Probabilistic analysis of the behavior of polymer matrix composite materials reinforced by different types of fibers

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Abstract. The requests of lightening of the structures and gains in performance lead to search for new materials and the associated processes for aeronautical and space applications. Long-fiber composites have been used for many years for these applications; they make it possible to reduce the mass of the structures because of their excellent compromise of mass/rigidity/resistance. The materials in general contain defects which are essentially due to their nature and their mode of elaboration.

To this purpose, we carried out a probabilistic analysis of the mechanical behavior in three-point bending of composite materials with a thermosetting matrix in order to highlight the influence of the number of folds of the fibers and the nature of the fibers on the dispersion of the defects in the stratified structures fiberglass, carbon fiber laminates and hybrid (carbon/glass) laminates.

From the results obtained, the dispersion of the defects is lower in the laminates of greater number of plies of the fibers and the hybrid laminates; the more the number of folds increases the more the mechanical characteristics increase; the hybrid laminates exhibit better mechanical properties compared to laminates of the same type of fiber. Finally, a morphological analysis of fracture structures and facies was investigated by scanning electron microscope (SEM) observations.

1. Introduction

The production of composite materials increases more and more, although their cost is higher than the traditional materials, they bring important advantages: Lightness, freedom of form, reduced maintenance, mechanical and chemical resistance. They make it possible to increase the life service of certain equipment due to their mechanical properties. Thanks to their chemical properties (resistance to corrosion), they reinforce safety due to their better resistance to shocks and to fire. They offer better thermal or sound insulation, and for some of them good electric insulation [1-3]. In composite materials with a polymeric matrix the fibers used as reinforcement are mainly synthetic fibers such as carbon or glass fibers, these fibers have very good mechanical and geometrical properties [4].

The study of the rupture behavior of composite materials with thermosetting matrix continues to be the subject of an abundant literature [5, 6].

The heterogeneous nature of these materials and the probabilistic aspect of the rupture are generally supplemented by rigorous statistical studies [7, 8]. The material architecture such as the orientation of
the reinforcements and the geometry create directional effects which influence the nature of the damage [9].
The objective of this work is in the context of a probabilistic characterization in static flexion of composite materials made up of a reinforced epoxy matrix with different plies and nature of the fibers in order to determine the Weibull modulus which is a parameter material characteristic of the dispersion of the defects (or criterion of fracture sensitivity) for a given material.

2. Experimental procedures

2.1. Used materials
The materials used are composite materials with a polymer matrix, and reinforcements made of glass fibers and carbon with a fiber / matrix weight ratio of (3/1).

2.1.1. Epoxy resin: The epoxy resin is a thermostetting polymer, widely used in high performance composites in many industrial applications.
In this work we used MEDAPOXY 812 INJ from Granitex (ALGERIA). The mass ratio between the monomer and the hardener supplied by Granitex is MR = 2.
The characteristics of the MEDAPOXY 812 INJ resin are presented in Table 1.

| Weight Ratio (A / B) | 2/1 |
|----------------------|-----|
| Density (ISO 758)    | 1.1± 0.1 |
| Viscosity (CF4/20°C) (NFT30 014) | 17sec (±2) |
| DPU : (NFP18 810)    | 30mn à 20°C |
| Resistance to compression RC | > 70 (MPa) |
| Tensile strength Rt   | > 57 (MPa) |

2.1.2. Reinforcements: carbon fibers, glass fibers. The Carbon and glass fibers shown in (Figure 1) are synthetic fibers with very good mechanical and geometrical properties [4].
The properties of the reinforcements used are shown in Table 2.

| Reinforcement  | Architecture | Surface mass(g/m2) | Density | Thickness (mm) | Tensile strength (MPa) | Elongation (%) |
|----------------|--------------|--------------------|---------|----------------|------------------------|----------------|
| Carbon UD      | unidirectional | 230 ± 10           | 1.76    | 0.13           | 4300                   | 1.8            |
| Woven glass    | Taffeta      | 225 ± 25           | 2.54    | 0.25           | 3100                   | 4.4            |

2.2. Method of preparation
The elaboration of materials is carried out by the vacuum method within laboratory of composite and plastic materials at the Algeria air maintenance base (Figure 2).

Figure 1: a) fiber glass. b) carbon fiber. c) hybrid carbon/glass.
The composite materials studied in this work are laminated plates reinforced by different fiberglass and carbon plies, as well as hybrid laminated plates reinforced by alternating glass fiber/carbon plies of dimensions 300 x 300 mm, in the drying oven at 80°C during 8 hours after their production. Then the specimens are cut with a diamond disc and lubricated according to the AFNOR NF T 57-105 standard for mechanical testing[10,11].

