Void Effect on Carbon Fiber Epoxy Composites

Abdellatif Selmi

***Abstract*—** The mechanic properties of CFRE are influenced by the presence of voids due to the method of manufacturing of carbon fiber epoxy composite itself. In the present paper a two-step procedure has been considered and a finite element model incorporating the necessary boundary conditions is developed to predict the void effect on the elastic properties of the composite. For verification, the numerical results of elastic properties are compared with the analytical solution. A good agreement is seen between these results and it is found that effect of voids is very serious for shear modulus and the longitudinal Young's modulus.

***Keywords*—** Carbon fiber, Resin, Void, Elastic properties

I. INTRODUCTION

IN recent years, there has been a rapid growth in the use of fiber-reinforced composites due to their ability to replace competitive materials on the basis of the low density and equivalent strength, low thermal conductivity, high corrosion and wear resistance and the possibility of combining the toughness of thermoplastic polymers with the stiffness and strength of reinforcing fibers [1]-[3].

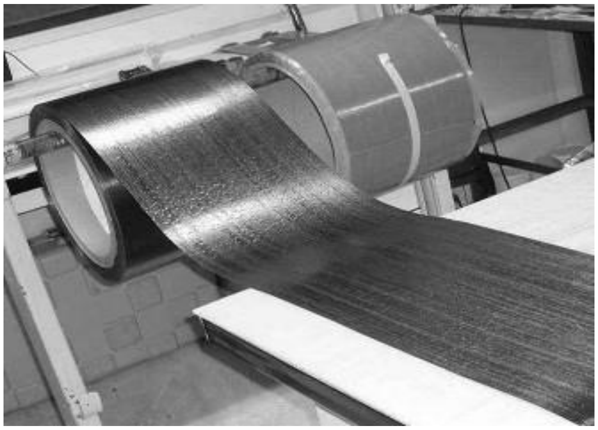

Fig. 1 Carbon fibers pre-impregnated epoxy resin unidirectional ply

The epoxy resins reinforced with long carbon fibers have good mechanical properties which have led to its use for producing structural parts of aircraft and for manufacturing several components such as flaps, aileron, landing – gear doors and others [4]-[5]. The long carbon fiber reinforced epoxy has been delivered in the form of unidirectional layers shown in Figure 1. The resin's main objective is to transmit the mechanical stresses to the reinforcement. It must also protect the reinforcement with respect to various environmental conditions (corrosion, oxidation, wet aging ...).

Improving the mechanical properties of these materials is an important task. Indeed, although combining the advantages of high mechanical performance for low density, these materials have several features that limit their use. One of the features is the presence of cavities [6]-[7].

These defects "cavities" may be due to several reasons such as the trapping of air pockets in the resin during its production phase (mixing, etc ...) or during the impregnation of the reinforcement [8]-[10]. Macro porosities are mainly present during low viscosity impregnation of the reinforcement as opposed to micro pores which are the majority when the flow is governed by capillarity (high viscosity) [11]-[13].

Once burnt, the carbon fiber actually undergoes physico-chemical sizing to promote adhesion of the organic matrix [10]. The nature of the physico-chemical treatment could be one of the causes of the appearance of pores. Another cause of creating porosity is the breakage of fibers. In this case soft microcavities are observed [10].

The difficulties of observation and quantification of porosity as a whole is one of limiting factors for the study of their formation and their influence. The literature researches on this point have highlighted many analysis methods of the porosity. However, only few can be used to quantify pores which are inaccessible by external agents (mercury, nitrogen, argon, ...). The most used are the microtomography [14], ultrasound [15], chemical degradation, and the image analysis [16]. Using these methods, the volume fractions of porosity are obtained and are used to validate the good quality cured parts. The limit from which the structural parts are discarded is 2%. Using the same methods, porosities were seen to have ellipsoidal shape rather than spherical one (Fig. 2).

