The Non-uniformity from the Composite Materials Reinforced with Fiber Glass Fabric

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In this paper we study the non-uniformity that appears in the composite bars reinforced with fiber glass fabric. We defined a factor which characterizes the non-uniformity from the composite materials. We will give a formula for calculating this coefficient and a formula for the elasticity modulus of the composite bars, with two zones in which the volumetric proportions of reinforcement are different. We compared the theoretical results, which give the values of the uniformity coefficient and elasticity modulus, with experimental results obtained for three sets of samples made from ambresit and reinforced with fiber glass fabric.

Keywords: composite materials, non-uniformity coefficient, elasticity modulus

Uniformity of physical property distributions in manufactured parts is a very important issue in many industries. This is particularly true for high volume manufacturing of fiber-reinforced composites parts where reinforcing fibers may be nonuniformly distributed within the matrix material. Resin transfer molding, thermostamping, structural reaction molding, and sheet molding compound processing are often used for such high-volume manufacture of composite parts, and all of these processes have the potential for nonuniform fiber distributions.

Physical property data for specimens cut from a composite panel often exhibit considerable experimental scatter because of nonuniform fiber distributions. For example in [1] is noticed that, in thermostamped glass fiber reinforced plymer composite panels, the modulus of elasticity varied by as much as a factor of three over a $152.4\,mm \; x \; 304.8\,mm$ area because of the redistribution of fibers induced by lateral resin flow during the thermostamping process. In [2], there was shown that, in composites made from sheet molding compounds, such scatter in property data may be large enough to mask out any effects of changes in processing variables.

The impulse-frequency response technique is a widely used experimental method for measuring the required vibration response data, and has been adopted for the determination of the globally averaged properties of orthotropic composite panels in conjunction with certain theoretical models such as Galerkin's method [3], the Rayleigh-Ritz method [4], the Rayleigh method [5], and the finite element method [6]. These are the main analysis methods of dynamic behaviour in the case of non-uniform composite materials.

In [7], it is given the initial result from a program used to develop a „rapid screening test" for determining the in-plane fiber distributions in unidirectional reinforced composite structures by the use of the vibration response measurements and Galerkin's method. Theoretical models and experimental data are generated on two methods basis: (1) the „shifting method" in which the effective length of the beam is changed, and (2) the „added mass method" in which the mass distribution of the beam is changed. The elastic constants and the density are all assumed to be functions of fiber volume fraction, while the spatial distribution of the fiber volume fraction is assumed to be given by a polynomial function. The concept of an effective density is employed to obtain the appropriate solution to the coefficients of the polynomial function. The results show that the fundamental mode gives better predictions of physical properties than the higher modes do.

In [8–12] there are studied other influences of non-uniformity over the composite materials behaviour.

Theoretical aspects

The mechanical behaviour of composite materials is influenced by many factors such as: anisotropy and non-homogenous nature of the material, mechanical incompatibility of constituent phases, the connections effect among phases, the elastic and plastic behaviour of matrix and reinforcing material, the volume fraction of components and mechanical loading directions. Due to these reasons, the composite materials have various properties. To determine them there are many calculus relationships.

For example, in the case of unidirectional composites, the most used relationship to obtain the elasticity modulus along the fibers is:

$$E_l = E_f V_f + E_m V_m, \qquad (1)$$

where

- E_f is the elasticity modulus of the reinforcement;
- E_m is the elasticity modulus of the matrix;
- V_f is the volumetric proportion of the reinforcement;
- V_m is the volumetric proportion of the matrix.

The values given by formula (1) are in accordance with the results obtained experimentally.

We considered that the fracture of composite material happen when the fibers are broken. Thus the tensile

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strength of composite material in fibers direction is calculated by the formula:

$$\sigma_r = \sigma_f \left(V_f + V_m \frac{E_m}{E_f} \right), \qquad (2)$$

where σ_f is the tensile strength of the fibers.