2.3. Test device
The tests were carried out in three-point bending, carried out at ambient temperature on samples prepared according to the ISO 178 standard, which specifies the dimensions of the test piece (figure 3). The distance L between supports is selected according to the thickness (h) and the width (b) of the elaborated composite [4,12]. The test velocity is 2 mm / min. Tests are carried out on a machine of Zwick / Roell type equipped with the sensor of force of 2.5 kN and controlled by the TestExpert 9.0 software.

The results obtained show the evolution of displacement according to the load applied until the rupture. The bending $\sigma_f$ stress, $E_f$ Young modulus, the shear stress $\sigma_{sh}$ are calculated respectively according to the following formulas:

$$\sigma_f = \frac{3FL}{2bh^2} \quad \text{[MPa]} \quad (1)$$

$$\sigma_{sh} = \frac{3F}{4bh} \quad \text{[MPa]} \quad (2)$$

$$E_f = \frac{L^3}{4bh^2m} \quad \text{[MPa]} \quad (3)$$

$$m = (f2 - f1) = \tan \alpha \quad \text{[MPa]}$$

(The slope of the elastic portion)

$\sigma_f$ and $E$ are respectively the stress and bending modulus (MPa); $\sigma_{sh}$ shear stress (MPa).

F: the maximum force (N), L: distance between supports (mm), L0: Length of the specimen (mm): $\geq$ 08 mm, b: Section width (mm); h: thickness of test piece (mm), f: the arrow of the specimen (mm).

3. Experimental results and discussion

3.1. Force-displacement curves
Figure 4 shows examples of the evolution of force / displacement curves for the various laminates. The shape of the curves is generally similar for laminates of the same type of fibers.
These curves are generally linear until fracture reflecting the fragile character of glass fiber laminates. However, carbon fiber and hybrid laminates are distinguished after a large linear portion which represents the elastic response of the material by a second deviating part of the linearity. This reflects the triggering and accumulation of damage that takes place within the structure before the total collapse. This diffuse and progressive damage is mainly caused by a multi-cracking of the matrix, a mechanism for loosening and detaching the fibers. Fiber-matrix decohesions which limit or prevent stress carry-overs between the broken fibers and the intact fibers as well as individual ruptures of the fibers which are minor.

A significant variation in flexural behavior of the various laminates is observed depending on the number of fiber folds and the nature of the fibers. We can say that the more the number of folds increases from 8 to 12 plies, the more the modulus of elasticity in inflexion increases from 23.97 to 29.74 GPa for the fiberglass laminates. From 55.90 to 61.99 GPa for the carbon laminates. From 56.78 to 60.92 GPa for hybrid laminates. The bending stress increases from 236.10 to 286.26 MPa for glass fiber laminates. From 330.20 to 411.50 MPa for carbon fiber laminates. From 423.22 to 465.33 MPa for hybrid laminates. Shear stress increased from 5.33 to 8.35 MPa for glass fiber laminates, from 7.13 to 10.80 MPa for carbon fiber laminates and from 9.80 to 12.20 MPa for hybrid laminates.

Table 3 summarizes the mean values of the measured mechanical characteristics of the various laminates.

It is also noted that hybrid laminates exhibit better mechanical characteristics except for the 12-plies hybrid laminate which presents a decrease in young's modulus compared to the 12-folds carbon fiber laminate from 61.99 to 60.92 GPa.
### Table 3. Mechanical characteristics of the various laminates.

| Sample | thickness h (mm) | Section width b (mm) | F max (N) | \( f_{F_{\text{max}}} \) (mm) | \( \sigma \) bending (MPa) | Shear stress \( \sigma_{sh} \) (MPa) | Young’s modulus E (GPa) |
|--------|------------------|----------------------|-----------|-----------------|-----------------|-----------------|---------------------|
| Stv1   | 2.10             | 10.70                | 151.07    | 2.81            | 236.10          | 5.04            | 23.97               |
| Stv2   | 2.29             | 10.42                | 222.57    | 2.70            | 278.38          | 6.99            | 26.99               |
| Stv3   | 2.83             | 10.29                | 287.67    | 2.34            | 286.26          | 7.40            | 29.74               |
| Stc1   | 1.90             | 10.90                | 188.77    | 0.97            | 330.20          | 6.83            | 55.90               |
| Stc2   | 2.23             | 10.85                | 295.33    | 1.11            | 390.96          | 9.15            | 59.15               |
| Stc3   | 2.70             | 10.95                | 458.72    | 1.04            | 411.50          | 11.63           | 61.99               |
| St[c/v]1| 2.01            | 10.95                | 323.24    | 1.57            | 423.22          | 11.01           | 56.78               |
| St[c/v]2| 2.35            | 10.25                | 332.56    | 3.18            | 439.24          | 10.85           | 59.95               |
| St[c/v]3| 3.36            | 10.30                | 520.77    | 2.98            | 465.33          | 11.29           | 60.92               |

St.V: fiberglass laminate. St.C: carbon fiber laminate. St.[C/V]: Hybrid (carbon / glass fiber) laminate.
1) Corresponds to 8 folds. 2) Corresponds to 10 folds. 3) Corresponds to 12 folds.

