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STUDY OF MECHANICAL BEHAVIOUR IN THREE-POINT BENDING OF FATIGUE-STRESSED COMPOSITE LAMINATES

The aim of this work was to conduct an experimental investigation of the mechanical behaviour in the three-point bending of fatigue-stressed cross-ply laminated composites. A 3-point static bending study was carried out on two types of laminated composite materials to determine their mechanical characteristics as well as to assess the influence of the test speed and the effect of the stacking sequence on their mechanical behaviour. Different damage modes leading to the rupture of these materials were highlighted to determine their types.

Keywords: three-point bending, composite, laminate, fatigue, damage, stacking sequence

INTRODUCTION

The use of composite materials in industry has increased in recent years in all areas: automotive, aeronautics, space, marine, rail, sports, medical and nuclear. In fact, composites make it possible to achieve performances that conventional materials cannot provide. In order to optimize their use and their suitability for industrial applications, some recent research works related to composite materials are being undertaken in laboratories over the world to better understand the behaviour of composite structures presented in published studies [1-4].

Laminates are primarily used for their specific stiffness and strength qualities; they have additional characteristics such as high rigidity in a defined direction, simplicity of preparation, light weight and good resistance to fatigue. The fatigue behaviour of composite laminates has been studied by several authors looking at the effect of the stacking sequence and the type of reinforcement on the mechanical characteristics of laminates [5, 6].

Numerous studies have been carried out on the influence of the ply orientation of a laminate in bending [7-12]. Wharmby et al. [13] found that increasing the ply orientation angle results in a decrease in the rupture stress. Sihn et al. [14] compared two quasi-isotropic laminates with an identical number of plies for the same orientation but stacked in different ways, grouped or dispersed. They showed that a quasi-isotropic laminate of the $[(0°/\pm45°/0°)_n]_s$ type is more resistant to damage than a laminate of the $[0_n°/\pm45_n°/0_n°]_s$ type. Moreover, they discovered the possibility to delay or remove damage (delaminating and splitting), by arranging the plies in the form of thin layers.

The effect of the loading frequency on the fatigue behaviour of an aluminium composite material with an aramid honeycomb core was studied in [15]. The mechanical behaviour under three-point static bending was assessed by cyclic flexural tests, with loading frequencies of 5, 7.5 and 10 Hz. The experimental study allowed determination of the necessary cycles to achieve resistance losses of 10 and 25%, respectively.

Nevadunski et al. [16] tested glass-epoxy specimens at the frequency of 30 Hz. The increase in temperature was not a direct consequence of the increase in frequency but rather a consequence of the heating of the resin caused by the breaking of some fibers, which undergo continuous friction during cycling.

The influence of the frequency, from 1 to 1.5×10^{-4} Hz, on the development of fatigue cracking in the layer oriented at 90° of a laminate $[(0, 45, -45, 0, 90)_3]_s$ in carbon/epoxy T300/914 was highlighted in [17].

Analysis of the mechanical behaviour of innovative materials is a field of continuous research in order to advance the mastery of composite materials, especially in the industrial context. To date, numerous studies have been carried out on the mechanical fatigue behaviour of composite materials [18-21].

Roudet et al. [22] conducted fatigue tests until rupture (10^7 cycles) under imposed displacement. The tests, by setting the nominal deflection, were performed using the load loss during a cycle. This was the damage indicator which shows the loss of rigidity.

Kim et al. [23], by conducting bending tests, concluded that imposed force tests are more severe than imposed deflection tests.

On the basis of three-point bending tests, it was found that in the case of displacement control (arrow), there is rapid growth of damage during the first cycles, followed by a decrease in the slope of the curve. The results show rapid damage accumulation at the beginning of cycling, thereafter the damage become progressive as the cycles increase. On the other hand, in the case of force control, a linear variation of the damage is noticed, resulting from gradual damage development throughout the fatigue test. The damage and the service life prediction (SLP) of composite materials have been the subjects of numerous investigations [25-27].

Many studies deal with the development of analytical models for numerical modelling and the determination of displacements with the best possible precision. The different methods of SLP do not yet make it possible to explain all the complexities of the fatigue damage phenomenon. Many models exist, even the most complex, to take this phenomenon into account when studying multilayer structures [28-30].