Experimentally, we find that the tensile strength has the inferior values than one given by the relation (2). This thing can be justified thus: not all the fibers are orientated perfectly after the same direction; not all the fibers are stretched and they not take over uniformly the loadings on which is exposed the composite material. In the ideal case there is the equality between ratios among the tensile strength and the elasticity modulus of fibers and composite material respectively. In practice this equality does not happen. We give the uniformity coefficient by:

$$c = \frac{\sigma_r \cdot E_f}{\sigma_f \cdot E_l}. \qquad (3)$$

This coefficient takes values between 0 and 1. The lasser is the value of the coefficient, the more nonuniform is the composite material. Because the elasticity modulus and tensile strength of fibers have well known values, then the composite material non-uniformity can be obtained if we evaluate its elasticity modulus and tensile strength. Therefore we consider a composite bar with l_0 length, having a rectangular section, with variable mechanical properties at the bar length, which was tested to a tensile stress.

Medium elasticity modulus along the bar length is calculated with formula:

c

$$E_{med} = \frac{l_0}{\int_0^{l_0} \frac{1}{E(x)} dx}. \qquad (4)$$

The composite material fracture is made when in the area in which the elasticity modulus is minimal, known as the area where the deformation is maximal, the breakage of fibers occurs. The uniformity coefficient value is given by:

$$c = \frac{E^*}{E_{med}}, \qquad (5)$$

where E* is the arithmetic mean between the minimum value of the elasticity modulus along the bar and the part from these fibers. We have chosen this mean value because the fracture appears in the area with the minimal elasticity modulus, but in the fracture moment we considered that only the fibers from this area assure the material strength.

A particular case is obtained when in the middle area of the bar, on a portion of length $l = \beta \cdot l_0$ $(0 \le \beta \le 1)$, the volumetric proportion of reinforcement is $\alpha \cdot V$ $(0 \le \alpha \le 1)$, where V is the volumetric proportion of reinforcement in the rest of the bar. In which case the medium elasticity modulus is given by the relationship:

$$E_{med} = \frac{\left[\alpha V E_f + (1-\alpha V) E_m\right] \cdot \left[V E_f + (1-V) E_m\right]}{\beta\left[V E_f + (1-V) E_m\right] + (1-\beta)\left[\alpha V E_f + (1-\alpha V) E_m\right]}. \qquad (6)$$

The uniformity coefficient is determined by the relationship:

$$c = \frac{\left[\alpha V(\gamma + 0.5) + 0.5\right] \cdot \left[1 + V\gamma(\alpha + \beta - \alpha\beta)\right]}{(\alpha V \gamma + 1) \cdot (V\gamma + 1)}, \qquad (7)$$

where

$$\gamma = \frac{E_f}{E_m} - 1 \qquad (8)$$

depends on the ratio between the elasticity modulus of fiber and the elasticity modulus of matrix.

In the figure 1 is shown the variation of the uniformity coefficient depending on the parameters α and β. It is observed that if $\alpha = 0$ the dependence $c(\beta)$ is linear, and if $\beta = 0$ the dependence $c(\alpha)$ is also linear.

Figure 2 shows the dependence between the parameters α and β, for various values of uniformity coefficient.

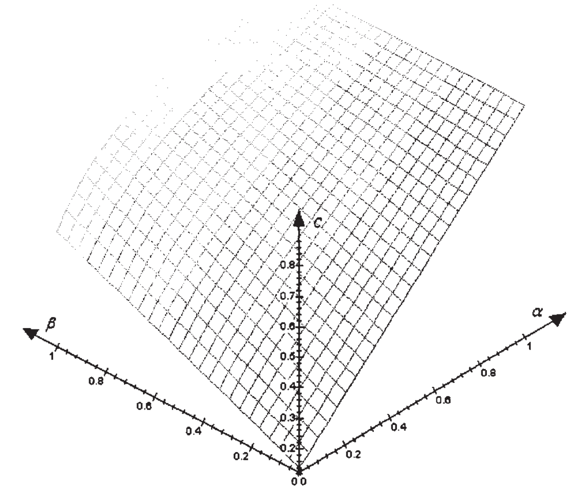

Fig. 1. The variation of uniformity coefficient c, depending on α and β, for $\gamma = 24$ and V = 0.15.

