FATIGUE BEHAVIOUR OF HYBRID COMPOSITE LAMINATES SUBJECTED TO BENDING LOADING

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ABSTRACT

This paper studies hybrid laminated composites fabricated with natural fibber/polypropylene core and glass fibbers reinforced polypropylene skins. These composite materials were tested in expectance they can offer an equivalent stiffness and strength when compared with full glass fibbers reinforced polypropylene laminates, improved stiffness to weight ratio and economical, ecological and recycling advantages. Full glass fibbers laminates were obtained from multi-layers of Vertotex "Twintex T PP". Each sheet was made up of seven woven balanced bi-directional ply layers with a fibber volume fraction of 0.338, as reported by the manufacturer. Hybrid laminates were hand manufactured with a hemp natural fibber/polypropylene core and two glass fibbers/polypropylene surface layers at each side of the specimen. Experimental tests were performed in three point bending for both laminates to evaluate flexural properties and fatigue behaviour. Fatigue results were plotted as the stress against the number of cycles to failure. The failure sites and mechanisms were investigated based on microscopy studies, interlaminar fracture toughness tests and on finite element method analysis of the stress distribution on loader contact regions. Fatigue damage was measured in terms of the stiffness loss. The advantages of the hybrid laminates were discussed by comparing with results previously obtained.

1.INTRODUCTION

Composite laminates replaced metals in many applications accounting their weight reduction, corrosion resistance, etc. Many applications of the polypropylene glass fibbers reinforced laminated are in boats, panel cars, sports equipments and transport boxes where bending are sometimes the main loading mode.

The static and fatigue properties of full glass fibbers laminates were analyzed in previous works of the authors [1,2] for tensile loadings. Flexural strength of the laminates and particularly of the sandwich laminates is not only influenced by tensile stresses but also by shear stresses playing the interlaminar fracture toughness of the interface layers an important role.

Sandwich structures offer an improved stiffness to weight ratio, hence being used widely in weight sensitive areas where high flexural rigidity is required. Gibson and Ashby [3] have analyzed the behaviour of foam cored and metal skin sandwich beams and its static and impact behaviour was discussed. Ferreira *et al* [4] studied the static and creep behaviour of sandwich beams made of glass fibber composite skins and PVC foam. Polymers have the propensity to creep at room temperature. In structural panels, the creep behaviour will be an important characteristic of the material. This subject was studied by Little *et al* [5] and Lowe *et al* [6].

The objective of this paper was to study the static and fatigue flexural strength of hybrid laminates fabricated with natural fibber/polypropylene core and glass fibbers reinforced polypropylene skins in expectance they can offer an equivalent stiffness and strength when compared with full glass fibbers reinforced polypropylene laminates, improved stiffness to weight ratio and with economical, ecological and recycling advantages.

2.MATERIALS AND EXPERIMENTAL PROCEDURE

Laminated composites (LC) sheets were manufactured using seven woven balanced bi-directional layers E glass fibbers/ polypropylene resin from Vertotex “Twintex T PP” (TPP) which were compressed in a mould under a pressure of 5 bar for 10 minutes after heating at 190ºC. This temperature is above the melting temperature of the polypropylene. Twintex TPP is composed of polypropylene (PP) reinforced with glass fibbers type E. The overall dimension of the plates is 160x250x3 mm. A fibber volume fraction (V_f) of 0.338 is reported by the manufacturer. The hybrid laminated composites (HLC) were manufactured in the same conditions, with the following layer set up: TPP/TPP/PP/random hemp/PP/random hemp/PP/TPP/TPP. The quality control of the plates was done by visual inspections of the colour and void content.

The specimens used in the static and fatigue tests were cut from these plates being the bending stresses oriented with one fibber direction of the skins. The geometry and dimensions of the specimens are shown in Fig. 1a).

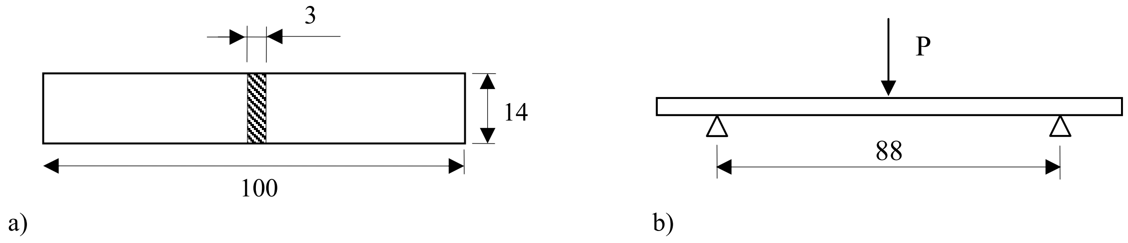

Fig. 1. a) Specimens tests (dimensions in mm). **b)** Three point bending apparatus.

