THE EFFECT OF TRANSVERSE CRACKS ON THE CHARACTERISTICS OF A LAMINATE

M. Boutaïb [1], M. Hamdaoui [1], R. Lavabre [1] and E. Ramahefarison [1]

[1] *Laboratoire de Génie Mécanique de Toulouse*
I.N.S.A. d pt Génie Mécanique, 31077, Toulouse, France.

SUMMARY: This study is related to the fatigue behaviour of a continuous fibre laminated composite structure. In particular to the experimental aspect of transverse cracking. The use of X-rays allows crack visualisation and quantification. The modification of laminate characteristics (graphite/epoxy material T300/914) by fatigue is underlined and connected to matrix cracking. The phenomenon is confirmed by a continuum damage model. The effects on dynamic behaviour are analysed in order to establish the links between damage and variations in natural frequency.

KEYWORDS: Fatigue behaviour, Continuum Damage, Stiffness prediction, Transverse cracking, Dynamic properties, Experimental approach.

INTRODUCTION

Many fields currently have recourse to the use of composite materials with an organic matrix. More and more, these materials enter are being used to manufacture high reliability parts. So that they remain competitive compared with metallic materials, it is therefore necessary to be able to guarantee their properties for one given life-time. Thus, in order to qualify such or such a material, it becomes important to know the change in its mechanical properties in fatigue.
Because of its heterogeneity and very strong anisotropy, the nature of the damages as well as the mechanisms related to its appearance and their progression differs from what is usually found in conventional materials. The object of this study is to formulate a representation of fatigue behaviour laws for composites with an epoxy organic matrix and carbon reinforcement. These materials are characterised by a type of test (the tensile test) and the fatigue damage is analysed.
When a laminate is subjected to a stress of monotonous traction or fatigue, several damage modes can be observed before the final rupture. Among these modes, four of them are usually indexed in the literature : transverse cracking, delamination, longitudinal cracking and fibre breaking.
Transverse cracking corresponds to the break of the matrix in the transverse layers, which are tilted in relation to the stress axis. It can also exist before any loading. In this case it is the result of residual stresses of thermal origin resulting from the manufacturing process [1].
Under the effect of static or cyclical stresses, transverse cracking is often the first damage mode observed. It is generally followed by delamination, a state of damage which develops

quickly involving the accelerated interaction of other damage modes and until final rupture preceded by the breaking of longitudinal fibres.

Since 1977, Reifsnider, Garrett and Bailey [2-3] have noticed that when a number of cracks on the edge of a specimen reached a threshold value, it became nearly impossible for new cracks to develop, and also, that all the cracks are almost equidistant from each other. This state of cracked saturation will be called Characteristic Damage State (C.D.S) by Reifsnider. In addition, the development and the accumulation of the various damage states involve a deterioration of the mechanical properties of the material and leave the laminate more susceptible to external aggressions (corrosion, moisture). Several authors have traced changes in longitudinal rigidity of an orthogonal laminate according to the number of loading cycles [4-5].

To model the fatigue behaviour of these materials, we have sought to analyse over time various physical sizes defined as damage variables. In this paper, we describe the material, the manufacturing process and the main experimental techniques used to observe and chart the progress of damage. The modification of the mechanical characteristics by fatigue is underlined and connected to the matrix cracking. These experimental observations have validated the use of a model based on continuum damage mechanics [6-7] and applied to transverse cracking. In addition, the effects on the dynamic behaviour have been explored in order to evaluate the possible effect of the damage rate on natural frequencies and damping.