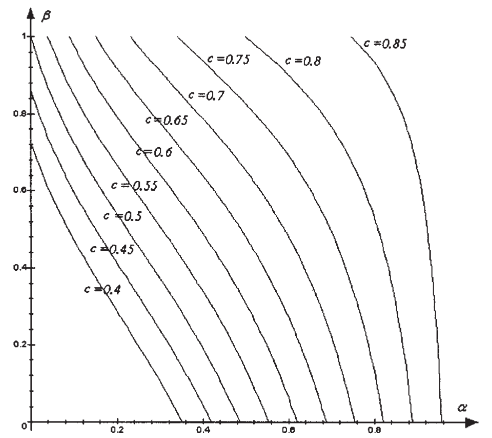

Fig. 2. The dependence between β and α for $\gamma = 24$ and V = 0.15, in the case in which the uniformity coefficient has the values 0.85; 0.8; 0.75; 0.7; 0.65; 0.6; 0.55; 0.5; 0.45; 0.4.

A special case is obtained when $\beta = 0$. This is interesting because it shows how to change the uniformity coefficient when appear the fractures in fibers under the action of external loadings. In this case, the dependence between the parameters γ and α is shown in figure 3, and the dependence between the V and α for different values of the uniformity coefficient is presented in figure 4. It is noted that a decrease of the parameter α leads to a decrease of the uniformity coefficient. From figure 3 it is observed that for the values of $\gamma > 20$, ordinary in the case of composite materials, the increase of elasticity modulus of fibers has little influence on the uniformity coefficient. A similar conclusion also appears for the volumetric proportion of fibers. Moreover, if a part of the fibers are broken, the uniformity coefficient decreases together with increasing of volumetric proportion of reinforcement. The same happens if the elasticity modulus of the fibers increase.

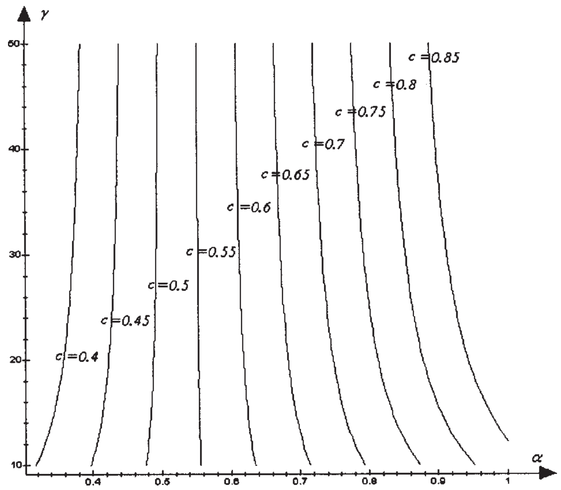

Fig. 3. The dependence between γ and α for $\beta = 0$ and V = 0.15, in the case in which the uniformity coefficient c has the values 0.85; 0.8; 0.75; 0.7; 0.65; 0.6; 0.55; 0.5; 0.45; 0.4.

