ISSN 1392–1320 MATERIALS SCIENCE (MEDŽIAGOTYRA). Vol. 9, No. 1. 2003

Investigation of Cross-Ply Laminates Behaviour in Three Point Bending Tests. Part II: Cyclic Fatigue Tests

A. Bezazi[2], A. El Mahi[1*], J.-M. Berthelot[1], A. Kondratas[3]

[1]*Institute of Acoustics and Mechanics, University of Le Mans, Avenue Olivier Messiaen, 72085 Le Mans cedex 9, France*
[2]*Laboratory of Structure and Mechanics, University of Guelma, BP. 401, Guelma, Algeria*
[3]*International Studies Centre, Kaunas University of Technology, Donelaičio 73, LT-3006 Kaunas, Lithuania*

Received 12 September 2002; accepted 17 October 2002

The main goal of this paper is to study and highlight the effects of the reinforcement on mechanical behaviour during the loading and to study the different damage modes induced in the rupture of laminates. The experimental investigation was conducted using three point bending tests in cyclic fatigue for different cross-ply laminates constituted of glass, Kevlar, and hybrid fibres and resin epoxy. At first the composite properties were evaluated in static loading. Then, stiffness loss curves in fatigue were derived for different applied loading levels. The Wöhler curves were deduced using N_{10} criterion, corresponding to 10% decrease in initial stiffness. The properties of glass fibre laminates in cyclic fatigue were compared with the ones obtained with Kevlar and hybrid fibre laminates.

The obtained results show the performance of glass fibre laminates during fatigue tests compared with the results obtained with Kevlar and hybrid laminates. The rupture of Kevlar and hybrid laminates is much less brittle when compared with glass fibre laminates. The presence of Kevlar fibre in laminate involves a lower strength in fatigue.
Keywords: cross-ply laminates, hybrid, flexural, fatigue, damage, stiffness, Wöhler curve, three point bending.

1. INTRODUCTION

Composites are used in wide variety of industrial applications such as transport, aerospace, marine largely because of their relative advantage over the structural materials in terms of improved stability and weight savings.

A laminate structure consists of two or more relatively thin, stiff, and strong faces joined by relatively thick layer of adhesive. A composite structure tends to be stiffer and stronger than a solid laminate. Weight savings can be achieved by reducing the number of reinforcing layers of material.

The fatigue damage can be evaluated in the global sense by stiffness, residual strength or other mechanical properties [1]. A fatigue modulus concept for fatigue life prediction of composite materials was proposed [2].

As residual strength, stiffness, and life are affected by fatigue damage, the residual stiffness can be monitored non-destructively [3]. While residual strength demonstrates minimum decrease with the increase of the number of cycles until a stage close to the end of life of the specimen, it begins to change and it is destructive in real sense [4]. The residual stiffness as a parameter to describe the degradation behaviour and to predict the fatigue life was selected [5].

It was suggested that changes in stiffness might be appropriate measure of fatigue damage. Many investigators have examined the effectiveness of the stiffness degradation in composite laminates as a measure of accumulated damage [6].

Stiffness degradation methods have the advantage of being able to allow measurements of effective stiffness during cycling without destruction of the specimens, and stiffness curve can be obtained from the single experiment. Smaller number of fatigue experiments is required for the comprehensive analysis [7].

Stiffness exhibits greater changes during fatigue life specifically at the early stage of specimen fatigue life. There is also an interesting feature in stiffness degradation approach that only limited amount of data is needed for obtaining reasonable results [8]. The critical element model, assuming that residual strength degradation rate is power law function of number of cycles and linearly dependent on the value of failure function was proposed [9].

Prediction of fatigue life and damage are of particular interest in composite materials during service conditions.

Fatigue life of laminate according to the levels of loading may be given by Wöhler ($S-N$ curves) curves [10 – 12]. These curves permit to show the influence of the constituents on the fatigue life of the laminates.

Accordingly, our contribution deals with a comparative survey in three point bending tests in cyclic fatigue of different cross-ply laminates. The purpose is to give an experimental approach of the influence of the constituents on the behaviour, the mode of damage, and the fatigue life of the three types of laminates.

