CHARACTERIZATION OF THE LONGITUDINAL AND TRANSVERSE THERMAL CONDUCTIVITIES OF CARBON/EPOXY COMPOSITE MATERIAL

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Abstract

The present work describes a method for the characterization of the longitudinal and transverse conductivities of the carbon/epoxy composites and its fibres. This method consists in two steps.
Firstly, composite specimens are fabricated with controlled fibre orientations and rates in a completely known DGEBA matrix. These specimens are used to measure thermal conductivities with a Nanoflash device. We designed a modulable mould with two different cores which allows to produce two types of specimen, one to measure the longitudinal conductivity and the other to measure the transverse conductivity of UD composite. The specimens are obtained by the fibre placement around the two cores and the matrix injection in the mould using the Vacuum Assisted Resin Transfer Moulding method.
Once the specimen is done, we take off samples that are tested in the Nanoflash device. This experiment provides us with the thermal diffusivity. After that, by calculation, we obtain the thermal conductivity. Secondly, the multiscale thermal behaviour of the composite is simulated with the use of the Finite Elements Method. The inverse and direct method is then used to determine the transverse and longitudinal fibre conductivity, respectively. Indeed, we can directly measure the longitudinal conductivity of the composite using our samples. This value follows very well the law of mixtures between matrix and fibre thermal conductivities. For the transverse conductivity, we use an inverse method to determine the transverse fibre conductivity using a FEM fitting of the experimental transverse conductivity results for the UD composite.
These homogenised values at the micro scale are then used for mesoscale simulation (REV) in order to compare with experimental characterisation of composite made of different fibrous architecture. We finally propose an upgraded analytical model which accounts for both the geometry at the mesoscale level and the components (fibre and matrix) individual properties.

1 Introduction

1.1 Industrial demand and interest

The industry shows a bigger and bigger interest for thermally conductive materials, For instance, high thermal conductivity can be needed to design on board heat drain. Last years have seen a considerable development in on board electronic devices and with that a permanent increase of the need of power of calculation and so on more heat to dissipate.
Some actors of the industry have made the choice of aluminium because it's well known but it's still heavy compared to composite materials that are more and more integrated on board, either in aeronautics, aerospace or trains.
In a will of consumption reduction and power efficiency, the reduction of the mass is highly studied and that the reason why we are developing a composite solution to fit this demand.
This approach of trying to improve thermal is quite recent and that's why, compared to about electrical behaviour, their are quite a few works and studies about this domain of investigation.

1.2 Matrix improvement

To design a composite thermally efficient, we have design both fibres and matrix and in that chapter, we will focus on the matrix. Given the fact that we have design a fire resistant composite, two different way can be followed to develop a thermally conductive matrix. The first one consists in choosing a model DGEBA matrix and in fact the system Huntsmann Araldite LY556 with Jeffamine D230 hardener. The second one would be to choose an already charged matrix that already respects the fire requirements and to charge it in order to make the matrix more conductive. We choose in this work the first way.
The Figure 1 presents the two main important characteristics of the matrix which are its thermal conductivity and its viscosity.

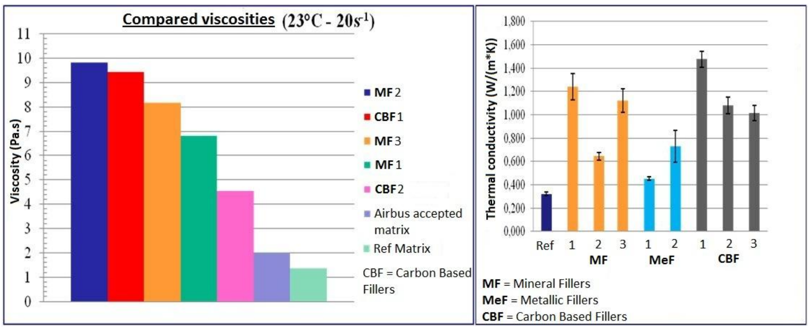

Figure 1. Viscosity and thermal conductivity for the model matrix charged with different particles