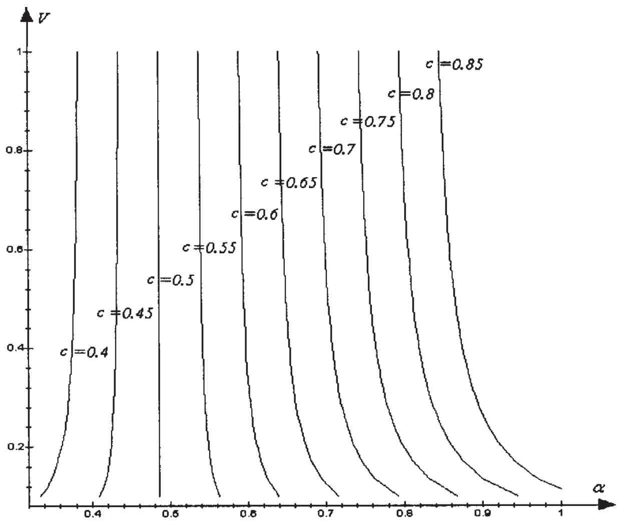

Fig. 4. The dependence between V and α for $\beta = 0$ and $\gamma = 24$, in the case in which the uniformity coefficient c has the values 0.85; 0.8; 0.75; 0.7; 0.65; 0.6; 0.55; 0.5; 0.45; 0.4.

