852g/m^2 was used as reinforcement. The fabric featured glass fibre stitching of 24g/m^2. Unidirectional laminates consisting of 2, 5 and 10 plies were manufactured by means of Vacuum Assisted Liquid Resin Infusion. The infused laminates were cured at 70^{o}C for 6 hours, which is the recommended curing profile specified by the supplier. The fibre volume content, which was determined using optical microscopy (Fig. 1), was approximately 57%. Disk shaped samples, with a diameter of 50mm, were made from the manufactured plates using waterjet cutting

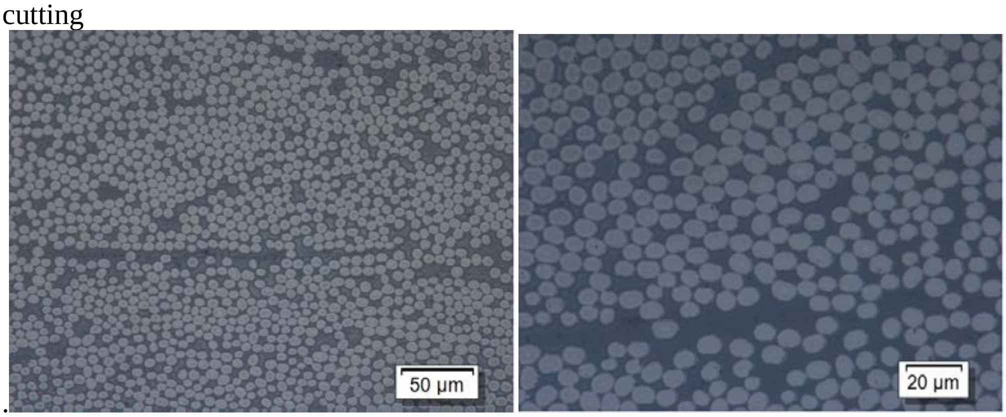

Figure 1: Micrograph for the [0^o]$_5$ laminate corresponding to 57% fibre content.

2.2 Experimental setup

To obtain the thermal conductivity in the through-thickness direction, CFRP samples were placed between two Brass substrates (Fig. 2). By applying a heat flux from the bottom substrate (hot plate) and by constantly extracting heat from the heat sink a one-dimensional heat flow can be achieved, assuming that no lateral heat losses exist. Steady-state conditions were assumed when the temperature difference between the substrates was not exhibiting fluctuations higher than ±0.5°C for 30min.

A heating element rated at 2W at 12V was connected with a DC voltage source to provide the heat flow. To accurately measure the heat flux a thin film flux sensor, HFS-4, OMEGA Engineering, United Kingdom was utilised. The flux sensor had a nominal thickness of 180μm and it was calibrated at 1.6μV/W/m^2 of sensitivity. The heat flux q was calculated with the use of Eq. (1).

$$q=V/S \tag{1}$$

Where V is the sensor's DC voltage in μV and S the sensitivity in μV/W/m^2.

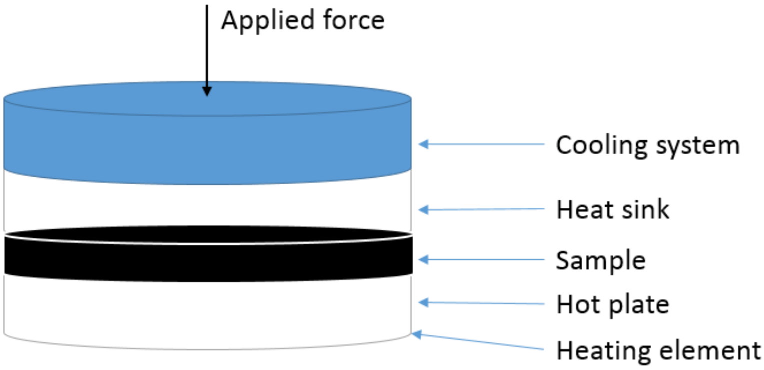

Figure 2: Schematic representation of the apparatus whithout the insulation.