We can see that that most efficient charges are the one that increase the more the viscosity of the matrix. The densities of the charges are also determinant in our context and that's why we will focus on two charges, CBF1 and CBF2.
In the matrix development, we have to keep in mind the process that will be used in order not to develop an unusable matrix thermally very efficient.
After a massive investigation in the charges available on the market, we have chosen to work with morphologically modified charges that are declined from the CBF1 and the CBF2, one of them is CF3, which a modified CBF2. The difference is the size and the granulometry of the charges that allow us to increase the charge rate without increasing that much the viscosity.
An other problem that can appear depending on the textile used is the filtration of the charges that's why granulometry is also very important and why we develop specific 3D textiles.
Finally, we have to balance a trio conductivity/viscosity/granulometry to produce the most efficient matrix.

2 Identification of the microscopic scale thermal conductivities

In order to identify the homogenised thermal conductivity of an unidirectional composite following the different orientations (transverse and longitudinal), the thermal properties of both individual components (matrix and fibres) have to be known. The epoxy matrix is considered as being fully isotropic while the carbon fibres are supposed to be transversally isotropic.
Given the fact that measuring thermal characteristics of carbon fibres is very difficult directly (especially for transverse fibre conductivity), we choose to use an inverse method using a Finite Elements Method.
In this part, I present the experimental method we developed to build test specimens with well oriented fibres to be able to measure longitudinal and transverse conductivities of a carbon/epoxy composite.

2.1 Development of an experimental method to build controlled test specimens

In the Figure 2, I present the mould we developed to build two different types of specimens. The first one, the thinnest one on the top is dedicated to the measure of the transverse characteristics whereas the second one is focused on longitudinal conductivity.
The orange line shows the orientation of the fibres and the two green ellipsis illustrate the design of the sample that the NanoFlash requires.

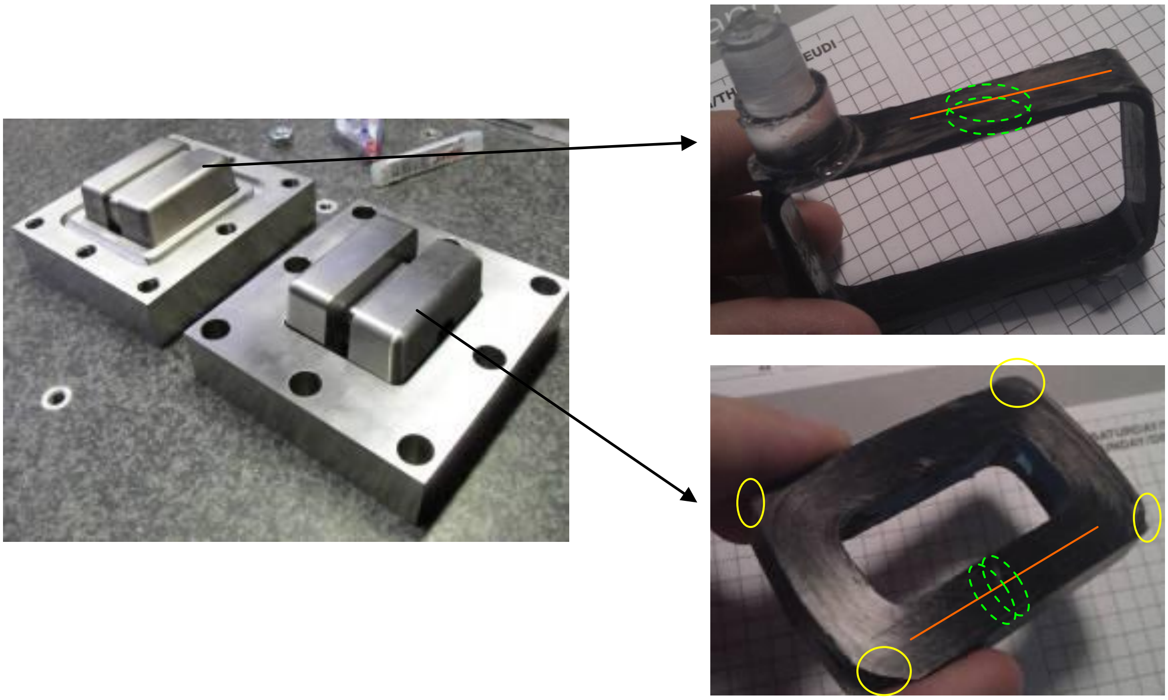

Figure 2. Modulable system to build the two type of test specimens

This system allows to build specimens with a very low porosity content which is under 1% and with an equal repartition of the fibres except in the yellow circles which will never be used for any measure so that we are confident in the quality of our specimens.

