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# Study of Inter-Ply Electrical Percolation Phenomena in CFRP Composite Materials

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In this paper, a predictive homogenization model that takes into account electrical percolation is used to predict the electrical properties of a unidirectional carbon-epoxy composites. A calculation of the tensor of electrical conductivities is proposed for different sequences of ply of a stratified composite material in order to highlight the phenomena around the interface between the plies.

*Index Terms*— Electrical percolation, Homogenization model, Phenomena of interface, Stratified composite material.

## I. INTRODUCTION

BEFORE the use of composites, the size and shape of the pieces were constrained by the mechanical strength of the material used. Thanks to the composites, it is now possible to create a material with mechanical capacities adapted to the shape and the stresses undergone by the part. Carbon fiber reinforced polymer matrix (CFRP) composites are becoming increasingly important in this industrial context, especially with the search for mass gain in aircraft structures such as fuselage. Thus, it is necessary to respond more effectively to the constraints of rate and temperature control by studying innovative methods of focusing the heating power. However, unlike homogeneous metal structures, composite structures (CFRP) have very anisotropic conductivity characteristics and inter-ply interface phenomena. Indeed, A CFRP is a pileup of several layers called plies, as shown in Fig. 1(a). In each ply, the carbon fibers are oriented in the same direction and maintain together by a thermoplastic matrix. Between the adjacent plies, the fibers can be oriented in different directions to ensure the mechanical performance of the composite, as shown in Fig. 1 (b).

Throughout life cycle of composite material, an input of heat is sometimes necessary (polymerization, forming, assembly, recycling process ...). Electromagnetic induction is an efficient way for direct and volumic heating for this type of material [1]. Indeed, with the induction heating the cycle time is short and there is an absence of contact between the treated part and the inductor. However, the relevance of this heating technique depends on the true knowledge of the location of the power in the composite since its impact is not negligible on the final heating profile. One need a model that can predicts the exact location of power densities. Depending on the relative orientation between neighboring plies one could have

conductivities that change at the interface [2]. It is then necessary to understand and evaluate this dependency and to propose a numerically viable model that takes into account these phenomena at the interfaces. The objective of this paper is to propose an electric model that allows to highlight the interface phenomena between plies.

## II. CRFP HOMOGENIZATION

Direct numerical modeling of the physical behavior of a CFRP structure is made impossible by the large scale factor between the fiber diameter and the composite dimensions. A multi-scale predictive homogenization method of the electrical behavior of a CFRP taking into account percolation is developed. This method is based, on the one hand, on a geometric decomposition on several scales of the stratified composite UD, and on the other hand, on ascending scale transitions. Fibers have a certain undulation in the plies. Electrical contacts are then established between adjacent fibers, thus allowing the passage of current by percolation phenomenon in all directions of the ply [3]. To understand this complexity, the ply is divided into several Representative Equivalent Volume (REV) with a good statistical representation.

For the numerical resolution, in order to obtain the tensor of homogenized electric conductivities of the 3D REV, the following procedure is applied:

- Generation of a 3D geometry of the REV taking into account the randomness of the position of the electrical contacts;
- Determining an equivalent impedance network thanks to the generated geometry;
- Determination of the tensor using a volt-ampereometric simulation, using the three-dimensional resistance network method.

In our previous work, the electrical conductivity tensor was only calculated for one ply using the virtual material homogenization procedure [4]. In this case, the generated REV consisted of fibers that are all oriented in the same direction. The tensor for the other ply directions was then deduced by a mathematical operation [5]. These transformations influence only the conductivities in the fiber direction and in the transverse direction, but do not affect the conductivity in the thickness direction (direction normal to the plies). This approach remains quite efficient, however, the complementary

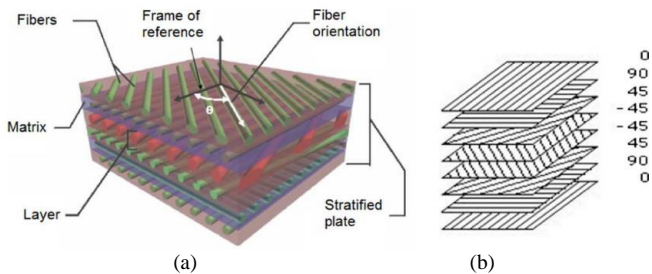


Fig. 1. (a) CFRP, (b) Fiber orientation.

experimental characterizations implemented in [2] showed that the conductivity along the thickness seems to be affected by the sequence of the plies. To study this phenomenon, a new approach is proposed. It consists of the assembly of two classical REV with relative orientation to create a new REV which include interface phenomena. Firstly, two REVs are generated in the same way as in the previous works. Then these REVs are replaced by their equivalent electrical circuits and then a protocol is implemented for rotating the second REV and interconnecting the two. This protocol will be more detailed in the final paper. Thus, an REV taking into account interface phenomena between plies is obtained. The electrical conductivity tensor will then be calculated as a function of the relative angle between the REVs. This will take into account the influence of the interface on the electric tensor.