The DC voltage measurements were logged through the Agilent Technologies 34401A multimeter. Temperature readings were achieved using K-type thermocouples connected to a Pico Technologies TC-08 data logger. To avoid lateral heat losses PMI (Polymethylacrilimide), Rohacell, foam was attached around the entire setup. As a cooling fluid an Ethylene Glycol mixture was circulating through the cooling block via a Heto CBN 8-30 cold bath/circulator. The temperature of the cooling fluid was controlled through the built-in thermostat.

To promote reproducibility of the measurements a M6 bolt was utilized to apply constant pressure. By applying 1Nm of torque to the bolt an axial force of ~555N was generated resulting in 0.28MPa of applied pressure. Mitigation of thermal resistance is crucial to obtain accurate results, as the sample surface roughness can lead to the formation of air gaps in the interface between the sample and the substrates. Thus to eliminate these factors both of the brass substrates were polished to achieve a surface roughness not greater than 5μm.

Finally a thermally conducting paste, Electrolube HTSP, with a thermal conductivity value of 3 W/mK was utilised to increase the thermal conductance and mitigate thermal resistance between the sample and the substrates. The samples were not polished to avoid any removal of material that might alter their morphology.

2.3 Validation of the technique

To validate the measuring performance of the apparatus capabilities prior its use, conducting measurements were carried out using materials with well-defined values, also known as reference materials. In this study two reference materials were used to obtain a two point calibration. PTFE (Polytetrafluoroethylene), supplied by RS Components, and Fused Silica (quartz glass), supplied by UQG Optics, were employed (Table 1). The thickness of both reference samples was 6mm. Calibration runs were conducted at a heat flux level of approximately 1000 W/m^2 for both materials to assure consistency in the measurement conditions. By applying a voltage of 12 V to the heating element the abovementioned heat flux was introduced to the sample. Constant heat extraction was achieved through the heat sink/cooling system. The obtained values for the reference materials are listed in the table below (Table 1). Each sample was tested at least twice.

Material	Thermal Conductivity (literature) (W/mK)	Thermal Conductivity (measured) (W/mK)
PTFE	0.25	0.261±0.004
Fused Silica	1.38	1.196±0.08

Table 1: Thermal conductivity values of reference materials at 20°C

The thermal conductance h was estimated at 1.33 kW/m^{2}K for the PTFE and at 2.6 kW/m^{2}K for the Fused Silica. By comparing the measured values with values found in the literature a deviation of 4.72% can be observed for the PTFE and 13.3% for the Fused Silica respectively. The higher percentage of deviation observed in the Fused Silica is assumed to be due to an increase of thermal resistance.

3 RESULTS AND DISCUSION

3.1 CFRP through-thickness thermal conductivity

Measurements in the through-thickness direction were conducted on the UD CFRP samples consisting of 2, 5 and 10 plies. Three samples were cut from each of the manufactured plates to eliminate any influence from variations of the fibre volume content, each sample was tested at least twice. From the obtained results listed in the table below (Table 2) it is seen that the thermal conductivity values measured were consistent for all three laminate thicknesses with minor variations.

Sample	Thermal Conductivity (W/mK)
$[0^o]_2$	0.633±0.098
$[0^o]_5$	0.655±0.044
$[0^o]_{10}$	0.695±0.042

Table 2: Through-thickness thermal conductivity of CFRP

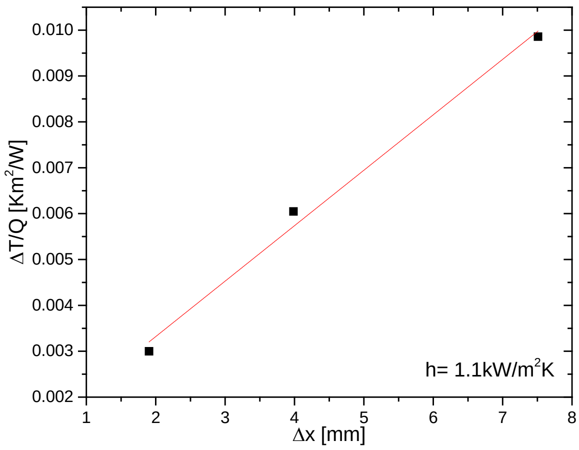

Figure 3: Plot of ΔT/Q versus Δx for the CFRP samples (three different thicknesses).