### 4. Probabilistic approach: probabilistic model of Weibull

The material rupture is controlled by the distribution of defects in volume related to the production process and to the characteristic values of the materials used...ect, this set of parameters is randomness.

According to Weibull, the probability of rupture \( P_f \) of a material of volume \( V \) subjected to a uniform distribution of stresses \( \sigma \), is given by [13,14]:

\[
P_f = 1 - \exp \left[ -\frac{\sigma}{\sigma_0} \right]^{\beta_f} \tag{4}
\]

\( \sigma_0 \) and \( \sigma_u \) are respectively the threshold stress below which the probability of rupture is zero (consider \( \sigma_0 = 0 \)) and the standardization constant. The most technique used for determining the Weibull parameter is the linearization of this equation, which allows us to write:

\[
\ln \left[ \ln \left( \frac{1}{1-P_f} \right) \right] = m \cdot \ln (\sigma - \sigma_u) + \ln (\beta) \tag{5}
\]

Representation of \( \ln \left[ \ln \left( \frac{1}{1-P_f} \right) \right] \) in terms of \( \ln (\sigma - \sigma_u) \) is a line of slope \( m \).

The probability of rupture is calculated from the expression:

\[
P_f = \frac{i}{N+1} \tag{6}
\]

It is a question of assigning a probability of rupture to each stress level as a function of rank \( i \) and according to an ascending order.

### 4.1. Analyse probabiliste

The probabilistic aspect of the rupture was highlighted by an analysis of the results from the application of the Weibull statistical model [7]. Figure 5. Shows the variation of the rupture probability according to the evolution of the bending stress in flexion.
Weibull modulus calculation for each type of laminate:

Examples of plots determining the weibull modulus in the case of stress at rupture are illustrated in Figure 6.

Table 4 summarizes the average weibull modulus values obtained for different laminates.

| laminate  | St.V1 | St.V2 | St.V3 | St.C1 | St.C2 | St.C3 | St.C/V 1 | St.C/V 2 | St.C/V 3 |
|-----------|-------|-------|-------|-------|-------|-------|----------|----------|----------|
| Weibull modulus (m) | 6.90  | 7.06  | 7.18  | 8.50  | 8.72  | 11.56 | 7.36     | 9.38     | 12.59    |
These weibull modulus values are included in the interval relative to composite materials [15,16]. A slight variation in weibull modulus of 6.90 to 7.18 was observed depending on the number of folds of the glass fibers laminates. A significant variation from 8.50 to 11.56 for the carbon fiber laminates and from 7.36 to 12.59 for the hybrid laminates. We notice that Weibull modulus vary according to the fiber’s nature and the number of plies.

5. Morphological analysis
A morphological analysis of fracture facies and structures of different materials was investigated by scanning electron microscope (SEM) observations and presented in Figures 7 and 8.

The crack generally follows a perpendicular plane to the load, glass and carbon fiber loosening, fiber breaks, delamination and cracks in the matrix have been observed. Laminate composite materials contain defects which are essentially due to the nature of the fibers and the number of plies used.

6. Conclusion
The influence of the nature of the fibers and the number of fibers on the mechanical behavior and defects in composite structures was determined by the weibull probabilistic analysis of the flexural behavior. The experiments are carried out on laminate composites with an epoxy matrix and differentiated by their natures of fibers (glass, carbon and hybrid[c/v]) and by their numbers of plies (8plies, 10plies and 12 plies).

The analysis of the results of flexural behavior of the various laminates leads to that conclusion:

- More the number of folds increases the higher the mechanical characteristics,
- Hybrid laminates have better mechanical properties than laminates of the same type of fiber except for the 12-plies hybrid laminate which has a decrease in young's modulus compared to the 12-plies carbon fiber laminate,
- In hybrid laminates and laminates with greater number of folds of the fibers, the dispersion of the defects is weaker.

The use of weibull statistics allowed us to calculate the weibull parameter for the case of the flexural rupture stress of the laminates with different plies and the nature of the fibers.

The Weibull modulus, m, is a material parameter characteristic of the dispersion of defects (or criterion of fracture sensitivity) for a given material.
- When the Weibull module is weak, there is a large dispersion of defects in the material. Consequently, there will be a great dispersion on the values of stresses of activation of the defects within the volume v of the material studied.
- When the Weibull modulus is high, the dispersion of defects is small, as well as the dispersion on the stresses of activation of the defects within the volume v of the material studied.

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