### III. SAMPLES AND RESULTS

Several REV cells of one ply are generated using the geometry generation algorithm described in [5]. In each case, the conductivities in the fiber direction, in the transverse direction and in the direction normal to the plies are calculated. Table I presents the results obtained with two selected REVs (Specimens 1 and 2). The simulation parameters are defined with  $n_z$  the number of layers of the REV cell,  $x$  its width and  $V_f$  the filling rate of the fibers. The distance  $dz$  between two consecutive layers is taken equal to  $300\mu\text{m}$  and the thickness of the REV cell is equal to that of a composite ply:  $185\mu\text{m}$ .  $\sigma_z$  represents the electrical conductivity of REV in the fiber direction,  $\sigma_x$  the transverse conductivity and  $\sigma_y$  the conductivity in the direction of to the thickness.

TABLE I  
SIMULATION RESULTS

Specimen	$x(\text{mm})$	$n_z$	$V_f(\%)$	$\sigma_z(\text{S/m})$	$\sigma_x(\text{S/m})$	$\sigma_y(\text{S/m})$
1	2.7	10	59.69	34637	7.27	7.85
2	4.2	15	59.72	34622	7.41	8.65

Now, we are interested in tensors of electrical conductivities of specimens constituted by the superposition of specimens 1 and 2. Specimen 1 is fixed at its original position and specimen 2 undergoes different rotations above specimen 1. The second specimen is bigger to cover the whole specimen for any angle. The part of impedance network of second specimen which are not strictly on the first specimen is deleted to obtain a composite with the same length and width of the first specimen but with two plies. The effect of orientation between plies on conductivity in the normal direction can be now studied.

Fig. 2 shows the variation of the electrical conductivities in the direction of the fibers and in the transverse direction as a function of the relative angle. The electrical conductivity in the transverse direction remains low for an angle less than  $45^\circ$  but increases quickly from  $45^\circ$  up to  $90^\circ$  where it is maximum. The curves are symmetrical with respect to  $90^\circ$ . When the angle is higher than  $45^\circ$ , some fibers in upper ply might go along the transverse direction, this will allow a highly conductive path for the electrical current.

With the same reasoning, the electrical conductivity in the fiber direction is maximum at  $0^\circ$  but decreases as a function of

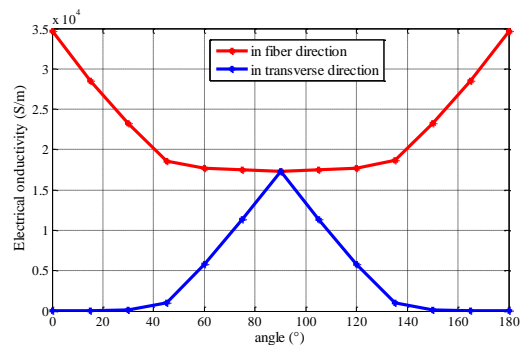


Fig. 2. Electrical conductivities in direction of the fibers and in the transverse direction as a function relative angle

the angle up to  $45^\circ$  from where it remains almost constant. The two curves coincide at  $90^\circ$ . This is explained by the fact that at this angle the configuration of the REV remains the same in both directions.

Fig. 3 shows the variation of the electrical conductivity in the direction normal to the plies for different angles. One can see that the electrical conductivity increases rapidly from 0 to  $7^\circ$  but varies slightly thereafter. It goes down to  $90^\circ$  and seems to find its maximum value at  $45^\circ$ . The increase of conductivity for angle higher than  $7^\circ$  can be explain by the increase of electrical contact between the two plies.

In the final paper, more details will be given on interconnection of impedance network and the statistical study done on these two specimens. The calculation of electrical tensors for stacks of more than two plies will be done and the results verified with experimental characterizations.

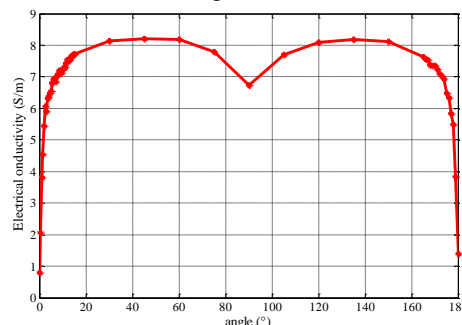


Fig. 3. Electrical conductivities in the direction normal to the plies as a function of relative angle

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