The static tests were performed in three point bending in an electromechanical Zwick, model 1435, with a strain rate of 5 mm/s. Four specimens were tested for each material. The fatigue tests were carried out at room temperature in an electromechanical machine whose frequency and stress ratio can be changed. A load cell is used to monitor the load. The load wave was sinusoidal with constant amplitude, a stress ratio R=0.25 and a loading frequency of 10 Hz. Fig. 1b) shows a schematic view of the three point bending apparatus used in the static and the fatigue tests.

The nominal bending stress (σ) is obtained using Eq. (1):

$$\sigma = \frac{3\,P\,L}{2\,b\,h^2} \qquad (1)$$

where P is the load, L the span length, b the width and h the thickness of the specimen.

3.RESULTS AND DISCUSSION

Static tests were performed to obtain the flexural properties of the materials. Two typical load-displacement curves are plotted in Fig. 2, for laminate and hybrid composites. The plots show, for both materials, a nearly fragile behaviour with a non-linear region only at the end of the tests and a significant drop of the stress after peak stress was reached. On the other hand, the LC laminates present a more stable propagation regime than hybrid composite.

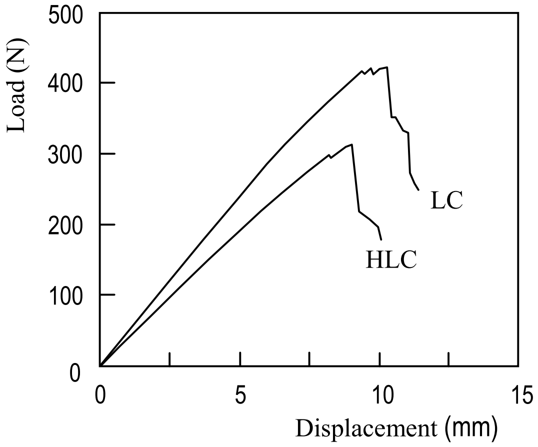

Fig. 2. Load displacement curves for laminate and hybrid composites.

Table 1 presents the results obtained in the three point static bending test and the average values. It can be observed that the laminates present an ultimate strength about 7.5% higher than the hybrid composites, while the Young's modulus was about 3% higher. The variation of bending strength is associated with the changes in failure mechanisms. These differences in failure mechanisms can be observed in Fig. 3a) and 3b) for the laminates and hybrid composites, respectively.

Table 1. Three points bending properties.

	σ_{UTS} (MPa)	Average σ_{UTS} (MPa)	Standard Deviation	E (GPa)	Average E (GPa)	Standard Deviation
Laminated composites	352.40	380.95	53. 8	11.4	11.75	0.971
	461.47			11.2		
	350.90			13.2		
	359.03			11.2		
Hybrid laminated composite	312.6	354.07	37.13	10.9	11.3	0.337
	402.9			11.7		
	385.3			11.2		
	362.8			11.4		

For laminate composites it is possible to observe a fracture of the fibbers, by compression, with quite small delaminations around of the fibbers that were broken. Probably, this delamination is responsible by propagation regime shown in Fig. 2. For all specimens tested the fibbers submited to tensile loads didn't break and the main failure process occurs in compression.

For the hybrid composites the failure process is faster. The ruptures of the fibbers appear first in compression region, like in the laminate composites, followed by a long delamination (detail C) between the core and the skin as consequence of the high gradients of shear and bending stresses. Finally this delamination produces the rupture of the fibbers in tension (detail B) and consequent failure of the specimen. Possibly this delamination is the cause of the perturbation in the load-displacement curve (Fig. 2) for sandwich composites.