2. EXPERIMENTAL PROCEDURE

2.1. Materials and experimental set-up

Three cross-ply laminates are fabricated in the lab (see part I). The first laminate is constituted of glass fibre and epoxy resin (designated by GFRP), the second - of Kevlar fibres and epoxy resin (designated by KFRP), and the third - of hybrid glass and Kevlar fibres and epoxy resin (designated by HFRP). The three point bending was carried in cyclic fatigue tests, with displacement and load

*Corresponding author. Tel.: + 33 2 43 83 34 56; fax: + 33 2 43 83 31 49.
E-mail address: *Abderrahim.Elmahi@univ-lemans.fr.* (A. El Mahi)

control on a hydraulic universal testing machine type INSTRON model 8516 (see part I).

2.2. Cyclic fatigue tests with load control

In the case of glass and Kevlar fibre laminates, the fatigue cyclic tests were conducted with load control of sinusoidal waveform at a constant frequency rate of 10 Hz. The applied load ratio $R_F = F_{min} / F_{max}$ (F_{max} and F_{min} are maximum and minimum applied load in cyclic tests) is kept constant at zero and the applied load level $r_F = F_{max}/F_u$ varied from 0.40 to 0.98 (F_u is the ultimate failure in static test).

2.3. Cyclic fatigue tests with displacement control

In the case of glass and hybrid fibre laminates, the fatigue cyclic tests were conducted with displacement control of sinusoidal waveform at a constant frequency rate of 10 Hz. The mean displacement d_m is kept constant equal to 40 % of the failure displacement in static test. Several applied displacement levels $r_d = d_{max} / d_u$ are considered, where d_{max} is the maximum applied displacement in cyclic test and d_u is the ultimate displacement in static test.

3. RESULTS AND DISCUSSION

Experimental results were obtained for the stiffness changes versus number of cycles. This evolution constitutes one of the most used methods to follow the progression of the fatigue damage of the composites.

3.1. Laminates behaviour in cyclic bending with the load control

During these tests, the maximum displacement d_{max} according to the cycle number N was recorded for different applied load levels. The maximum displacement is referred to the initial maximum applied displacement d_0.

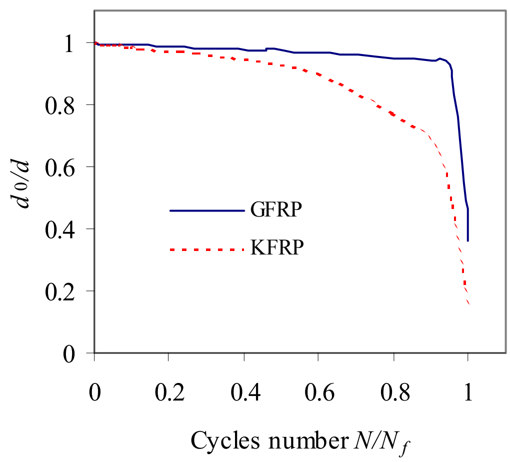

Fig. 1. Curve types of the evolution of stiffness according to the number of cycles

The evolution of stiffness measured by d_0 /d according to the number of cycles in the two types of laminates (GFRP and KFRP) for an applied load level r_F = 50 % was reported in Fig. 1. The cycle number is normalised using the cycle value N to failure cycle number N_f. The results obtained in the two types of laminates GFRP and KFRP show that the stiffness loss until the rupture of the specimen can be observed in two phases:

- in the first phase reduction of the stiffness is observed during initial number of cycles; this reduction becomes very slow, corresponding to the total loss of the fatigue life of specimen;
- in the second phase that is very short with the loss of the stiffness brutally accelerating until the rupture of the specimen.

The two distinct portions of curves can be explained by:

- the cracking multiplication of the resin and stable propagation of this cracking during the first phase;
- the rupture of fibres and delamination in the second phase. It is to be noted that the first stage constitutes only 20 % of the fatigue life whereas it corresponds to 80 % of the final damage state.