EXPERIMENTAL APPROACH

Experimental procedure

For the manufacture of a test-piece, we used unidirectional tapes (prepreg). Plates were obtained by draping the plies in a temperature controlled clean room (23°C) and at constant relative moisture (50%). A compaction was carried out with each pair of plies placed. The polymerisation phase is carried out in an autoclave which fulfilled the necessary temperature and pressure conditions. Five different laminates were chosen :

* Unidirectional $[0_{16}]$
* Angle ply $[+45/-45]_8$
* Cross-ply A $[0_5/90_3]_S$
* Cross-ply B $[0_4//90_4]_S$
* Cross-ply C $[0_3/90_3]_S$

The first two laminates are intended for the manufacture of product reception tests allowing the mechanical characterisation of the ply. The laminates A, B, and C, intended for the fatigue tests, have a sequence of stacking favourable to the cracking formation. They were selected in order to study the influence of the transverse layer thickness. For each one of these laminates, several plates of 300x200x*h* mm^3 were made up (*h* is the plate thickness, 2 mm for the unidirectional and the angle ply laminates and 1.5 mm for the cross-ply laminates). Specimens were cut by using a circular diamonds saw and a precision workbench. These specimens were fitted at their ends with glass/epoxy tabs (0,5 mm thickness). To decrease the influence of the edge effects, the sections of the specimens were polished before the tests. For the type of tests requiring several identical specimens, we took care to prepare those starting from the same batch of plates (i.e. worked out simultaneously and under the same conditions). In addition we took on each batch of plates (laminates A B and C) of the specimens in order to determine through experiments the static mechanical characteristics according to the direction of the fatigue load.

The fatigue tests were carried out on a hydraulic machine (Schenck) coupled to a microcomputer. A test control program was also developed. The imposed loads on the specimens during the tests were of two types :

- For the tensile static tests, the constant displacement rate of the piston has been fixed at 2mm/mn in accordance with the AFNOR standard specification.

- The tension-tension fatigue tests were carried out by controlling the sinusoidal load (3 Hz) and the ratio between the maximum and minimum loadings (R = 0,1).

Two levels of fatigue loading (load factor *k*) for orthogonal laminates : 60% and 70% of the static rupture stress have been studied.

Longitudinal elastic modulus

To measure longitudinal strains and transverse strains in static or fatigue, unidirectional strain gauges were connected in quarter bridge on an extensometry bridge. The longitudinal elastic modulus of a sample required the use of an extensometer making it possible to measure the elongation. During measurement, our acquisition programme installed on the microcomputer made it possible to record the values delivered by the various force, displacement, and strain sensors. This recording was made in real time :

- Either throughout the tensile quasi static test,
- Or at certain times during the fatigue cycles carried out at frequency 0.03 Hz for measurement.

During postprocessing, the real load was transformed into stress in order to plot the stress-strain curve for each cycle. The longitudinal elastic modulus is determined by smoothing. In accordance with the AFNOR T57-301 standard specification, it is calculated with the part of the curve ranging between 10% and 50% of the maximum applied load (ascending phase for the fatigue tests). During the fatigue tests, we charted the evolution of the instantaneous Young modulus thus defined for the following numbers of cycles : 1, 10, 100, 1000, etc.

Experimental X-ray observation of damage

The experimental observation of cracking consists in impregnating the test specimens with a darkening agent based on zinc iodide which absorbs part of the X-ray energy. The image thus obtained presents a contrast of the damaged areas where the chemical solution filled. The photograph (Fig. 1) corresponds to a superposition of the damage in the various layers.

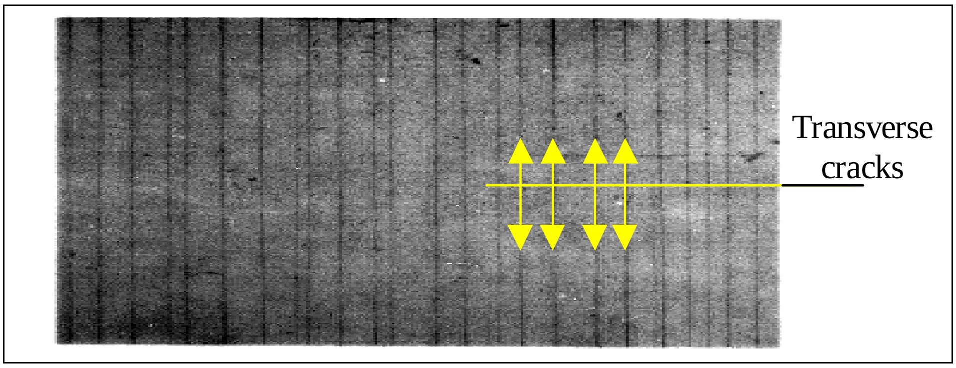

Fig. 1 : Example of X-ray photography.