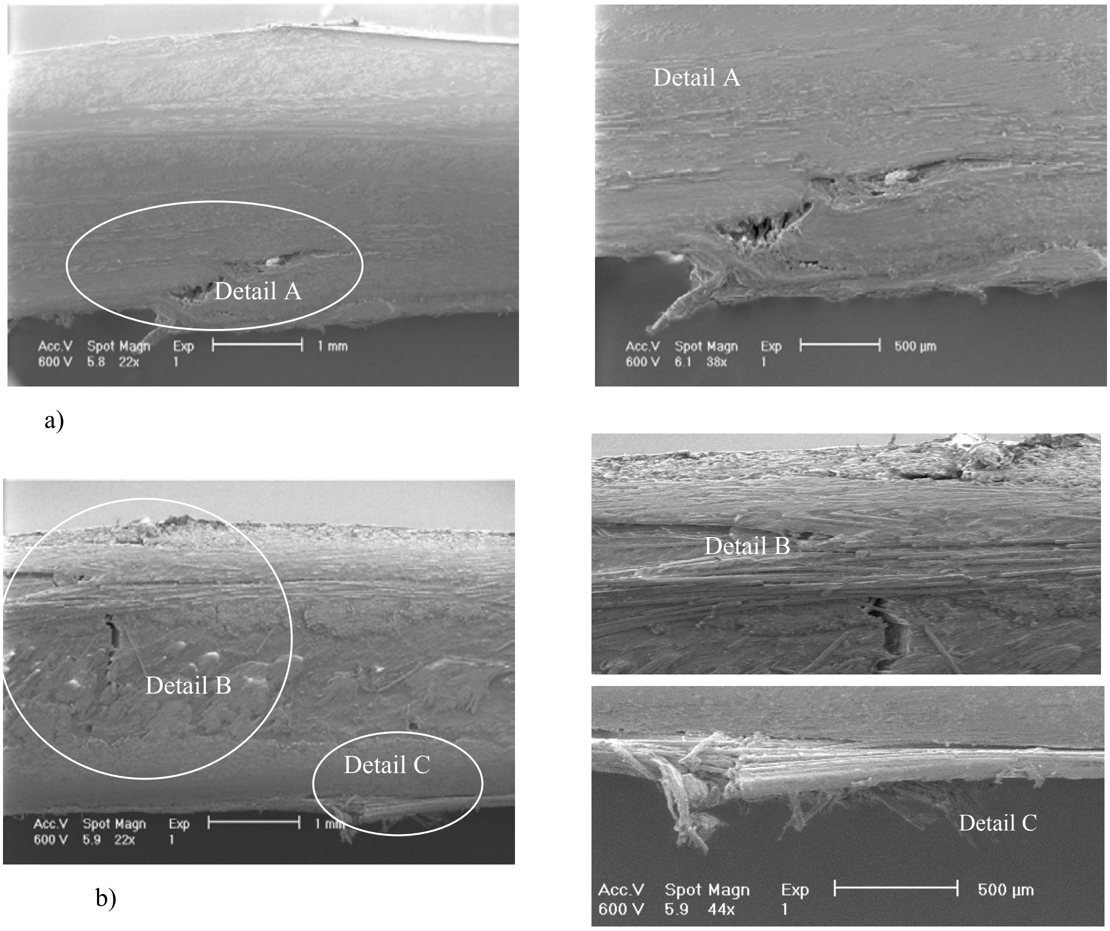

Fig. 3. Failure mechanisms for: **a)** Laminated composites, **b)** Hybrid laminated composites.

In both laminates the delaminations between layers has an important role on failure process. Taking in account this aspect the interlaminar fracture toughness was carried out using double cantilever beam specimens, following ASTM D5528-94a [7], for Twintex laminates and hemp/polypropylene laminates. The tests were performed in an electromechanical Instron Universal Testing machine in displacement control at a rate of 5 mm/min using double cantilever beam specimens. The results are presented in Fig. 4 showing that Twintex laminates has a fracture toughness about 25% higher than the natural fibber/polypropylene laminates which can be a determinant reason for the lower bending strength obtained for hybrid laminate composites.

The results of the fatigue tests were plotted in Fig. 5 in terms of stress range at the beginning of the test, in MPa, versus the number of cycles to failure. Failure was defined as the moment when the loss of stiffness reaches 20 % of the initial value. This figure shows that the fatigue strength of the laminate composites is 1.2-1.4 times higher than hybrid composites in consequence of the static strength decrease and different failure mechanisms as observed before.