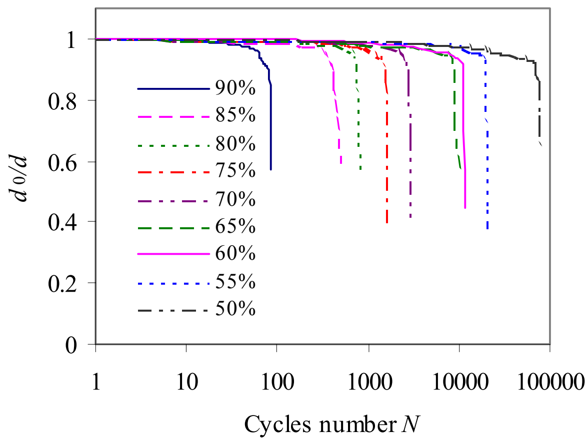

Fig. 2. Evolution of the stiffness of the GFRP laminates according to the number of cycles N for different applied load levels

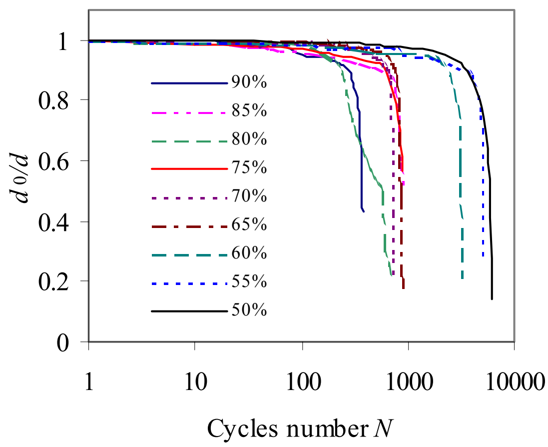

Fig. 3. Evolution of the stiffness of the KFRP laminates according to the number of cycles N for different applied load levels

The stiffness evolution, measured by d_0 /d, of glass and Kevlar laminates according the cycle number in the test with load control for the different applied load levels r_F using a semi-logarithmic scale is presented in Fig. 2 and Fig. 3.

All specimens used in this study were broken with applied load levels. It is evident that the fatigue life increases with the decreasing of r_F for the two types of laminates (Fig. 2 and Fig. 3). For the same load level the fatigue life in GFRP laminate is superior than that of KFRP laminate. The brutal rupture of GFRP laminates occurs after a weak reduction in stiffness, whereas in the case of KFRP laminate the rupture is less brutal. The presence of Kevlar fibre in the laminate is the cause of a non-linear behaviour and a less brittle rupture.

Fig. 4 presents a comparative study of glass fibre laminate (GFRP) and Kevlar fibre laminate (KFRP) for two applied load levels r_F (0.50 and 0.80).

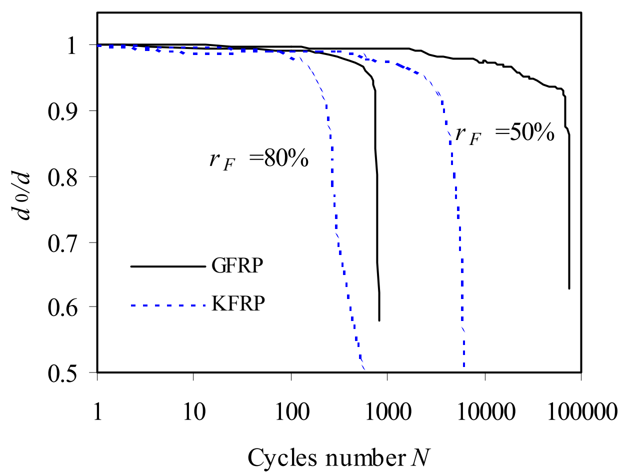

Fig. 4. Comparative study of GFRP and KFRP laminates for two applied load levels

The analysis of these results shows that the rates of the stiffness degradation in two laminates for the same applied level are identical at the beginning, but with increasing the number of cycles the rate of stiffness degradation in KFRP laminates is superior than in GFRP laminates. The fatigue life of GFRP laminates is ten times greater than one of KFRP laminates for an applied load level of $r_F = 0.50$. We observe that GFRP laminates have a better resistance to the fatigue.