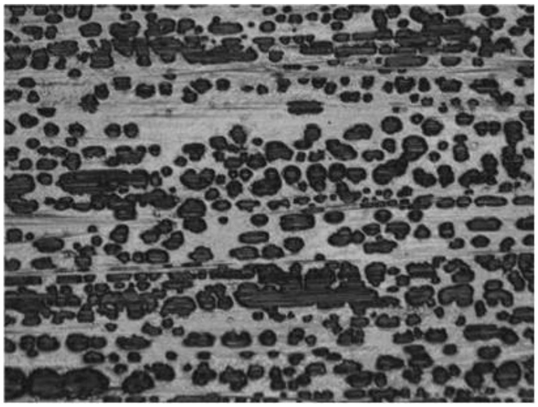

Fig. 2 Representative micrographs of the surface state of the prepreg

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Highly sought in the production of foams or membrane filters, porosity however detrimental to high performance composite material. The impact of this default is the subject of much attention, as evidenced by some studies on this subject [17]-[18].

All authors agree that below a certain volume fraction, between 0.5 % and 1 %, the porosity does not influence on the behavior of the carbon fiber reinforced composite mechanical characteristics. However, for higher levels of porosity, mechanical properties of carbon fiber resin composite are significantly affected, particularly the interlaminar shear. In fact, interlaminar shear strength denoted ILSS is very responsive to the presence of these gas inclusions. The average reduction in ILSS was estimated to average 6% per unit volume of porosity for carbon / epoxy laminates [17], [19].

The most realistic study to explain the decrease in ILSS according to increasing the volume ratio of porosity is given by Wisnom et al. [18]. They highlight the crack initiation from pores when these are sufficiently large (equivalent diameter > 0.2 mm). Their results also show that the presence of porosity reduces the contact area between the fibers and the matrix, which promotes cracks on the composite.

Other mechanical properties (tensile, compression, shear plane) are also affected by the presence of porosity, but to a lesser extent, although not negligible [20].

In general, an increase in the volume fraction of porosity causes reduced mechanical properties of the material. It is also reasonable to think that the presence of porosity in the laminate changes both the transfer of force between the resin and the reinforcement but also cohesion of thereof. This assumption, however, remains to be demonstrated.

The interest this study is to estimate the effect of porosities on the carbon fiber epoxy behavior using a two step model and FE analysis. The void effect is studied for different void volume fractions and quantified for varied carbon fiber volume fractions.

First, a direct finite element (FE) based numerical approach is used, which allows to model fully aligned, long and homogeneously dispersed carbon fiber in an epoxy composite. Second, a tow-step procedure based on Mori-Tanaka micromechanical model is investigated.

II. OVERALL ELASTIC PROPERTIES OF CARBON FIBER RESIN COMPOSITE

Carbon fiber epoxy composites can be seen as reinforced materials made up of three phases: epoxy matrix, carbon fibers and ellipsoidal cavities. The carbon fibers used in this study are described as 'high-strength'. Their diameter is about 7 microns. The different material properties of both matrix and fiber are shown in the Table 1. The void inclusions are assumed to be perfect ellipsoids of length 2500 μm, and diameter (d = 10 μm).

TABLE I

ELASTIC CONSTANTS OF EPOXY RESIN AND CARBON FIBER.

	Young's modulus E (GPa)	Poisson's ratio
Epoxy resin	3	0.22
Carbon fiber	265	0.40

In this section, two ways to predict their overall elastic properties are explored: mean field homogenization procedure and unit-cell finite element calculations. The main ideas of these methods are summarized hereafter.

A. The two step procedure

In this section, a two-step method is used to predict the overall elastic properties of fully aligned long carbon fiber reinforced epoxy containing voids.

The principle of the two-step procedure is depicted on Figure 3 for composites with aligned carbon fibers and randomly oriented ellipsoidal cavities. Carbon fiber and void inclusions (having different shapes and orientations) are thus lying in the matrix. The first step consists of homogenizing the epoxy with randomly oriented void inclusions and then the effective properties of carbon fiber reinforced epoxy with voids are computed (second step). For both steps almost any homogenization scheme valid for two-phase composites can be used, here, the Mori–Tanaka (M–T) method is chosen for the two steps. Other choices can be made [21-22]. Combined with M–T at first step, the two-step approach degenerates then into the classical direct extension of the M–T scheme to multi-phase composites. We draw attention to the fact that this two-step procedure can handle long carbon fibers composites as well as short ones, aligned or not in the matrix. The two-step approach appears to be well suited (see Section 3) to carbon fiber epoxy composites.