Fatigue failure process is similar to that observed in static tests. In the laminates submited to high stress levels the compression rupture of the fibbers was observed first, with a relatively small scatter of results while for lower stress levels the delamination becomes the predominant failure process and produces a higher scatter of the results. On the other hand for hybrid composites the compression fracture is the main failure mode for high and low stress levels, similarly to that observed for static tests.

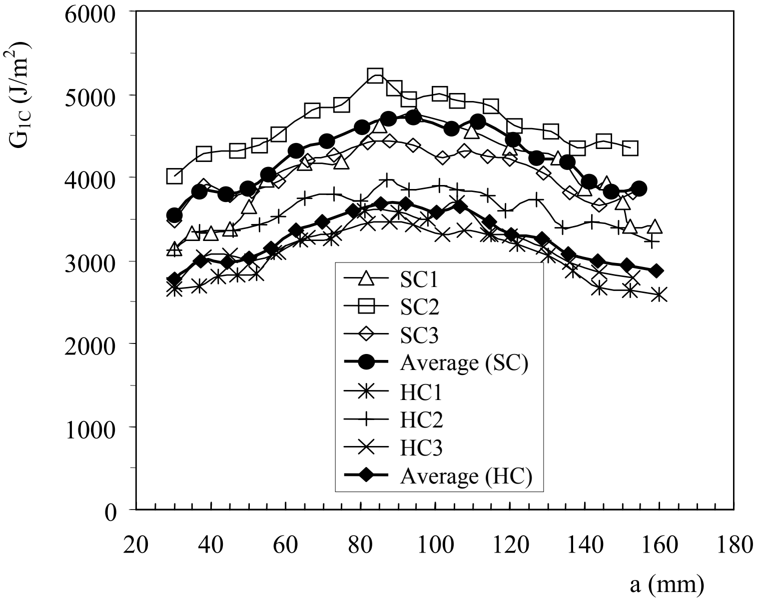

Fig. 4. Interlaminar fracture toughness versus the crack length.

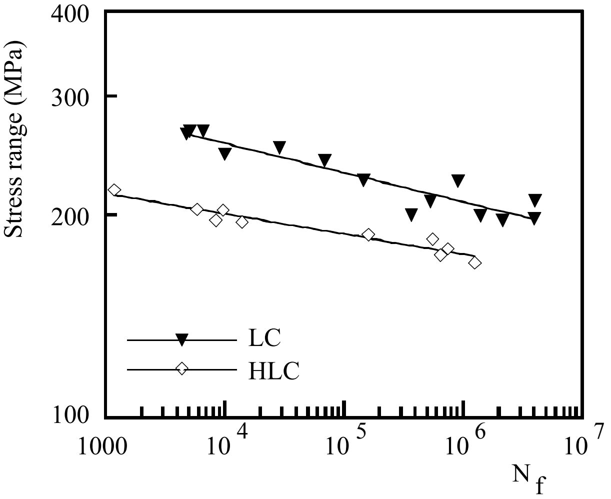

Fig. 5. S-N curves for laminated composites and hybrid laminated composites.

The microscopy analysis did reveal that the faster failure mechanism was always the compressive broken of the longitudinal glass fibbers in the compression side of the specimen consequence of the low compressive strength of the fibbers. To improve the understanding of this process a finite element stress analysis was performed on the compressive and interface regions for the HLC specimens.

Fig. 6 presents the physical model considered in the numerical analysis. A 3D analysis was made, considering only ¼ of the specimen along with adequate boundary conditions. The specimen was loaded with 50 N as indicated, for a total load of 200 N. Three different layers of material were considered, each with 1 mm thickness. The inside layer was made of PP reinforced with natural fibbers and the other two were made of Twintex TPP composite. Both materials were assumed to be continuous, homogeneous and with orthotropic linear elastic behaviour. Table 2 present the orthotropic properties considered. The main orthotropic directions are coincident with Cartesian coordinate system indicated in Fig. 6.