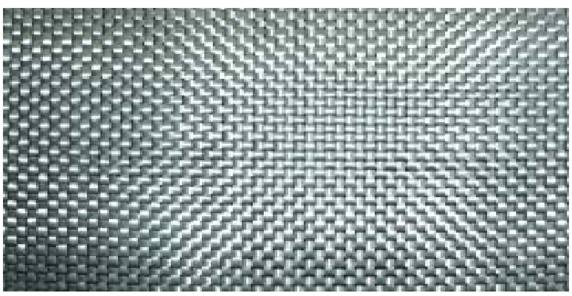

Fig. 5

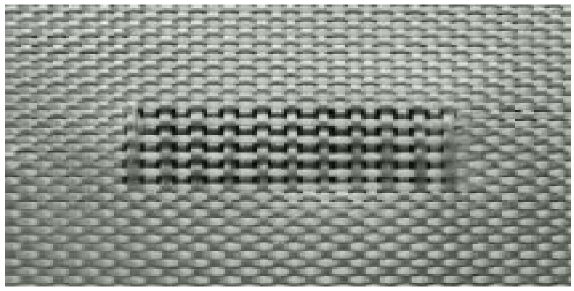

Fig. 6

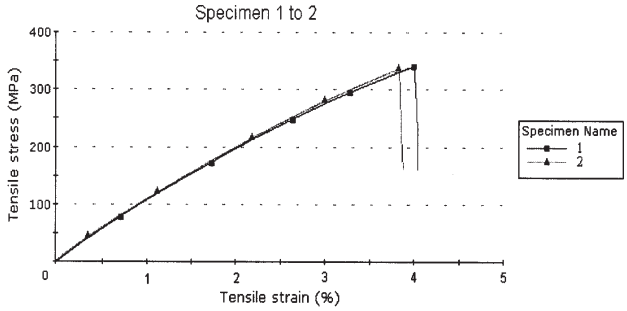

Fig. 7

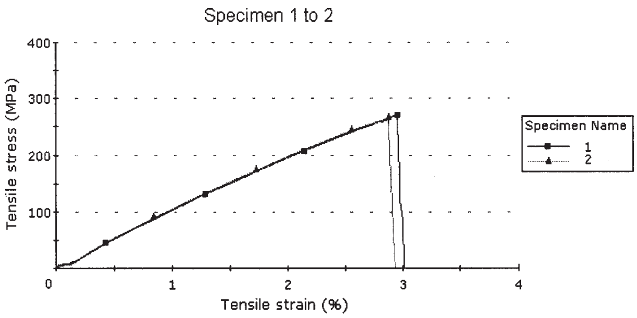

Fig. 8

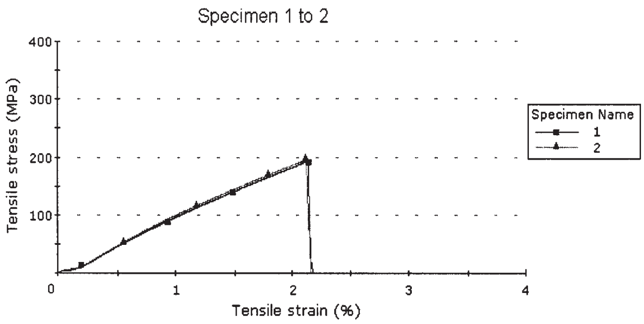

Fig. 9

Table 1

Sample set	Fracture strength (MPa)	Elasticity modulus (MPa)		Uniformity Coefficient	
		Theoretical	Experimental	Theoretical	Experimental
1	340.5	11875	11639	0.891	0.901
2	268.7	10742	10372	0.816	0.798
3	193.7	10308	9951	0.629	0.599

We can say that the influence on the uniformity coefficient, given by the variations of the parameters γ and V, is much smaller than the influence of parameter α, which in the case of $\beta = 0$, represents the proportion of unbroken fibers.

Experimental part

We have made three sets of samples from composite materials, having the reinforcement from fiber glass (the elasticity modulus of fibers is E_f = 74000 MPa) and the matrix from ambresit (elasticity modulus of resin is

E_m = 3000 MPa). The fabric from which is made the reinforcement is shown in figure 5 and in figure 6 is shown how the fibers were removed by reinforcement to obtain the values of parameter α.

At the first set of samples, the fiber glass fabric is unmodified, having $\alpha = 1$.

At the second set of samples, from the fabric were removed fibers, so that to be obtained $\alpha = 0.8$ and $\beta = 0.6$.

At the third set of samples, from the fabric were removed fibers, so that to be obtained $\alpha = 0.55$ and $\beta = 0.3$.

The three sets of samples were subject to tensile test.

In figure 7 are shown the characteristic curves for two representative samples from the set 1.

In figure 8 are shown the characteristic curves for two representative samples from the set 2 and in figure 9 are shown the characteristic curves for two representative samples from the set 3.

The experimentally obtained results (medium values on set of samples) versus the theoretical ones are shown in table 1.

Conclusions

Composite materials properties are influenced by their non-uniformity which is arising from processes of production and processing. Material defects, the non-uniform distribution of reinforcement, the variation of volumetric proportion of reinforcement, have the effect of lowering capacity to takeover the efforts. The uniformity coefficient is an indicator which appreciates the influence of different factors over the mechanical behaviour of composite materials. The main parameters that influence the value of uniformity coefficient are: the volumetric proportion of the reinforcement in the area with minimal strength, the volumetric proportion in the rest of the material, the size of the minimal strength area, and the ratio between the elasticity modulus of fibers and the elasticity modulus of matrix.

Under the action of external forces, the punctual fracture of a reinforcement thread makes the loading to be taken over by the others fibers in respective area. Therefore, the influence study of the fibers fracture phenomenon on the uniformity coefficient can be framed in the case when the parameter β has the zero value. In this case, is observed that the volumetric proportion of reinforcement in the minimal strength area, so of the unbroken fibers, has an important influence over the uniformity coefficient. On the other hand, the volumetric proportion of reinforcement in the rest of the material and the ratio between the elasticity modulus of fibers and elasticity modulus of matrix, for their usual values ($V \in (0.2, 0.7)$ and $\gamma \in (20, 50)$), have minor influences over the uniformity coefficient.

The values of uniformity coefficient close to 1 show that the composite material is homogenous, without discontinuities in the reinforcement distribution, while small values of the coefficient show the defects existence. Although it does not show the nature of defects and their position, a small value of the uniformity coefficient show the presence of some areas where the material properties are damaged, or the fact that these defects are focused in a restricted area. This fact is shown by the curves in figure 2. For example, a uniformity coefficient with the 0.7 value is obtained for a sample that has on all its length a volumetric proportion of reinforcement that gives the value of parameter α of aproximately 0.24, as well for a sample that, focused in a point, has a volumetric proportion of reinforcement that gives the value of parameter α of aproximately 0.75.

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