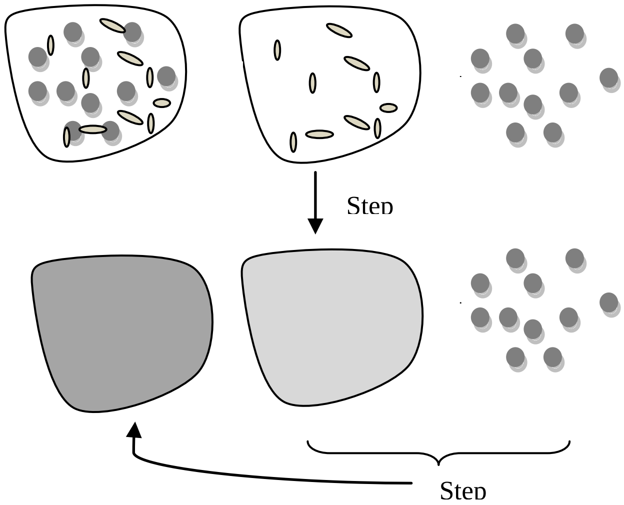

Fig. 3 Schematic view of the two-step homogenization procedure

B. FE with periodic boundary conditions

The following FE procedure is valid for composites with long and aligned carbon fiber. We suppose a hexagonal array arrangement (Fig. 4) of the fibers in the matrix. As a result, the unit cell is the large rectangle of Figure 4, i.e. with one tube at its center and a quarter of a tube at each corner. Knowing the dimensions of the carbon fibers (radii R on Fig. 4) and their volume fraction, one can compute the half fiber interdistance d. The height and width of the reduced unit-cell are h = d and l =d $\sqrt{3}$, respectively.

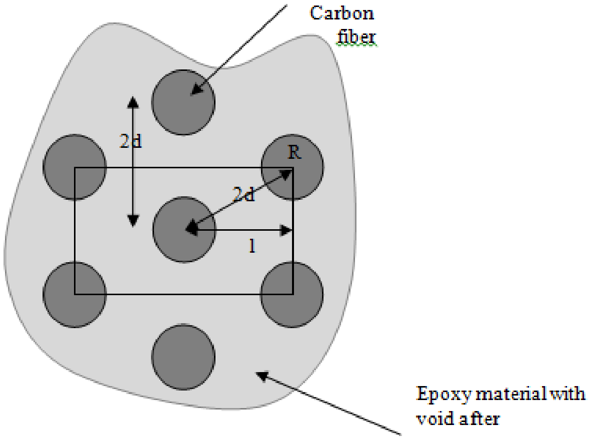

Fig.4 Periodic hexagonal array arrangement of long carbon fibers inside the composite

Actually, a 3D cell with unit thickness is considered. Periodic boundary conditions are applied, as in [23] for other micro-structures.

Periodic boundary conditions are written in a form representing periodic deformation and antiperiodic tractions on the boundary of the cell. The boundary conditions applied on an initially periodic cell preserve the periodicity of the cell in the deformed state. This model allows us to compute the whole mechanical properties of the transversely isotropic composite.

The selected cell is meshed using NETGEN [24] mesher, with which periodic boundary conditions can be applied.

The FE meshes consisted of linear tetrahedral elements; Figure 5 shows a 3D view of the FE mesh corresponding to 60% of CFRE.