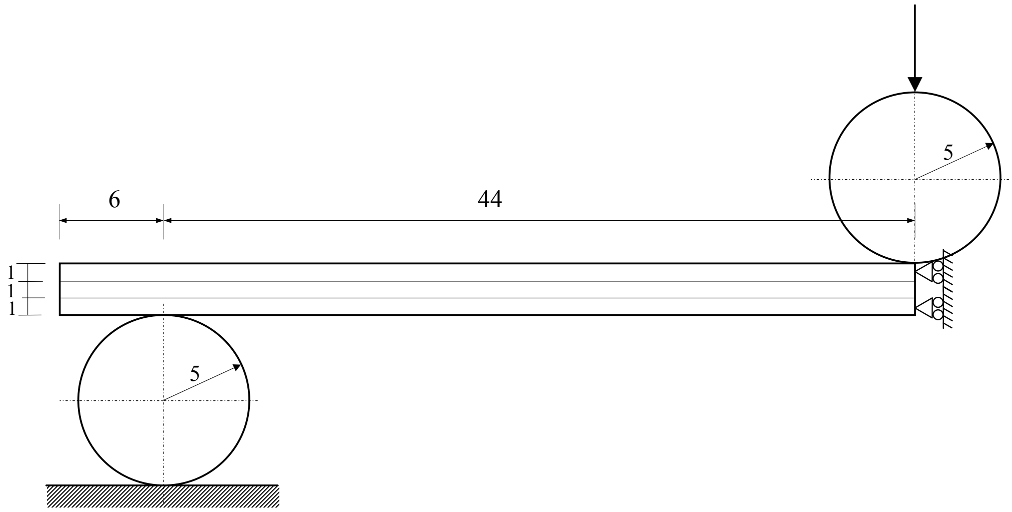

Fig. 6. Physical model of three-point bend geometry (dimensions in mm).

Table 2. Orthotropic elastic properties.

Property	Twintex	PP+ natural fibbers	Comment
E_1 [MPa]	17289.2	3370 MPa	Experimental value
E_2 [MPa]	1500	1500 MPa	Typical value for PP
E_3 [MPa]	17289.2	3370 MPa	$= E_1$
ν_{12} [-]	0.32	0.32	Typical value for PP
ν_{23} [-]	0.028	0.142	Considering orthotropic properties
ν_{31} [-]	0.125	0.39	Experimental value
G_{12} [MPa]	6548.86	1276.515	$= E_1/[2(1+\nu_{12})]$
G_{23} [MPa]	729.57	656.742	$= E_2/[2(1+\nu_{23})]$
G_{31} [MPa]	7684	1212.23	$= E_3/[2(1+\nu_{31})]$

The physical model was analysed by the finite element method using commercial finite element package MARC- MENTAT 2003 [8]. Fig. 7 presents a finite element mesh having a total number of 27320 elements and 32509 nodes.

Fig. 8 presents the longitudinal stresses σ_1, the thickness direction stresses σ_2 and Von Mises equivalent stresses σ_{VM}, versus distance to point A, measured along the thickness. Point A is the contact of the specimen with central pin. It can be seen that σ_2 stresses are different from zero near contact point. σ_1 stress has a linear variation typical of flexure distributions, however higher values are obtained near point A resulting from contact. Between 1 and 2 mm, corresponding to the layer of PP with natural fibbers, stresses are lower which is explained by the lower elastic rigidity. Therefore its deformation is easier and it supports lower forces. The high stress concentration of compressive stresses in contact loader pin region associated with the low compressive strength of the fibbers promotes the compressive broken of longitudinal fibber in this region as the early failure mechanism.

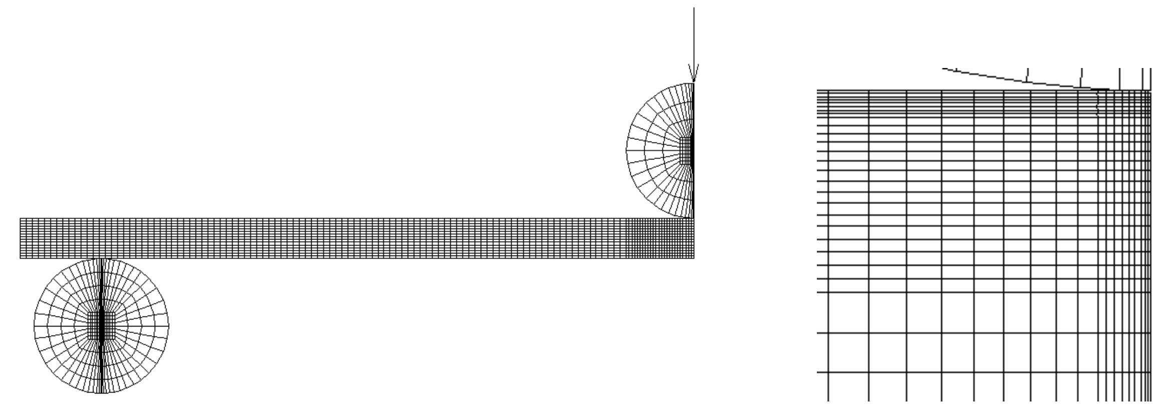

Fig. 7. a) Finite element mesh. **b)** Mesh detail near contact region.