DAMAGE MECHANICS APPLIED TO TRANSVERSE CRACKING

There is a considerable amount of work on the damage of laminated composite materials. Various approaches have been used by the authors. Our interest lay in the phenomenological approaches and more particularly in the Allen & al. model [6-7] which expresses the damage by a second order tensor related to the opening of defects taken as internal state variables. For matrix cracking damage, these variables are defined by the dyadic product between the displacement (of components u_i) of the crack face and its normal face (of components n_j) in accordance with Kachanov definition [8] :

$$\alpha^{C}_{Lij} = \frac{1}{V_L} \int_{s_C} u_i \, n_j \, ds \tag{1}$$

Where V_L is the local volume having the thickness of a ply, taken as being rather large so that the internal variable of state, α^{C}_{Lij} , does not depend on the size of V_L. S_C is the crack surface area in the local volume V_L where the damage is supposed to be homogeneous. The continuum damage model developed by Allen [7] takes the form of the conventional equations of the laminated plates modified in order to take account of the matrix cracking. The stress-strain relations on the ply level are given by :

$$\sigma_{Lij} = \left[Q_{ij}\right]\left\{\varepsilon_{Lij} - \alpha^{C}_{Lij}\right\} \tag{2}$$

- σ_{Lij} represent the local stress tensor components,
- Q_{ij} the elastic constants of the undamaged ply in the local reference mark,
- ε_{Lij} the local strain tensor components,
- α^{C}_{Lij} the second order cracking damage tensor components

Damage growth prediction

The prediction of the initiation and the growth of damage constitutes one of the most interesting problems in the behavioural study of composite laminates. The model presented here has the capacity to predict various mechanical characteristics with a suitable choice of the damage parameters. The determination of evolution laws, allowing the effects of the damage on an unspecified laminate and with an unspecified loading history to be predicted, is the long-term objective of this study. Several considerations have to be taken into account in order to provide model of damage initiation and growth. These are mainly : the type of material, the type of loading and environmental conditions and geometry both of the structure and the damaging modes.

The material modelled in this study is a graphite/epoxy T300/914 whose matrix is a polymer which presents a brittle behaviour. On a macroscopic scale, its behaviour lends itself well to the conventional approaches of elastic fracture mechanics. Lo [9] has developed a propagation law of transverse cracking for composites with long fibres and an organic matrix. This law is based on the observations carried out by Wang [10] which show that the variation of the cracks area, S_C, follows a Paris type relation :

$$\frac{\partial S_C}{\partial N} = \kappa G^{\eta} \tag{3}$$

The term G being the released energy rate calculated at the ply level, κ and η are intrinsic material parameters, N is the number of cycles. Lo adopted the following hypothesis : the existence of a single orientation, and a single geometry for all the cracks present in the ply. In our case, the cracks are parallel to the fibres : only the component n_2 (Fig. 2) of the normal face is not negligible in Eqn 1.

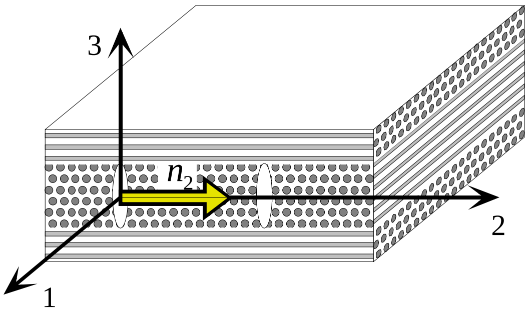

Fig. 2 : Normal face of a crack parallel to fibres.