2.2 Inverse method to determine fibres conductivities

In parallel of the experiments, we have to design an Elementary Representative Volume at microscopic scale to calculate its homogenised transverse conductivity function of the conductivity of the fibre and to fit the result of the calculation to the experimental result to obtain the transverse thermal conductivity of the fibre.

The Figure 3 presents one ERV with a 50% fibre volume ratio on which we impose a 1K temperature gradient between two faces. We obtain the homogenised thermal conductivity integrating the heat flux on one face using Fourier's Law.

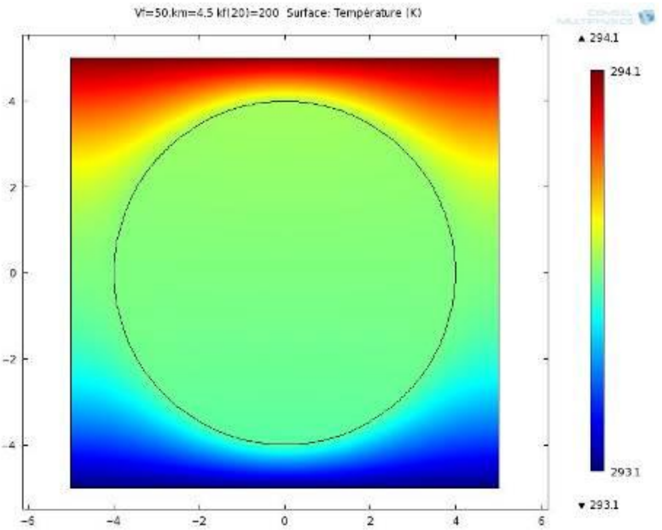

Figure 3. Elementary Representative Volume for the characterization of transverse thermal conductivity.