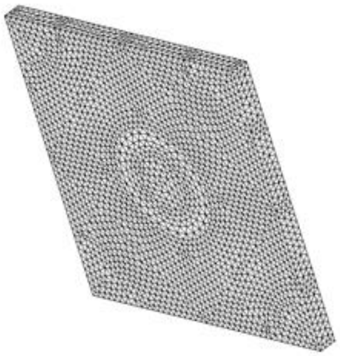

Fig.5 Unit cell with periodic boundary conditions: 3D view of FE mesh corresponding to 60% of CFRE

III. PREDICTIONS OF VOID EFFECT ON CARBON FIBER RESIN COMPOSITE

A. Prediction of void effect for 60% of carbon fiber

The stiffness reduction of resin matrix comprising 60% of carbon fiber is investigated here using two-step procedure. The composite with long carbon fiber is transversely isotropic; hence, five mechanical proprieties are to be predicted.

Figures 6a–6c contain respectively the effective and normalized longitudinal Young’s modulus (EL/Em) , transverse Young’s modulus (ET/Em) and longitudinal shear modulus (GL/Gm) of epoxy reinforced with 60% aligned carbon fibers and randomly oriented void inclusions as a function of void volume fraction.

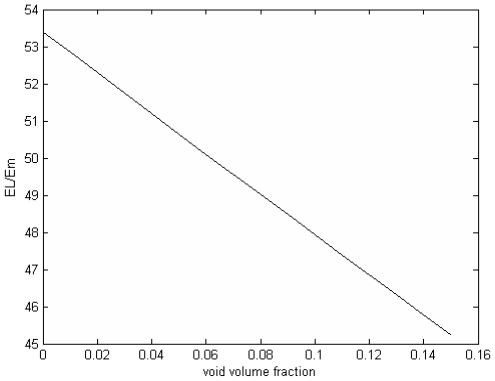

Fig.6a. Carbon fiber / porous resin composite with long and aligned reinforcements. Normalized longitudinal Young’s modulus

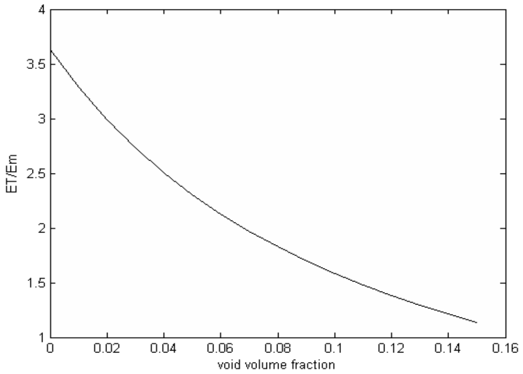

Fig.6b. Same as Fig. 6a. Normalized transverse Young’s modulus

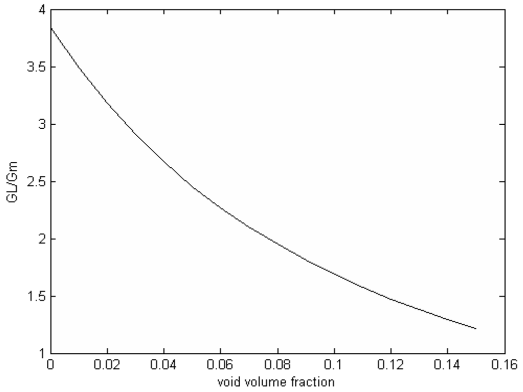

Fig.6c. Same as Fig. 6a. Normalized longitudinal shear modulus

Interpretation: From Figures 6a–6c, it can be seen that for 3D random void inclusions and for 60% of aligned long carbon fiber, the effect of void is very grievous; the normalized transverse Young’s modulus and the normalized longitudinal shear modulus are decreased by a factor of 3 for 15% void inclusion volume fraction.

One can deduce that the reinforcement of resin without voids with 60% of carbon fiber increase the normalized transverse Young’s modulus and the normalized longitudinal shear modulus with up to 350%. For these mechanical properties, from Figures 6a–6c, 15% of voids may cancel the effect of 60% of carbon fiber.

B. Influence of void volume fraction for various carbon fiber contents

The predicted mechanical response of composites made of resin without voids and with 2% void volume fraction, reinforced with carbon fibers, relative to the mechanical properties of resin is reported in Figures 7a–7c. For 2% void volume fraction, the predictions are made using two-step procedure and finite element calculations.