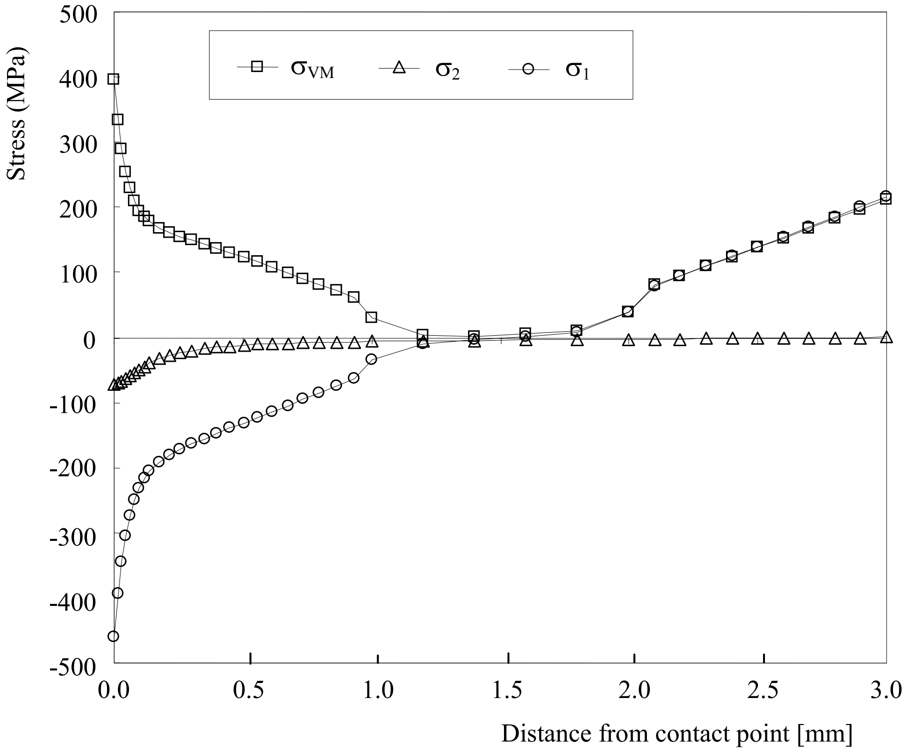

Fig. 8. Stresses along the thickness.

During the fatigue tests, the stress and the temperature rise were also monitored. The stiffness modulus was then calculated by the linear regression of the stress-strain data. This fatigue damage parameter was plotted in Fig. 9a) and Fig. 9b) in terms of E/E_o versus N/N_f, where E is the current stiffness modulus, E_o the initial stiffness modulus, N the number of loading cycles and N_f is the number of cycles to failure.