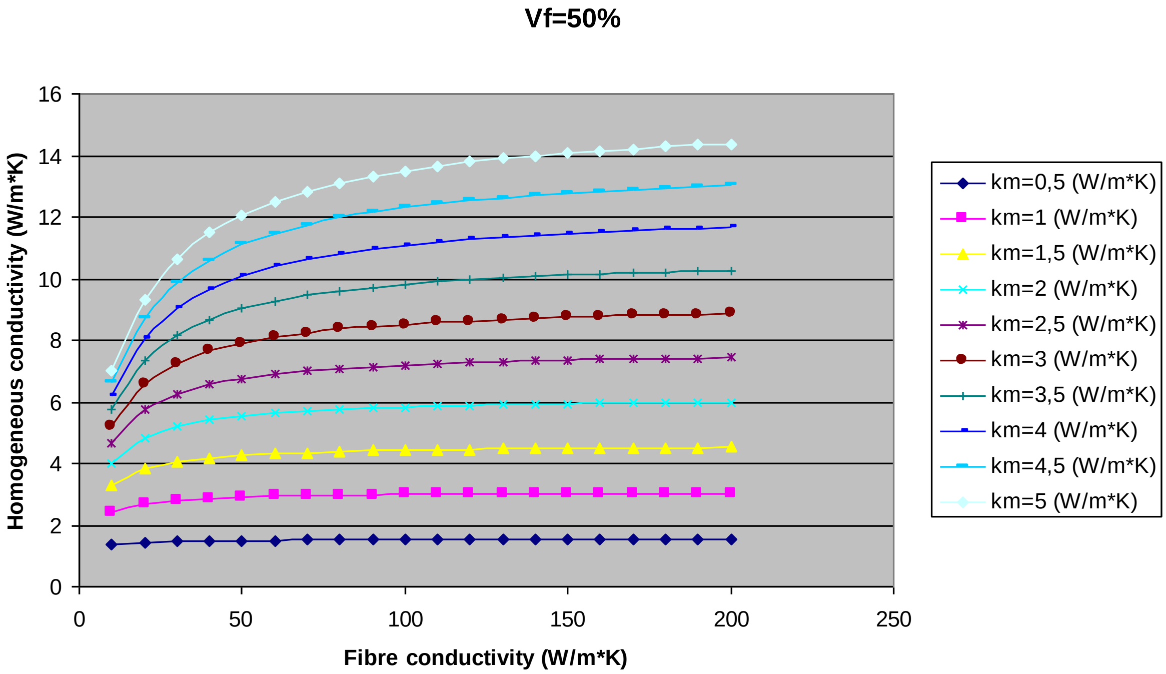

Figure 4. Homogeneous transverse conductivity function of the matrix and fibre conductivities at a 50% fibre ratio.

The Figure 4 shows the simulated homogeneous conductivity of a composite at microscopic scale. We can observe that the higher the matrix conductivity is the higher the correlation between the fibre conductivity and the homogeneous one is. In this paper, we only present the most classical microscopic REV (a circle embedded into a square), but in order to effectively fit and understand the experimental data, we have had to modify this REV (modifying the geometry -circle into a rectangle- and the material properties). Full results will be presented at the conference.

The Figure 5 stands to illustrate the measurement system we use which is a NanoFlash from Netzsch. This method illuminates the specimen with a known quantity of energy on one side of the sample and measures the temperature on the other side.

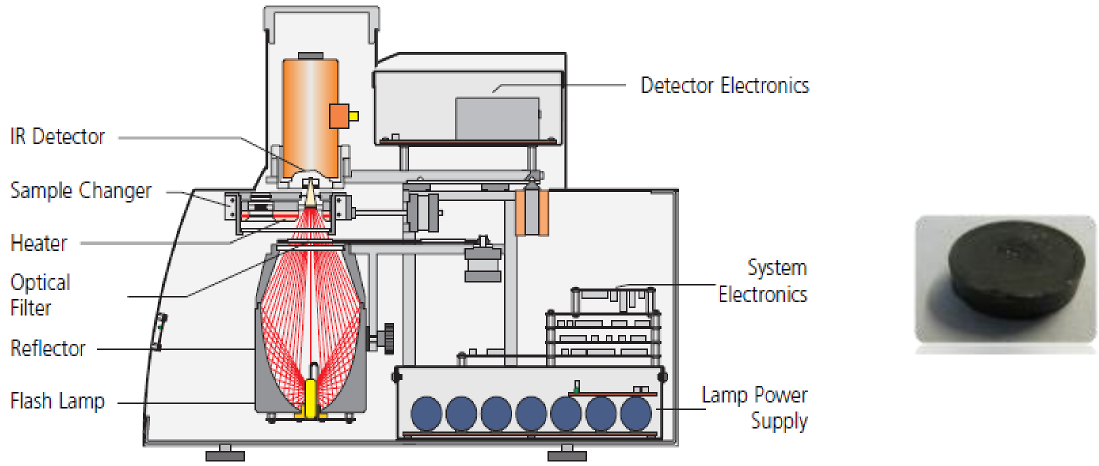

Figure 5. The NanoFlash system used in this work and the test specimen needed to make a measure.

2.3 Analytical model for micro scale

We briefly describe here the most classical models used to model the homogenised longitudinal and transverse thermal conductivity. The electrical network analogy is widely used in the literature [] for this kind of analogy. In the case of longitudinal homogenised conductivity, the model compares quite well with the experimental results, but for the transverse case, a correction has to be applied because of the geometric effect of the circle in the box instead of a stack of layers which would fit quite exactly with the analytical model.