It is admitted here that the crack opening mode is of type I. Then, only the component α_{22} is sufficient to describe the damage state. Consequently, the contribution of the two other opening modes will be neglected. The variation of this internal state variable related to the matrix cracking according to the number of loading cycles can be written in the following form [9] :

$$\frac{d\alpha_{22}^{C}}{dN} = \frac{\partial\alpha_{22}^{C}}{\partial S_C}\frac{\partial S_C}{\partial N} \tag{4}$$

The term $\frac{d\alpha_{22}^{C}}{dN}$ reflects the loading and strain conditions of the laminate away from the crack. By combining Eqn 3 and Eqn 4, we obtain the following evolution law :

$$\frac{d\alpha_{22}^{C}}{dN} = \frac{\partial\alpha_{22}^{C}}{\partial S_C}\kappa G^{\eta} \tag{5}$$

Where $\frac{\partial\alpha_{22}^{C}}{\partial S_C}$ must be given for the loading conditions. This term reflects the changes of the internal state variable according to the variations of the cracks surface.

Calculation of the growth law parameters

The damage evolution parameters ($\frac{\partial\alpha_{22}^{C}}{\partial S_C}$, κ and η) are unique for each material system and must be given before the analysis. By supposing that the cracks are flat and perpendicularly aligned to the plane formed by the ply, it is possible to describe the internal state variable according to, S_C. The interest of this assumption is the simplification of the relation between the surface (S_C) and the cracks spacing ($2a$). It then makes it possible to use the model developed by J.W. Lee & D.H. Allen [11] to calculate the term $\frac{\partial\alpha_{22}^{C}}{\partial S_C}$ starting from the equation :

$$\alpha_{22}^{C} = \frac{-\frac{P}{2t}}{\frac{\pi^4}{64\,\xi} - E_{22}} \tag{6}$$

which characterises in the initially a cross-ply laminate made up of an infinity of layers and subjected to a tensile load P [11]. Variable ξ is given by the series :

$$\xi = \sum_{m} \sum_{n} \frac{1}{E_{22}(2m-1)^2(2n-1)^2 + G_{12}\left(\frac{a}{t}\right)^2(2n-1)^4} \tag{7}$$

where $2t$ is the thickness of the cracked layer, E_{22} and G_{12} are respectively the transverse and shear modulus of the undamaged unidirectional.

For the graphite/epoxy, Eqn 6 shows that the term $\frac{\partial \alpha_{22}^{C}}{\partial S_C}$ varies linearly with the load. This relation must be given for each loading case. κ and η are then estimated by smoothing the experimental data using a Paris equation (Eqn 5).

MODEL – EXPERIMENT COMPARISON

Radiographic photo analysis

The study of radiographs taken at various stages of the life-time leads to the following observations. After a more or less rapid initiation time during which the specimen remains free from any damage, some cracks appear. Their distributions in the useful part of the specimen is random. With the increase in the number of cycles, the transverse cracks are increasingly numerous and spacing between those becomes increasingly regular. At the end of a certain number of cycles, the number of cracks stabilises. At this stage, no additional cracking appears. It is clear that the first damage mode which occurs is transverse cracking. Let us note that, for the A laminate which presents a very fine transverse layer, our X-ray radiography device does not allow them to be distinguished from real transverse cracking. Radiographs on the other stacking sequences (B and C) reveal very visible transverse cracks throughout the specimen.