3.2. Laminates behaviour in cyclic bending with displacement control

The follow-up load loss in displacement control constitutes one of the most used methods to follow the progression of the damage by fatigue of the composites. During these tests the maximum load F was recorded according to the number of N cycles, for different applied displacement levels r_d. The maximum load F is normalised with the first F_0 cycle.

In Fig. 5 the evolution of the load according to the number of cycles in the case of glass fibre laminates and hybrid fibre laminates for an applied displacement level r_d = 60 % was reported. The results obtained testing two types of laminates (GFRP and HFRP) show that the load loss until the rupture of the specimen can be observed in three phases:

- in the first time the brutal reduction of the ratio F/F_0 since the first few cycles appear;
- the reduction, corresponding to the total loss of the fatigue life of specimen becomes very slow in the second phase;
- the third phase is very short with the load loss brutally accelerating until the rupture of the specimen.

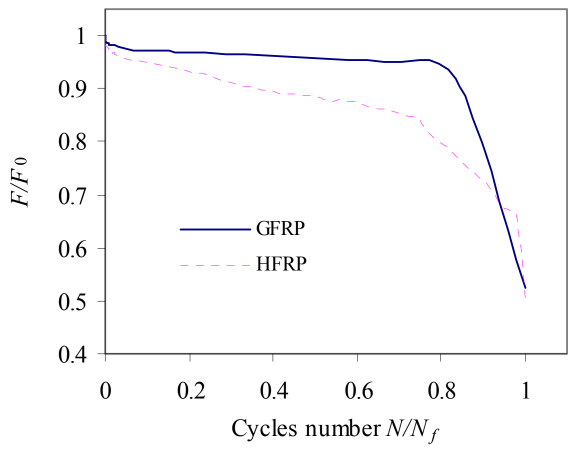

Fig. 5. Typical curves of the evolution of the load testing the glass (GFRP) and hybrid (HFRP) fibre laminates according to the number of cycles during fatigue test

The distinct three parts of curves can be explained by:

- the cracking multiplication of the resin in the first phase;
- the stable propagation of this cracking during the second phase;
- the rupture of fibres in the last part. The first stage constitutes only 20 % of the fatigue life whereas it corresponds to 80 % of the damage rate.

Fig. 6 and Fig. 7 present the evolution of the load loss (F/F_0) according to the number of cycles for different applied displacement levels r_d using semi-logarithmic scale.

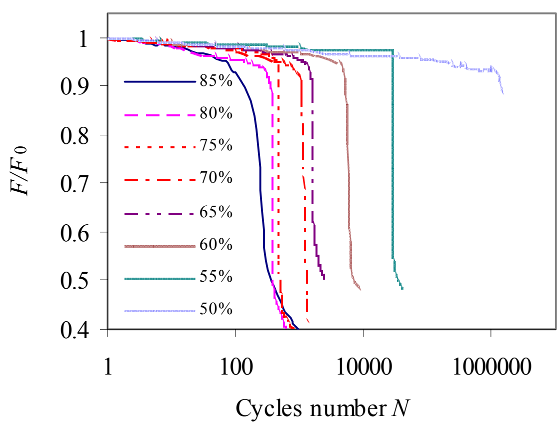

Fig. 6. Evolution of the load F/F_0 of glass fibres (GFRP) laminates according the number of N cycles

It is evidently noted that the fatigue life increases decreasing r_d for laminate GFRP (Fig. 6) and for laminate HFRP (Fig. 7) as well. The brutal rupture of laminate GFRP occurs after a weak reduction of the load loss, whereas one of hybrid laminate HFRP is progressive and much less brutal than that for the laminate GFRP. The presence of Kevlar fibre in the hybrid laminate is the cause of a non-linear behaviour and a less brittle rupture.