The proposed experimental study concerns two symmetrical laminated materials reinforced with E-glass fibres and an epoxy resin matrix. These materials were manufactured by a successive lamination process of sixteen identical reinforced layers in the form of unidirectional fabric VEX 300, of mass per unit area M_s = 300 g/m^2, oriented at 0° and 90° according to stacking sequences $[0/90/0/90/0/90/0/90]_s$ for the first one designated as "Lam 1" and $[0_4/90_4]_s$ for the second designated as "Lam 2". Impregnation with the SR 1500 epoxy resin was carried out by the wet lay-up process and then subjected to vacuum polymerization using the vacuum bag technique for 8 hours at ambient temperature.

TEST STAND AND PROCEDURE

The specimens were cut using a diamond-disc chainsaw from plates 250×250 mm. The specimen dimensions were 80×15×4 mm according to AFNOR standard NF T 57-105. The distance between the supports was l = 64 mm.

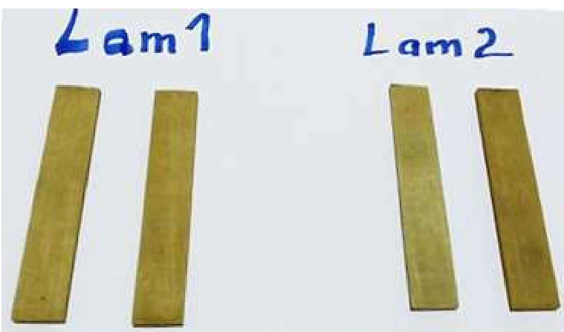

Fig. 1. Test specimens

The assembled specimens were clamped and then placed on the magnetic table of a flat grinding machine. Thanks to a grinding wheel, the lateral sides (thicknesses) of the specimens were sanded in one pass. The goal of this operation was to prepare these surfaces for proper microscopic observation of the damage.

The three-point bending tests were performed on a Zwick/Roell Z005 testing machine with a capacity of 5 kN and controlled by a computer (Fig. 2 and 3).

Fig. 2. Zwick/Roell Z005 testing machine

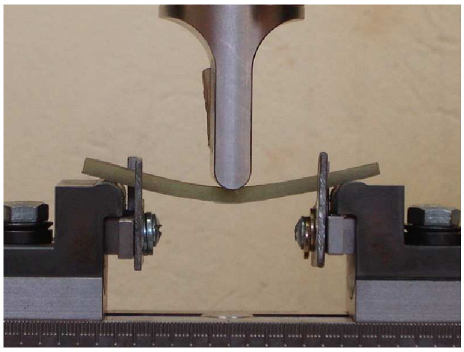

Fig. 3. Three-point bending test

Static tests

Four specimens were tested for each material type. The load-displacement mechanical behaviour curves obtained from the static three-point bending for the two types of materials are shown in Figure 4. The obtained results allow calculation of the rupture stress values and the flexural modulus of elasticity using the equations below:

$$\sigma_{rup} = \frac{3\, F_{max}\, \ell}{2\, b\, h^2} \tag{1}$$

$$E_x = \frac{F_{max} \ell^3}{4 b h^3 w_c} \tag{2}$$

where σ_{rup} is the rupture stress, F_{max} is the maximum load to rupture, E_x is the bending Young's modulus, w_c is the maximum deflection to rupture, ℓ is the distance between the supports, b is the specimen width, and h is the specimen thickness.

The results are reported in Table 1.

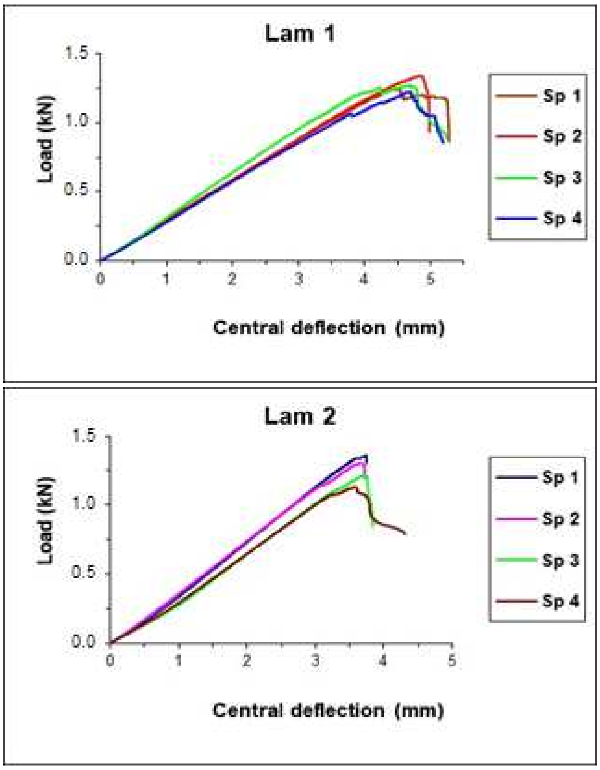

Fig. 4. Load evolution with deflection (Lam 1 and Lam 2)