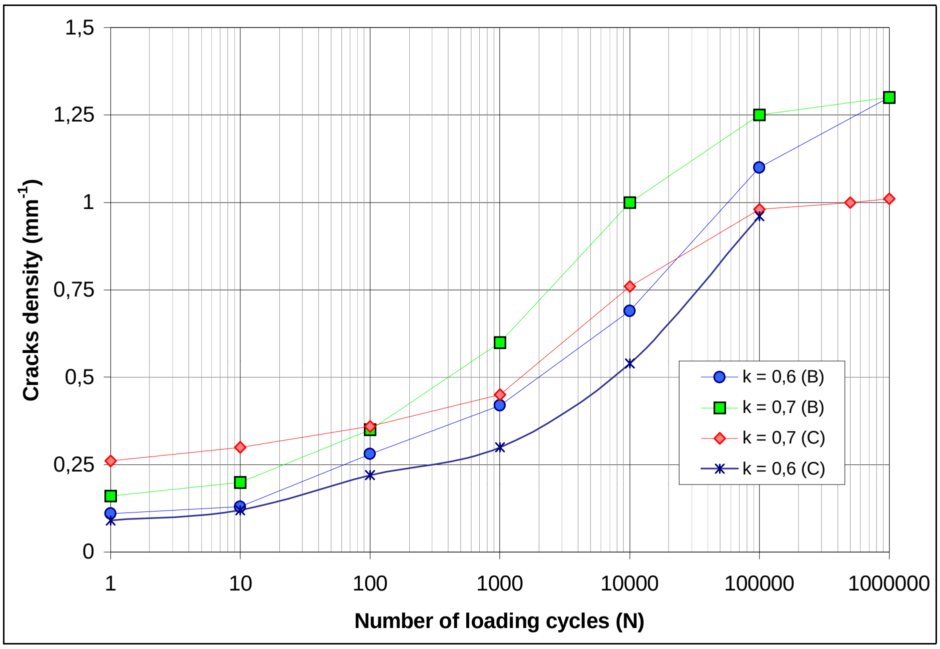

Fig. 3 : Experimental evolution of the number of cracks compared with the number of cycles for laminates B and C.

Fig. 3 shows the evolution of the number of transverse cracks according to the number of cycles for the two cross-ply laminates B and C subjected to two fatigue loading levels (*k*=0,6, et *k*=0,7). For the B laminate, and a number of cycles lower than 10^6 cycles, an examination of the radiographs indicates that transverse cracking is the only damage present. On the contrary, the C sequence reveals longitudinal cracks and delamination (Fig. 4) before 10^6 cycles.

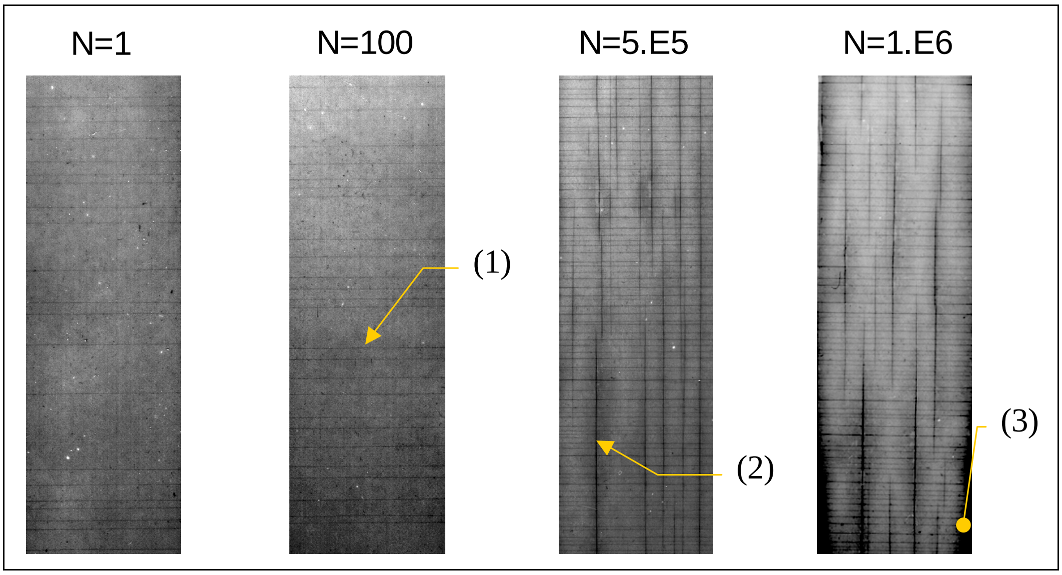

Fig. 4 : X-ray observation of damage evolution for cross-ply laminate C with *k*=0.7 (transverse cracking (1), longitudinal cracking (2) and delamination (3)).