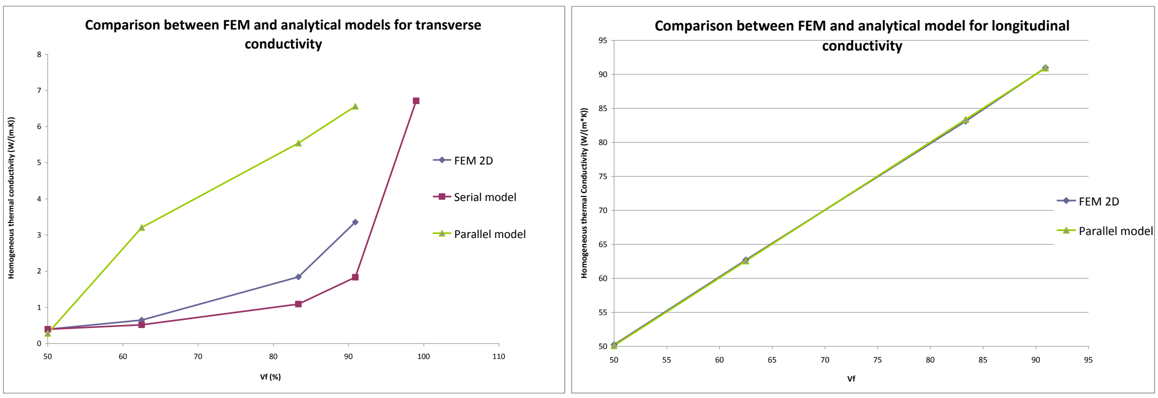

Figure 6. Comparison between FEM and analytical models for transverse and longitudinal conductivity

3 Characterization of the mesoscopic scale thermal conductivities

3.1 Different textile architectures

In order to reach our goal in terms of through thickness thermal conductivity, one of the classical idea consist in adding through thickness fibres which will transport heat from one side to the other. In the framework of this project, we have used different kind of reinforcement: 2D, 2.5D woven and knitted based architectures which allow to produce fibrous architectures comprising through thickness fibres.

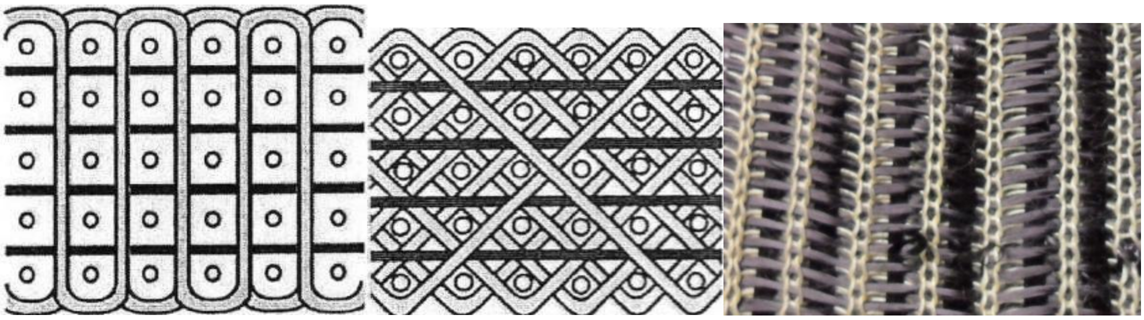

Figure 7. A 3D orthogonal Interlock, an Angled Interlock and a 3D textile developed by JTT Composite.

3.2 Mesoscopic scale models

2D and 2.5D textile geometry have been produced and simulated in order to better understand the heat flux conduction through the thickness as function of the fibrous architecture and component properties. Examples of such geometries are presented bellow as well as some FEM calculation results showing the relative influence of the homogenised tow on the homogenised reinforcement properties.

