INVESTIGATION OF COMPOSITES VIBRATION FATIGUE BEHAVIOUR: HIGH FREQUENCY MODE II DELAMINATION PROPAGATION

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Abstract

Mode II crack propagation tests were conducted at high frequencies on carbon fiber/epoxy laminates under vibration fatigue at resonance. In parallel, classical fatigue tests were carried out at 10Hz on a servo-hydraulic machine in order to compare results in terms of Fatigue Crack Growth Rate (FCGR) vs Energy Release Rate (ERR) curves. Different load ratios were considered for classical tests. Frequency and load ratio effects were determined from both high and low frequency tests results. Using an appropriate definition of ΔG, master propagation FCGR vs ERR curves were plotted.

1. Introduction

Increasing use of composite materials in aircraft and aerospace fields subject them to aeroelasticity effects, near engines for example, and thus to vibration fatigue [1]. Fluid-structure interactions create complex load spectra with various amplitudes and frequencies. Consequently, defects may initiate and propagate for the long term. And since safety margins are always reduced, structure dimensioning problems make particularly relevant the investigation of delamination propagation prediction under such loadings.

Experimental data is obviously needed for numerical simulations and structure sizing. On one hand, high frequency tests have been developed [2] [3] and, on another hand, tests have been conducted in order to study the load ratio effect in mode II.

The procedure developed by Backe [2] allows reaching ultrasonic frequencies using piezoelectric principle, up to 20kHz. The small specimen geometry (33*15*4 mm^3) sets the resonance frequency. But the test fixture does not allow crack propagation studies due to specimen dimensions.
An accelerated procedure was developed by Maillet [3] to study mode II delamination propagation at high frequencies: a notched specimen is embedded at one side on a electrodynamic shaker and excited at its resonance frequency. Due to delamination propagation, the resonance frequency decreases during the test and the shaker pilot follows the frequency to remain at resonance. It is then possible to plot Fatigue Crack Growth Rates (FCGR) as a function of Energy Release Rates (ERR).

The resonance frequency mainly depends on the specimen geometry. Hence, frequency effects can be easily highlighted through several tests. Former results show for a specific material it was possible to plot a master curve of FCGR vs ERR for different frequencies and load ratio [3].

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Regarding load ratio effect on mode II propagation, Mall [4] led tests on graphite/epoxy adherents bonded with an epoxy adhesive. The load ratio ranged between R=0,01 and R=0,75.The observed effect was an offset of the FCGR vs ERR curves. Its increase resulted in a lower propagation rate for the same ERR value. Matsubara [5] observed the same phenomenon on Glass Fiber Reinforced polymers (GFRP), the load ratio ranging from R=-1 to R=0,3. Allegri [6] also obtained this load ratio effect on carbon/epoxy specimens, where the load ratio ranged between R=0,1 and R=0,5.
Working on the elimination of the load ration effect on FCGR vs ERR curves, Rans' [7] developed a new ΔG definition, based on Hojo's work [8].This definition allowed plotting a master FCGR vs ERR curve, independent of the load ratio effect.

The present work objective is to evaluate the consistency of Maillet's approach for different composite materials. Three different materials are considered, other than T700/M21, which was originally employed to develop the procedure. The vibration fatigue method will be compared with classical fatigue tests performed at 10Hz but at different load ratios. Rans' definition [7] is then used to obtain a master curve of FCGR vs ERR.

2. Experimental procedure

2.1 Materials and specimens

Three materials have been used to realize the tests: G939/M18 and G947/M18 (Hexcel@), NC66-1808-42/60. These materials were chosen for their particularly different reinforcement structure, matrix type and temperature of polymerization. Their characteristics are presented in Table 1.

Material	Matrix	Reinforcement	Glass Transition Temperature (°C)
NC66-1808-42/60	Thermosetting	Carbon fiber – Unidirectionnal	~100
G947/M18	Thermosetting	Carbon fiber – Unidirectionnal	~160
G939/M18	Thermosetting	Carbon fiber – Weave	~160

Table 1. Description of materials

For each, the beam specimens were cut out from a press manufactured plate cured following a standard cycle. A 25µm thickness Teflon film is inserted in the mid-plane of the laminate during the manufacturing to create an initial crack.
Dimensions of specimens are summarized in Table1, according to Figure 1.