A key parameter in thermal conductivity measurements is to achieve a high thermal conductance (h) between the substrates and the sample. Thermal conductance estimations can be achieved by conducting measurements in samples with different thickness by plotting ΔT/Q versus Δx. This is shown in Fig. 3 from which 1/h can be calculated. In this case the thermal conductance h was found to be 1.1 kW/m^{2}K. The mean heat flux during the measurements was 1380W/m^2.

Estimations of the measurement uncertainty were achieved by calculating the temperature drop in the interface between the brass substrate and the sample since the addition of the flux sensor and the thermal paste (Fig. 4) can interfere with the measurement of the temperature drop across the samples thickness, ΔT. Knowing the thickness Δx of each component and its thermal conductivity value (Table 3) in conjunction with temperature readings from T1 and T2 thermocouples, estimations of the uncertainty were achieved depending on the applied heat flux and temperature drop at the interface.

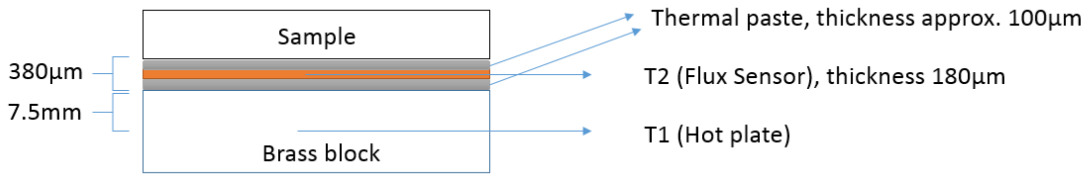

Figure 4: Schematic representation of the interface between substrate and sample (dimensions not to scale).

Component/Material	Brass substrate	Thermal paste	Flux sensor
k (W/mK)	105[1]	3[2]	9.52[3]

[1] Literature value
[2] From manufacturer
[3] Calculated based on the thermal resistance provided by the manufacturer

Table 3: Thermal conductivity values of interface constituents.

Based on the methodology described above, the uncertainties were estimated to 15.5% for the 2-ply, 6.68% for the 5-ply, and 6% for the 10-ply laminate respectively. While the uncertainty for the 5 and 10-ply laminates is quite similar, the measurements for the 2-ply laminate showed a higher percentage of deviation.

4 CONCLUSIONS

A technique for measuring the thermal conductivity has been presented. Whilst the technique is simple, it has been shown to be robust and able to provide accurate results for CFRPs and polymer composites. By conducting measurements in samples of different thicknesses similar results were obtained, thus verifying the applicability of the technique over a wide range of sample thicknesses. Good interfacial conductance was achieved with the use of a silicone based heat transfer paste, which also helped to mitigate the influence of sample surface roughness. The obtained thermal conductivity values for the manufactured CRFP samples exhibit good correlation with values found in literature for PAN-based CFRP with similar fibre volume content. The existence of glass fibre stitching does not seem to affect the heat conduction in the through thickness direction since its fibre volume fraction is low compared to volume fraction of the carbon fibres. Minor alteration in the design of the apparatus will enable investigation of the transverse thermal conductivity, and this is planned for future research.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to Dr. Wendell Bailey for providing both components and help during the early stages of this research. This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 642771. Weblink: http://sparcarb.com/

REFERENCES

[1] S. Han, J. T. Lin, Y. Yamada, and D. Chung, "Enhancing the thermal conductivity and compressive modulus of carbon fiber polymer–matrix composites in the through-thickness direction by nanostructuring the interlaminar interface with carbon black," *Carbon,* vol. 46, pp. 1060-1071, 2008.