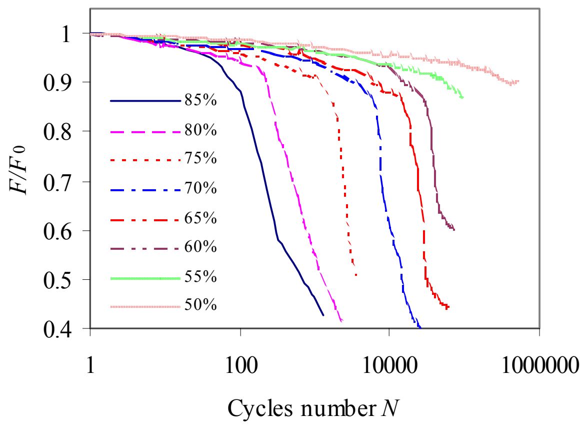

Fig 7. Evolution of the load F/F_0 of hybrid HFRP laminates according the number of N cycles

Fig. 8 presents a comparative study between glass (GFRP) and hybrid fibre laminates (HFRP) for two applied displacement levels r_d (0.50 and 0.85).

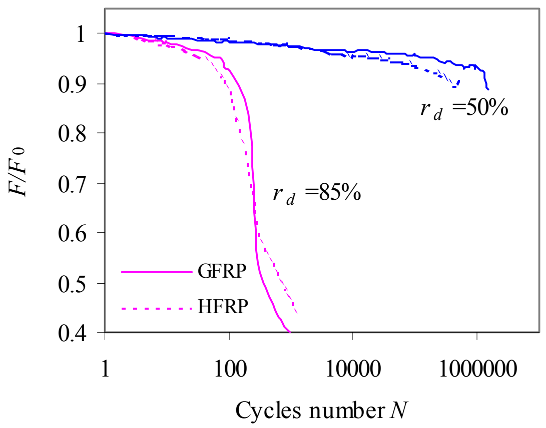

Fig. 8. Comparative study of GFRP and HFRP laminates for two applied displacement levels

The analysis of these results shows that the rupture for a weak applied displacement level is not reached even when the number of cycles is superior than 10^6, whereas the rupture for a larger applied displacement level is obtained only for a few thousand cycles. This rupture is even more marked in laminate GFRP than that of laminate HFRP. We note a good resistance to the fatigue of the GFRP laminates.

3.3.Observed fractures on the frontal test-specimen's surfaces after cyclic fatigue tests with load and displacement control

The typical ruptures-fractures on the frontal test-specimen's surfaces after cyclic fatigue are presented in Fig. 9 – 11.

The analysis shows that the mechanism of ruptures for high-applied load levels are similar to those observed in static tests for GFRP, KFRP, and HFRP laminates.

Several damages are initiated in the first cycle when the applied load level r is higher. The fatigue loading in this

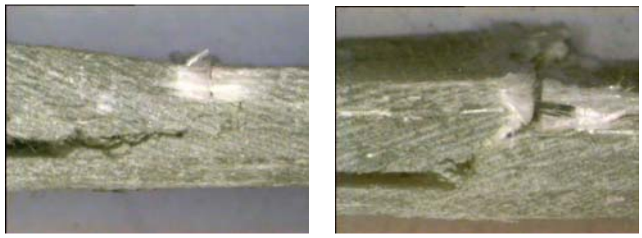

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Fig. 9. Fractures on the frontal surfaces of the test-specimens in GFRP laminate after cyclic fatigue tests

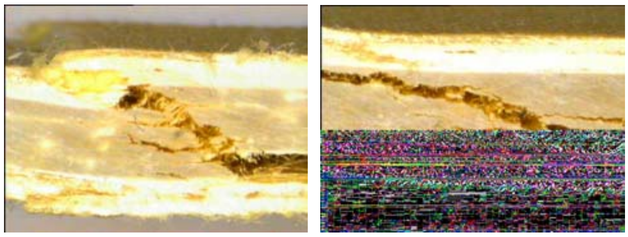

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Fig. 10. Fractures on the frontal surfaces of the test-specimens in KFRP laminate after cyclic fatigue tests

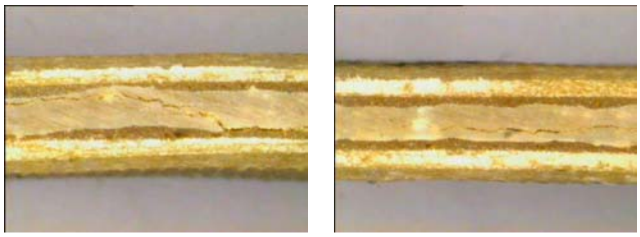

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Fig. 11. Fractures on the frontal surfaces of the test-specimen in HFRP laminate after cyclic fatigue tests

case induces propagating of these damages until the total rupture. This rupture is obtained in a few hundred cycles.