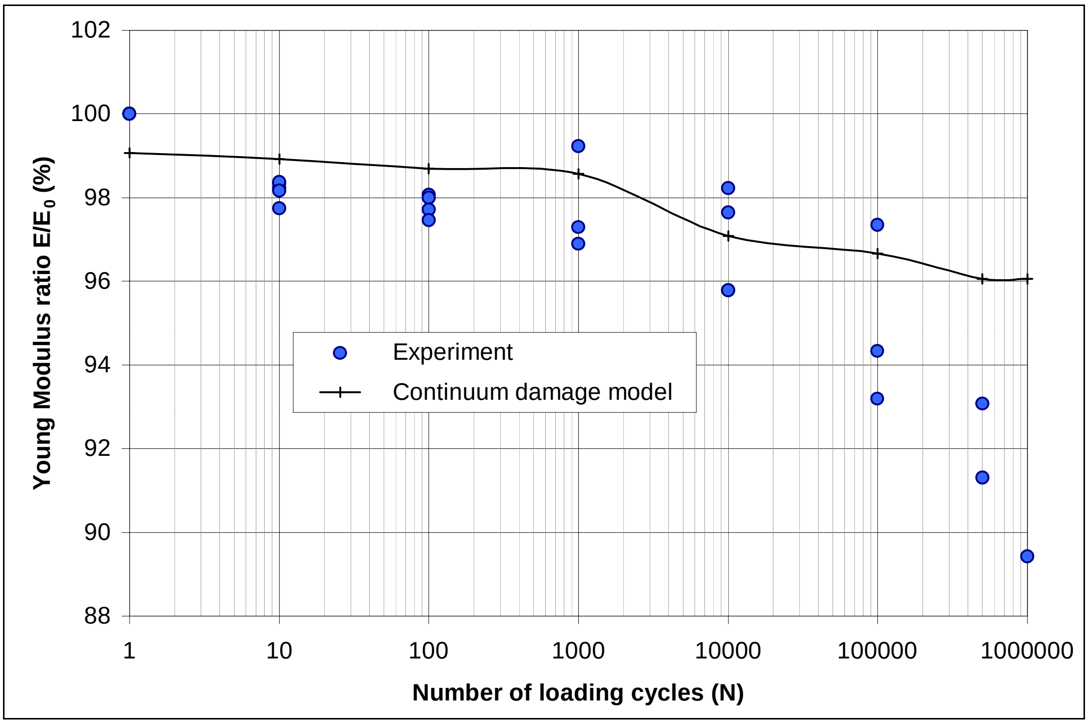

Fig. 5 : Theoretical and experimental development of Young's modulus (E_0= Young's modulus of the undamaged laminate).

Cracks were observed from the start of the first cycle of loading. The great majority of cracks occurred instantaneously over the whole width of the specimens and according to the thickness of the transverse layer. This abrupt propagation takes the form of micro shocks inside the specimen. To observe them, it is sufficient to coat the specimen with chalk powder, which becomes unstuck at the time of the matrix cracking. In addition, for the same sequence of stacking, the state of transverse cracking saturation (C.D.S) is the same whatever the stress level *k*. The difference lies in the speed of multiplication : the closer the load on the specimen is to its ultimate strength, the more rapidly do cracks multiplication. In the two cross-ply laminates (B and C), one notes that the first cycle of loading is that where the greatest number of cracks appears. This is explained by a stress redistribution in the various layers, the stress in the transverse layer having reached the ultimate strength. As an example, Fig. 5 shows the evolution of Young's modulus according to the number of cycles. It concerns the C laminate tested with a maximum loading fixed at 70% of the limit. When delamination occurs, the experimental results move away from the theoretical ones, because the model does not take into account this damage mode.