[2] Y. Lin, M. Gigliotti, M. C. Lafarie-Frenot, and J. Bai, "Effect of carbon nanotubes on the thermoelectric properties of CFRP laminate for aircraft applications," *Journal of Reinforced Plastics and Composites,* vol. 34, pp. 173-184, 2014.

[3] M. Rosemeier and M. Bätge, "A concept study of a carbon spar cap design for a 80m wind turbine blade," in *Journal of Physics: Conference Series*, 2014, p. 012039.

[4] F. Rachidi, M. Rubinstein, J. Montanya, J.-L. Bermudez, R. R. Sola, G. Sola, *et al.*, "A review of current issues in lightning protection of new-generation wind-turbine blades," *IEEE Transactions on Industrial Electronics,* vol. 55, pp. 2489-2496, 2008.

[5] B. M. Radičević, M. S. Savić, S. F. Madsen, and I. Badea, "Impact of wind turbine blade rotation on the lightning strike incidence–A theoretical and experimental study using a reduced-size model," *Energy,* vol. 45, pp. 644-654, 2012.

[6] A. Candela Garolera, S. F. Madsen, M. Nissim, J. D. Myers, and J. Holboell, "Lightning Damage to Wind TurbineBlades From Wind Farms in the U.S," *IEEE Transactions on Power Delivery,* vol. 31, pp. 1043-1049, 2016.

[7] E. Kandare, A. A. Khatibi, S. Yoo, R. Wang, J. Ma, P. Olivier, *et al.*, "Improving the through-thickness thermal and electrical conductivity of carbon fibre/epoxy laminates by exploiting synergy between graphene and silver nano-inclusions," *Composites Part A: Applied Science and Manufacturing,* vol. 69, pp. 72-82, 2015.

[8] N. Burger, A. Laachachi, M. Ferriol, M. Lutz, V. Toniazzo, and D. Ruch, "Review of thermal conductivity in composites: Mechanisms, parameters and theory," *Progress in Polymer Science,* vol. 61, pp. 1-28, 2016.

[9] J. Tan, S. Tsipas, I. Golosnoy, J. Curran, S. Paul, and T. Clyne, "A steady-state Bi-substrate technique for measurement of the thermal conductivity of ceramic coatings," *Surface and Coatings Technology,* vol. 201, pp. 1414-1420, 2006.

[10] J. R. Gaier, Y. YoderVandenberg, S. Berkebile, H. Stueben, and F. Balagadde, "The electrical and thermal conductivity of woven pristine and intercalated graphite fiber–polymer composites," *Carbon,* vol. 41, pp. 2187-2193, 2003.

[11] K. Sharp, A. E. Bogdanovich, W. Tang, D. Heider, S. Advani, and M. Glowiana, "High Through-thickness Thermal Conductivity Composites Based on Three-Dimensional Woven Fiber Architectures," *AIAA Journal,* vol. 46, pp. 2944-2954, 2008.

[12] B. Beltrán-Pitarch, L. Márquez-García, G. Min, and J. García-Cañadas, "Measurement of thermal conductivity and thermal diffusivity using a thermoelectric module," *Measurement Science and Technology,* vol. 28, p. 045902, 2017.

[13] M. Pilling, B. Yates, M. Black, and P. Tattersall, "The thermal conductivity of carbon fibre-reinforced composites," *Journal of Materials Science,* vol. 14, pp. 1326-1338, 1979.

[14] S. E. Gustafsson, "Transient plane source techniques for thermal conductivity and thermal diffusivity measurements of solid materials," *Review of Scientific Instruments,* vol. 62, p. 797, 1991.

[15] R. Rolfes and U. Hammerschmidt, "Transverse thermal conductivity of CFRP laminates: a numerical and experimental validation of approximation formulae," *Composites Science and Technology,* vol. 54, pp. 45-54, 1995.