As for the weak values of r_F and r_d is observed:

- in GFRP laminates the rupture of some fibres on the face in compression, the transverse cracking in the 90° plies, the delamination between the 0° and 90° of plies in the layers in tension (Fig. 9),
- in KFRP laminates transverse and longitudinal cracking in the layer at 90° plies and delamination between the tense layers between 0° and 90° of plies. The damage processes increase with the number of cycles causing the total rupture of the specimens (Fig. 10).
- in HFRP laminate longitudinal cracking in the layer in Kevlar fibres in the centre of the specimen, whereas the layer in glass fibres oriented at 90° seems to remain intact (without meaningful or considerable damage) (Fig. 11).

3.4. Fatigue life

To determine the performances of materials in fatigue, different criteria of damage (N_s, N_3, N_5, N_{10}, and N_R) are considered from the curves giving evolution of the load or displacement according to the number of cycles. The most severe criterion is the one that characterises the material by

N_s value that corresponds to the number of cycles at the end of linear domain. The criteria N_3, N_5, and N_{10} correspond respectively to 3 %, 5 %, and 10 % decrease in the initial stiffness. The N_R criterion corresponds to the number of cycles of the complete rupture of the specimen when it is reached. The most used criterion N_{10} has been chosen for our study [7, 8, 9, and 10]. Too many mechanisms interfere beyond 10 % and their descriptions become more difficult.

The description of Wöhler curves of the organic matrix composites is very often done by the linear relations according to the logarithm of the number of cycles up to rupture. The constants of these equations depend on parameters obtained in static test, the conditions of loading in fatigue (controlled strain or stress) and on the materials [2, 7, 9, and 10].

3.4.1. Fatigue life with load control

Fatigue life can be given in a diagram of endurance (Wöhler curve), giving the applied load level r_F according to the fatigue life N_{10}.

Fig. 7 presents the Wöhler curves in load control of the GFRP and KFRP laminates. These curves give the evolution of the applied load level according to the number of cycles N_{10}, in the case the load ratio R is kept constant and is equal to zero.

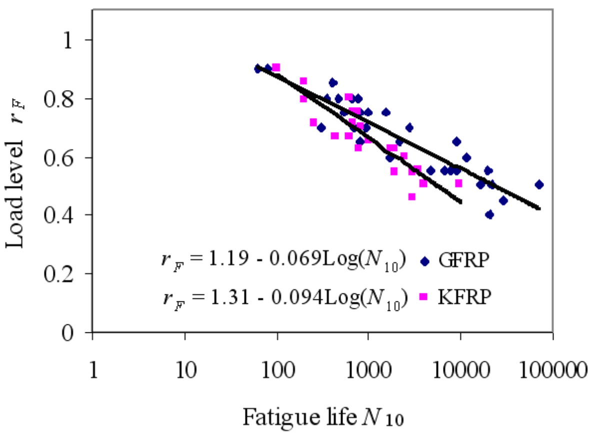

Fig. 12. Wöhler curves of the GFRP and KFRP laminates

The analysis of these results permits to highlight the influences of the reinforcement on the fatigue life of the studied laminates. Experimental results of KFRP laminates are below those of GFRP laminates. The KFRP laminates are more sensitive to the fatigue in the case of three point bending tests.

Normalised equation is used to study the Wöhler curves for two laminates in the following form:

$$r_F = A - B_F \log (N_{10}) . \quad (1)$$

This form of description permits better visualisation of the fatigue resistance of materials through an intrinsic value of B_F , representing the slope of the curve as a function of N_{10}. This value corresponds to the rate of applied load level decrease with increasing number of cycles. The value B_F is weaker in the case of GFRP laminates (0.069) than the one of KFRP laminates (0.094). Indeed, the degradation occurs faster in KFRP laminates than in GFRP laminates. In equation (1), A presents static strength of the material, which is generally close to one. In the presented case this value is different to unity caused by the dispersion.