EXPERIMENTAL DYNAMIC ANALYSIS

A vibration test of specimens was carried out under free/free conditions and at various stages of damage. As Fig. 6 testifies to some extent, the experimental results obtained showed a natural frequency variation with respect to the state of damage for the torsional mode only (the other modes results are not significant for the tested laminates). The large frequency variation which one can observe for laminate C, between 10^5 and 10^6 cycles, results from damage not only by transverse cracking, but also by longitudinal cracking. The difficulties encountered in measuring the damping capacity prevent us from drawing conclusions on this point. Large variations of the natural frequencies of a real structure would then make it possible to detect a vast extent of damage.
However, it perhaps presumptuous to affirm that it is possible to detect the damage mode by simple observation of the change in natural frequencies. The experiments undertaken here simply underline an abrupt fall in the natural frequencies, which can only be connected to an advanced damage state.

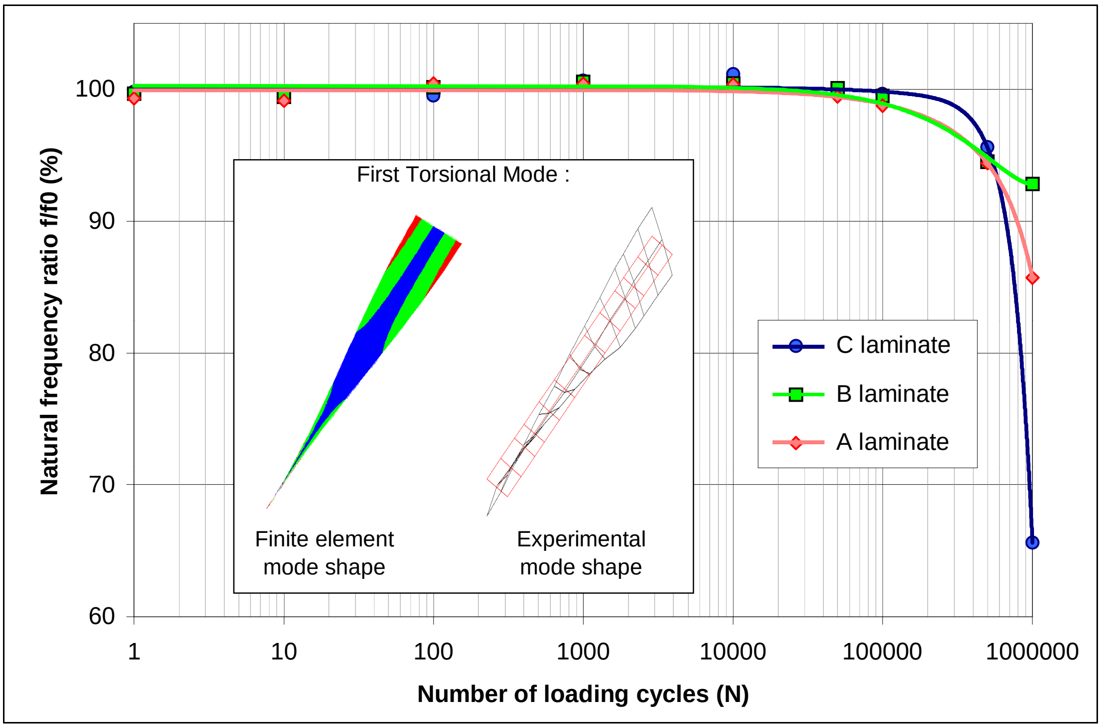

Fig. 6 : Natural frequency decreasing with the number of loading cycles (k=0.6); first torsional mode (f_0=natural frequency of the undamaged laminate).

CONCLUSION

A fatigue test approach has been used to evaluate the effect of transverse cracking on the longitudinal elastic modulus and the natural frequencies in cracked cross-ply laminates. The application of the continuum damage model was further extended in order to simulate the progression of the transverse cracking damage. This model has been validated by fatigue tests. It has been shown that this evaluation is accurate for cross-ply B and C. In contrast, for cross-ply C, the experimental and theoretical results diverge when delamination occurs. One of the perspectives is the possible extension of the model to take into account the delamination effect. The modifications of the dynamic behaviour of a laminate caused by its state of damage has also been underlined.

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