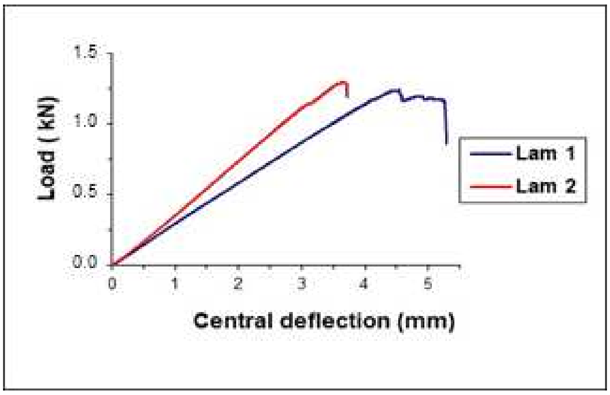

Fig. 5. Mean loading curves vs deflection (Lam 1 and Lam 2)

TABLE 1. **Rupture stress and flexural modulus of elasticity**

	Lam 1	**Lam 2**
Maximum load to rupture F_{max} [kN]	1.27	1.25
Maximum deflection to rupture [mm]	4.67	3.66
Bending rupture stress [MPa]	539	505
Calculated Young's modulus [MPa]	20414	27275

Specimens damage tested under static stress

The conducted observation using a light microscope of the damaged specimens of the two investigated materials made it possible to distinguish four types of damage.

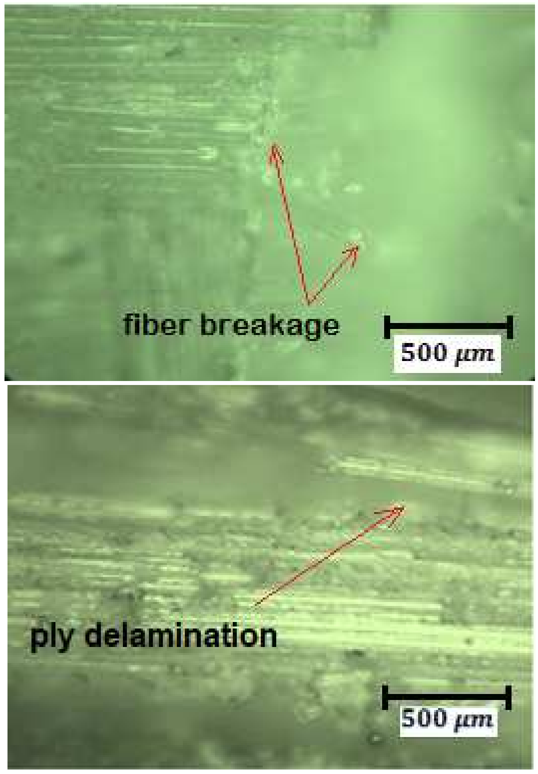

Fig. 6. Fractography of damaged Lam 1 specimen

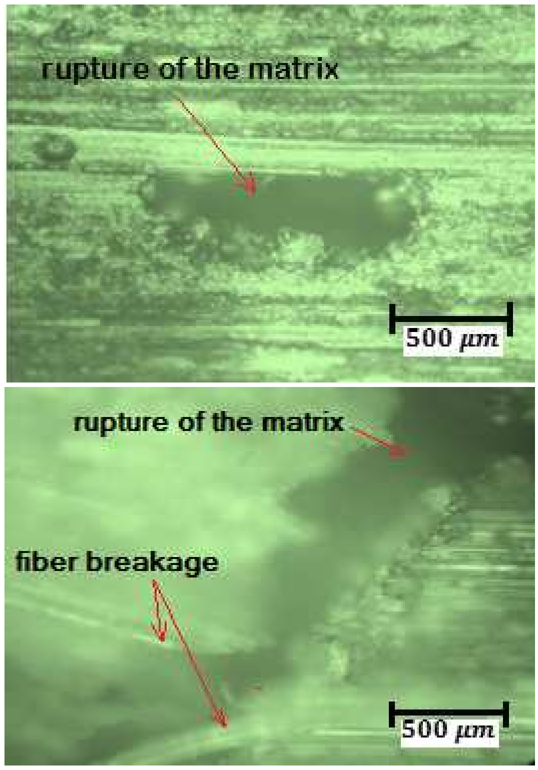

Fig. 7. Fractography of damaged Lam 2 specimen

Comments:

- The lateral surfaces of the Lam 1 specimen in Figure 6 show that the fibres rupture with delamination of the outer layer.
- The lateral surfaces of the Lam 2 specimen in Figure 7 show that the matrix and fibres rupture. Lam 2

$[0_4/90_4]_s$, whose plies are external and oriented at 0° with significant thicknesses, are a little damaged by transverse cracks and the rupture mainly occurs due to delamination between the plies at 0° and 90°.

Fatigue tests

Cyclic fatigue tests were carried out by imposed sinusoidal displacement at the frequency of 50 Hz. The specimens were tested for cyclic fatigue up to 10,000 cycles for every single test considering two speeds, 10 and 100 mm/min.

The loading level was fixed at 60% of maximum load F_{max}, for each material, which corresponds to the maximum displacement values of 2.54 mm for the Lam 1 specimen $[0/90/0/90/0/90/0/90]_s$ and 2.22 mm for the Lam 2 specimen $[0_4/90_4]_s$.

In order to characterize the material performance in fatigue, we studied the loading evolution as a function of the number of cycles. The change in flexural modulus as a function of the number of cycles is shown in Figure 8.

The variation in stiffness loss ($\frac{E_f}{E_{f0}}$) according to the number of cycles of the studied laminates for the above specified velocities (10 and 100 mm/min) is shown in Figure 9.

Damage factor D represents the variation in the material flexural modulus, and it is expressed as:

$$D = \frac{E_{f0} - E_f}{E_{f0}} = 1 - \frac{E_f}{E_{f0}} \qquad (3)$$

where E_f is the material flexural modulus after n stress cycles and E_{f_0} is the flexural modulus of the E-glass fibres and epoxy resin.