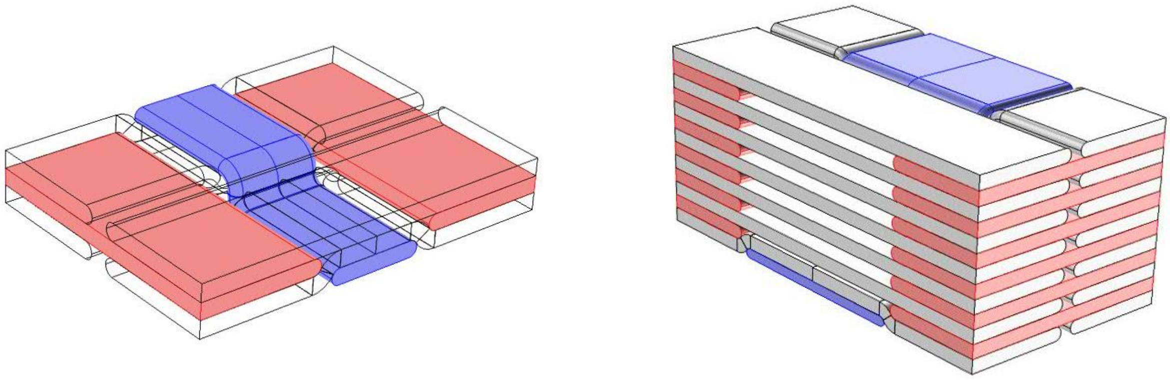

Figure 8. Example of 2 and 2.5D fibrous architectures used for composite thermal simulations.

The figure bellow illustrates the evolution of through thickness homogenised thermal conductivity of a 2.5D architecture based composite as function of the longitudinal conductivity of the tows, the isotropic conductivity of the matrix and a ratio defining the quotient of the longitudinal over the transversal conductivity of the tows.

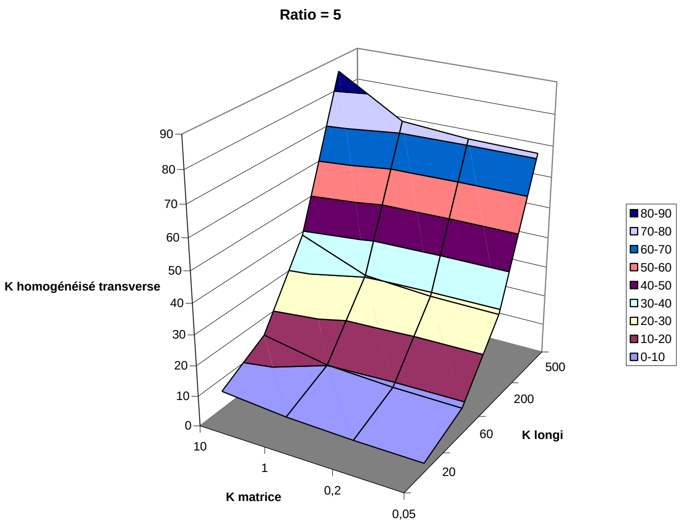

Figure 9. Example of computations on 2.5D fibrous architectures based composite.

Following these 3D FEM calculations, a simple analytical model still based on the electrical network analogy and similar to ref[5] has been developed in order to allow fast prediction of the thermal homogenised properties of a given composite (especially the fibrous architecture) in particular for optimisation purposes.

4 Synthesis of the results

At the moment I'm writing this article, we are able to produce macroscopic samples with different textile architectures, matrix and processes. The characterizations are done at this moment and more results will be available at the conference.

With the characteristics we have figured out for the moment we can think that to develop a thermally efficient composite material we'll have to control fibre orientations mostly for the out plane conductivity. We keep on developing specific textiles architectures and studying in the market architectures such as interlock to improve thermal performance.

In the same time, Rescoll team keep on developing the best matrix possible testing lots of charges and processes to produce industrially compatible quantities of charges.

We have established a goal of 250 W/(m*K) in plane thermal conductivity and a 50 W/(m*K) out plane conductivity. and we are very confident and optimistic in our chance of success.

5 Conclusion and aperture about future work

We developed an efficient method to measure thermal properties of a carbon fibre which are the most important characteristics needed to design a composite part with thermal functions such as thermal dissipation instead of aluminium plates.

We will know focus on one hand our work on developing FEM models that will allow us to design and dimension more efficiently parts and structure at bigger scales.

On the other hand we are already developing analytical models that will be able to predict thermal behaviour of a composite plate given its composition and the architecture of the textile.

Acknowledgments

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