3.4.2 Fatigue life with displacement control

Fatigue life can be given in a diagram of endurance (Wöhler curve), giving the applied displacement level r_d according to the fatigue life N_{10}.

Fig. 13 presents Wöhler curves in displacement control of the GFRP and HFRP laminates. These curves give the evolution of the applied displacement level according to the number of cycles N_{10}, in the case of an average displacement is kept constant and equal to 40 % of the ultimate displacement in static test.

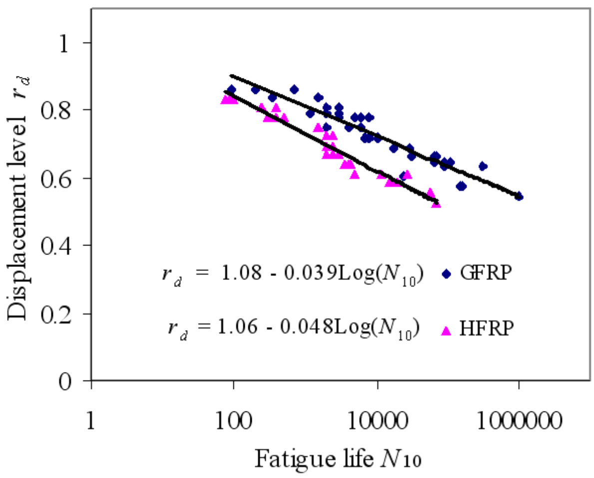

Fig. 13. Wöhler curves of the GFRP and HFRP laminates

The experimental results of hybrid laminates HFRP are below those of GFRP laminates. The presence of Kevlar fibre in the hybrid laminate renders it more sensitive to the fatigue in the case of three point bending.

For the better account of fatigue phenomena of the two laminates the normalised curves of the type

$$r_d = A - B_d \log (N_{10}) \quad (2)$$

were used, where B_d value corresponds the rate of the admissible loading level decrease with increasing number of cycles. The value of B_d is weaker in the case of GFRP laminate (0.039) than the one of HFRP laminate (0.048). Indeed, the degradation is done more quickly in HFRP than in GFRP laminate. It can be noted that the evolution of the applied displacement level according to the fatigue life N_{10} intersects the r_d axis approximately at the level of one, which corresponds to the applied displacement equal to that at the rupture in static test.

4. CONCLUSIONS

The rupture mechanisms in the case of cyclic fatigue tests depend on the loading levels r_F and r_d . The rupture is similar to the static loading for the higher values of r_F and r_d. Several damages are initiated from the first cycles and the rupture is obtained quickly after a few hundreds of cycles.

Nevertheless, the rupture of the specimens for the small values of r_F and r_d is not complete even beyond $10^5 – 10^6$ cycles. This rupture proceeds several damaging modes (transverse and longitudinal cracking, delamination and some fibre rupture), which develops slowly during the cyclic fatigue.

The endurance tests permitted to plot Wöhler curves using the criterion N_{10} corresponding to 10 % decrease in the initial stiffness in the cases with load or displacement control.

The GFRP laminate constituted only of glass fibre showed better resistance to fatigue than KFRP and HFRP laminates. The presence of the Kevlar fibres in the laminates makes it more sensitive to fatigue in the case of three point bending tests, which can be attributed to the bad fibres-matrix adherence.

The evolution of the loading levels r_F and r_d according to the logarithm of the fatigue life N_{10} has been fitted linearly. The slopes B_F and B_d of these curves correspond to the rate of admissible maximum of applied load decrease with increasing number of cycles

This presentation gives evidence of the influence of the reinforcement type on the fatigue life and on the degradation rate. Indeed, the B_F, value of KFRP laminate and the B_d value of HFRP laminate is superior than the GFRP laminate, which shows that the degradation is faster in KFRP and HFRP laminates than in GFRP laminate.

It is to be noted that the rupture in fatigue tests results from damage processes depends on some random process in the test fabrication and storage of specimens. These processes are the main cause of life dispersion even at the same loading conditions with same type of specimens. These dispersions are due to the heterogeneous nature of the laminates related to their fabrication (volume fraction, fibres orientation, dimension of the specimens, etc.).

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