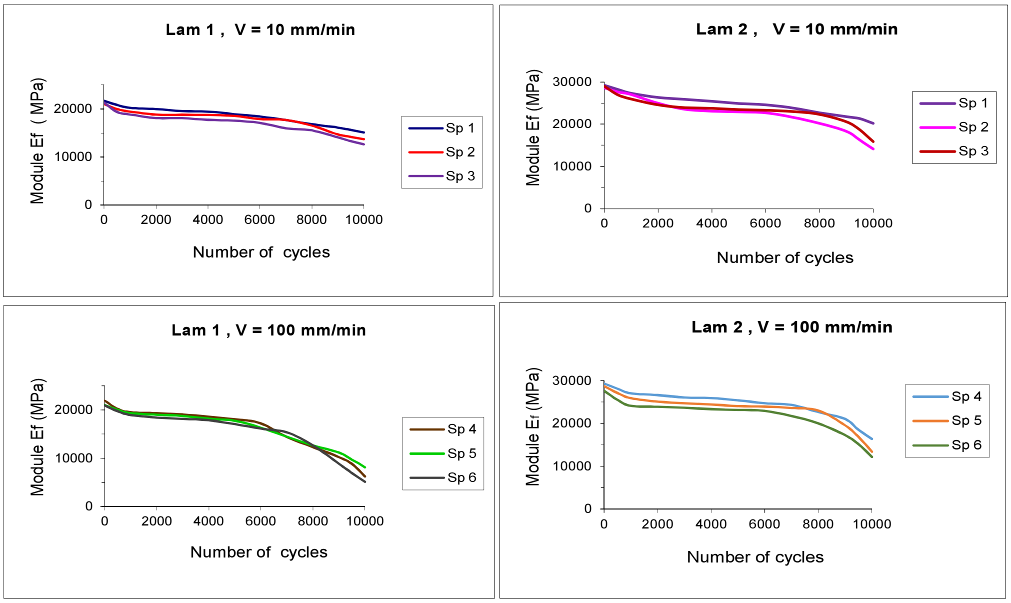

Fig. 8. Flexural modulus mean curves vs cycles, for given velocities

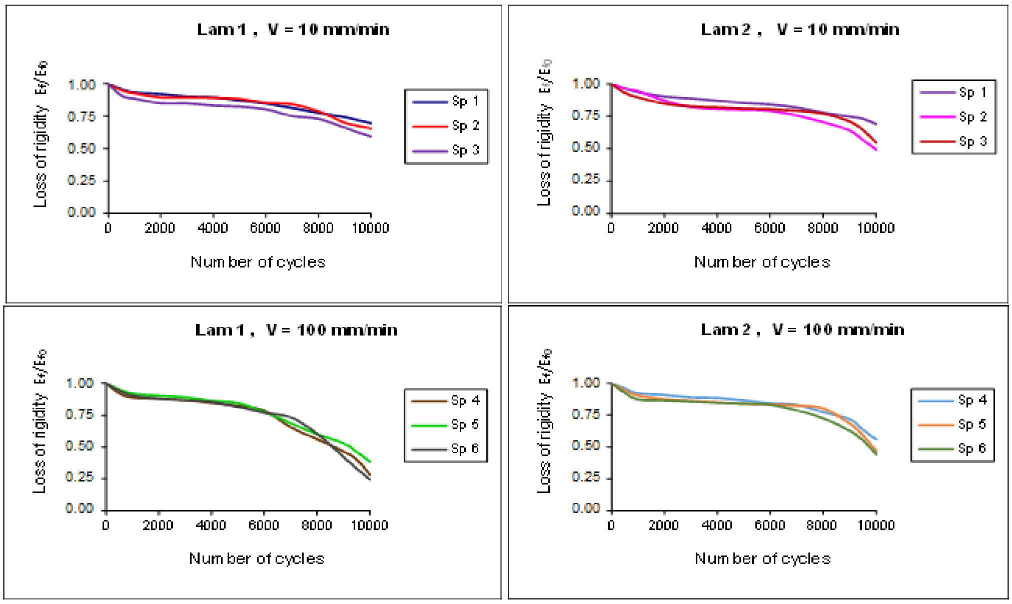

Fig. 9. Loss of rigidity mean curves vs cycles, for given velocities

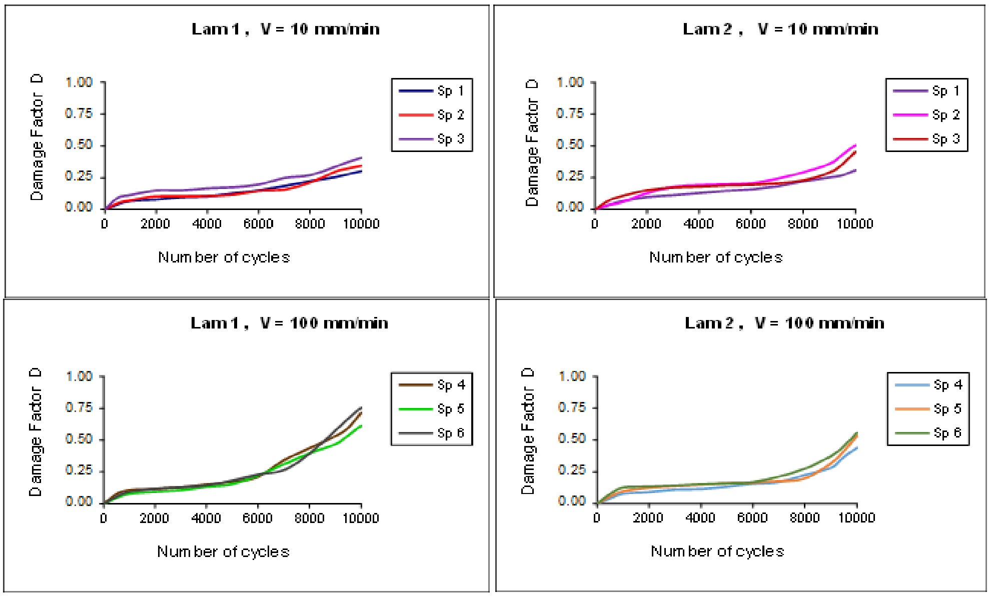

Fig. 10. Damage factor mean curves vs cycles, for given velocities

RESULTS ANALYSIS

For the Lam 1 material $[0/90/0/90/0/90/0/90]_s$, the flexural modulus decreases moderately with increasing test velocity; this behaviour is more visible with the increase in the number of cycles.

For the Lam 2 material $[0_4/90_4]_s$, the rigidity loss of the material evolves in three phases: in the first phase there is a sudden decrease in rigidity during the first cycles, in the second phase the decrease is very slow and stable and in the third phase, there is a rapid loss of rigidity when the number of cycles reaches 8000 (Fig. 9).