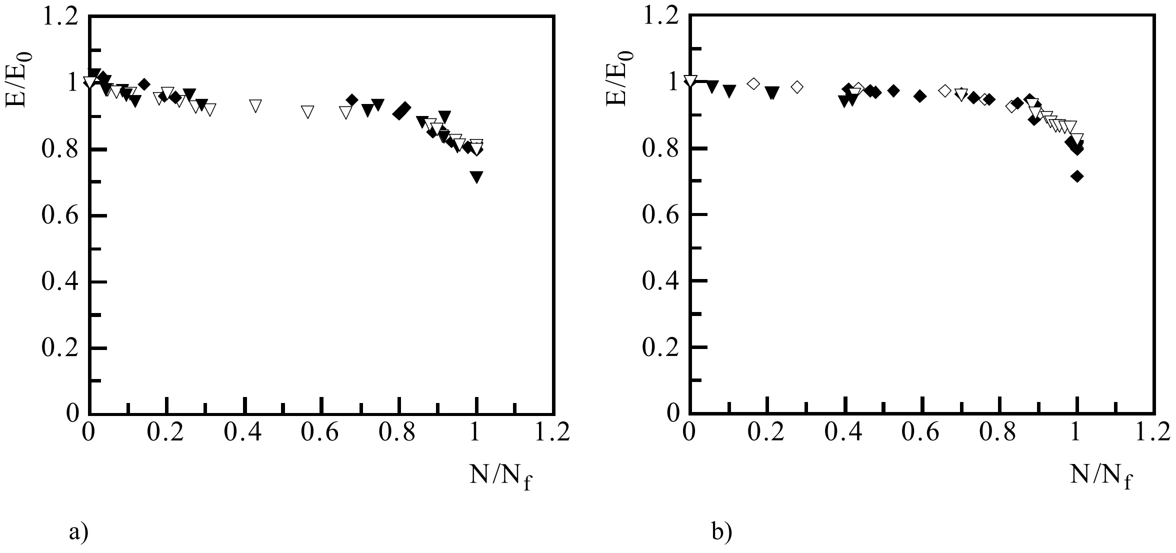

Fig. 9. E/E_o against the normalised number of cycles N/N_f a) laminate composites b) hybrid composites

For the laminate composites (Fig. 9a) a significant drop of E/E_o (4-6%) can be seen at the early stage of the fatigue life (5%), followed by a second stage where only a slow decrease was observed. Finally, during the last 5% of fatigue life a sudden drop of E/E_o until failure was observed. This behaviour is controlled by the damage occuring in the composite being each stage associated with a defined failure mode and is similar to that observed in tensile tests [1]. For the hybrid composites the first stage was not observed. The parameter considered decreases slowly up to the last 15-20% of fatigue life where it has a sudden drop until failure. The absence of first stage stiffness drop can be a consequence of the lower stress levels of the tests being not enough to produce significant creep or matrix failure which are two important mechanisms of the early fatigue damage.

In order to improve the understanding of fatigue damage growing the residual strength in laminate composites was also evaluated. Residual stress were obtained after $5x10^4$, 10^5, $2.5x10^5$ and $4x10^5$ fatigue cycles with a stress range of 215 MPa. The results are presented in Fig. 10 in terms of residual strength (MPa) versus number of fatigue cycles.

The figure shows that up to $5x10^4$ cycles, residual strength is similar to that observed in static tests. This behaviour indicates that no significant damage occurred in laminates. Lately, residual strength decreased up to about 40% of static resistance for a life of $4x10^5$ cycles. By microscopic analysis it was possible to observe that about 10^5 loading cycles, rupture occurs by compression in some fibbers, producing delamination and posterior propagation.

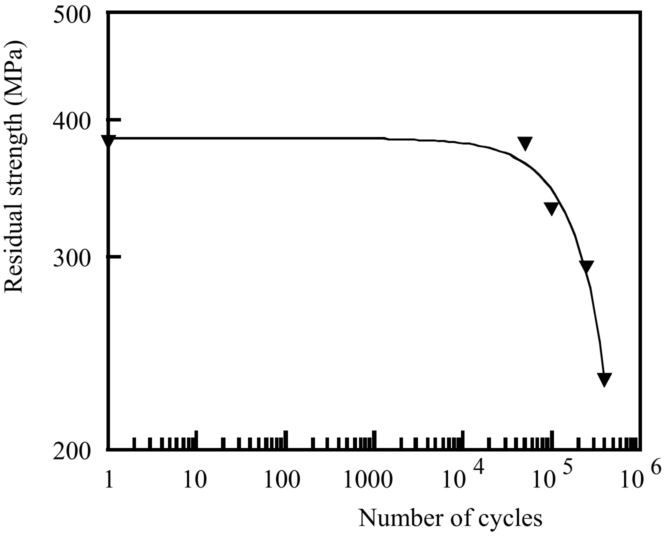

Fig. 10. Residual strength versus the number of fatigue cycles for the laminates composites.

5. CONCLUSIONS

Fatigue strength of hybrid laminated composites is about 20 % lower than the laminated composites. This decreasing is consequence of the loss in static strength (about 7.5 %) and of the change of failure sites and mechanisms. Failure mechanisms in hybrid laminated composites are strongly influenced by the high gradients of shear and bending stresses near the interface between the core and the skin and by the high magnification of compressive stresses around the contact of specimen with pin bonder. Fatigue damage was quantified in terms of stiffness losing and of residual strength after fatigue cycling.

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