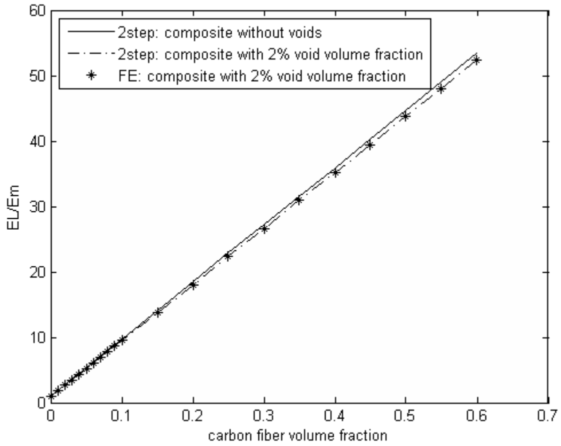

Fig. 7a. Carbon fiber / porous resin composite with long and aligned reinforcements. Normalized properties: comparison between the predictions of unit cell FE and two-step procedure. Longitudinal Young’s modulus

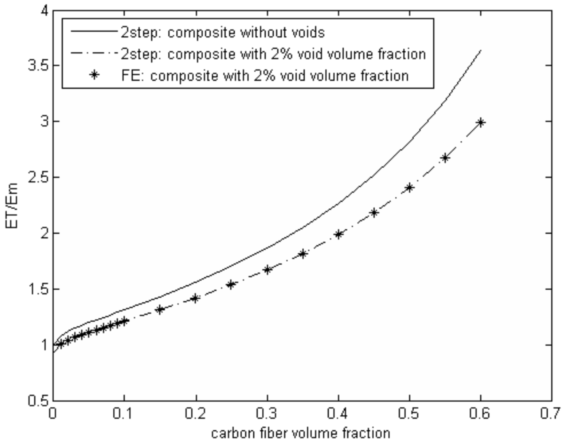

Fig. 7b. Same as Fig. 7a. Transverse Young’s modulus

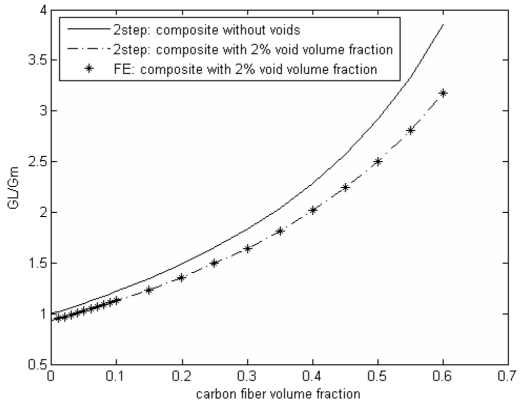

Fig. 7c. Same as Fig. 7a. Longitudinal shear modulus

Interpretation: Figures 7a–7c show respectively the effective and normalized longitudinal Young’s modulus, transverse Young’s modulus and longitudinal shear modulus of aligned long carbon fiber reinforced resin with and without randomly oriented voids.

As one can expect, the FE results and two-step model gives the same prediction of the longitudinal Young’s modulus which indeed obeys to the rule of mixture. For other mechanical properties, predictions are close to FE results.

For various carbon fiber volume fractions, the effect of 2% void volume fraction can be seen clearly for the normalized transverse Young’s modulus and the normalized longitudinal shear modulus. The gap between these mechanical properties for composites without and with 2% of randomly oriented voids increase with increasing carbon fiber volume fraction. For 2% of void volume fraction and 60% volume content of carbon fiber, the gap can reach 20%. For the normalized longitudinal Young’s modulus the gap remains constant when the carbon fiber volume fraction is varied.

IV. CONCLUSION

A two step homogenization model has been developed for the evaluation of the effect of voids on the effective mechanical properties of resin reinforced with carbon fiber. Elastic properties of the composite have been evaluated for various fiber and void volume fractions with the help of FE calculations. The FE data are compared with the results obtained using the two-step procedure. It was seen that the results delivered by finite element simulations are in good agreement with the analytical results.

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