- The effect of the test speed on the degradation of the flexural modulus: the effect of the stress rate on the rigidity loss and the lifetime of the material is shown in Figure 11. The degradation of the studied materials is progressive for the test speed of 100 mm/min. This is well illustrated for the Lam 1 material when the number of cycles exceeds 6000. However, in the case of the speed value of 10 mm/min, both the materials have a significant resistance to fatigue.
- The effect of the stacking sequence on the degradation of the flexural modulus: the results of analysis of the fatigue tests carried out on the two types of laminates, Lam 1 $[0/90/0/90/0/90/0/90]_s$ and Lam 2 $[0_4/90_4]_s$, allow the remarkable influence of the stacking sequence to be highlighted (Fig. 12).

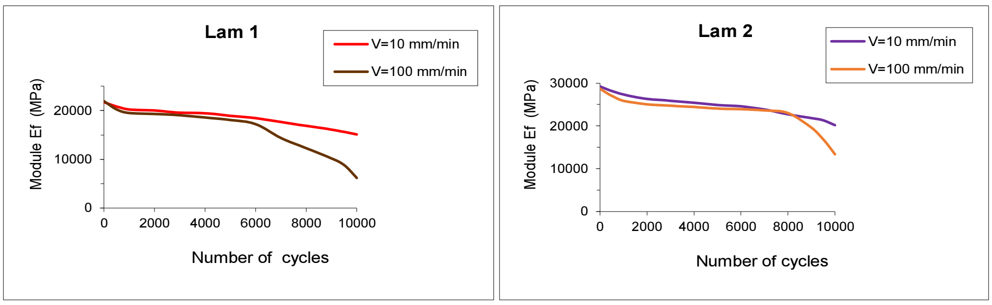

Fig. 11. Effect of testing velocity on fatigue behaviour of laminates

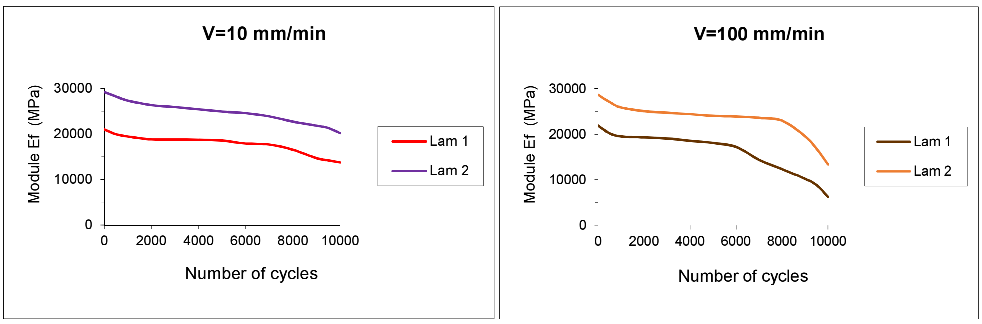

Fig. 12. Fatigue behaviour comparison for selected speeds

During the first cycles of the fatigue tests (Fig. 8), the degradation of the flexural modulus is slower for both Lam 1 and Lam 2. After 2000 cycles, the flexural modulus moves towards stabilization for the Lam 2 material; this feature is more visible for the speed of 100 mm/min (Fig. 12). The flexural modulus decreases faster for Lam 1 compared to Lam 2. In fact, the loss of rigidity is significantly more apparent for the Lam 1 material (Fig. 9).

The fatigue resistance decreases when the plies at 0° and 90° are alternated. It was found that Lam 2 with four layers on the outside at 0°, has the greatest rigidity and the lowest rupture strength.

CONCLUSIONS

– Thanks to the static three-point bending tests, we were able to determine the mechanical characteristics of the studied materials as well as their failure modes.
– During the cyclic three-point bending tests, we were able to notice three phases in the loss of rigidity of the laminate: a sudden decrease in the first cycles, then a slow and stable decrease and finally a rapid loss of rigidity when the number of cycles reaches 8000.
– The flexural modulus is inversely proportional to the testing velocity and the loss of rigidity is significant when the number of cycles increases for a relatively high speed.
– The ply orientation has an influence on the fatigue resistance, which decreases when the plies at 0° and 90° are alternated.
– The results highlight the elastic and linear behaviour of the investigated laminates. The appearance of the first macro-cracks and their coalescence lead to sudden rupture of the test pieces.

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