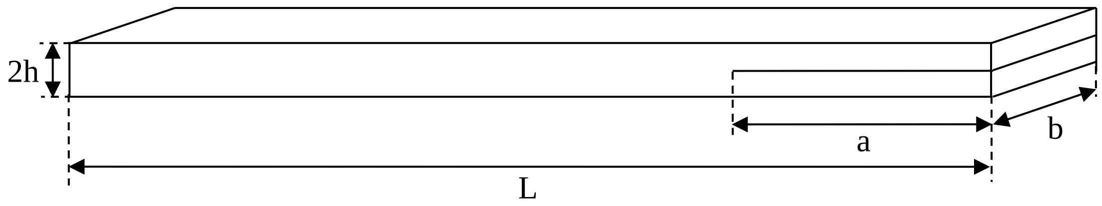

Figure 1. Specimen geometry

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Material	a (mm)	b (mm)	L (mm)	h (mm)	Number of plies
NC66	40	25	170	2.5	32
G947	40	25	190	2.4	30
G939	40	25	180	2.4	20

Table 2. Dimensions of specimens

For each material, specimens were used both for classical end dynamic fatigue tests. All the specimens were pre-cracked to get at least a 2mm delamination extension before the fatigue tests.

2.2 Fracture toughness test and fatigue test

First, fracture toughness tests under quasi-static loading were performed on a servo-hydraulic machine for the three materials, considering an ELS configuration. Loading head speed was 3mm/s. Compliance parameters and critical energy release rates were then obtained.

Classical fatigue tests were carried out on the same machine at 10Hz for two displacement ratios, R=0.1 and R=0.4. Crack propagation was followed thanks to a binocular microscope. Crack lengths were also determined by use of an unloading/loading cycle between two stages of fatigue, measuring the stiffness.

Mode II delamination dynamical fatigue tests are based on End Load Flexure classical tests. The delaminated beam is clamped on a shaker and tested on its first flexure resonance mode frequency to take advantage of the large amplification factor. The displacement of the specimen is monitored by a Laser Doppler Vibrometer. The tests were performed under displacement control with a displacement-ratio of R=-1 at two resonance frequencies by adjusting the length of the beam (cf. Fig. 2.).

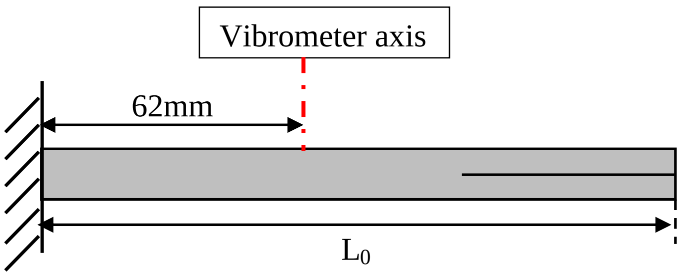

Figure 2. Dynamic test fixture

Material	Free lengths (mm)	Frequency reached (Hz)
G947	120 - 150	250 - 360
G939	120 - 140	200 - 280
NC66	120 - 140	300 - 400

Table 3. Dynamic test configurations

The resonance frequency of the system tested is linked to the crack size by the compliance law. As the delamination propagates the resonance frequency of the system slowly decreases. It is then followed during dynamical tests by keeping constant the phase quadrature between the input acceleration and the displacement measured. The test stops when the resonance frequency reaches the final desired

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frequency, corresponding to the desired crack length. The temperature evolution is measured with a thermal middle wavelength camera (sensitivity between 2 and 5µm).

3. Results and discussion

In mode II, the maximum Energy Release Rate reached during a cycle is calculated with the compliance method:

$$G_{IImax} = \frac{3maP^2_{max}}{2b} \tag{1}$$

Where P_{max} is the maximal applied load, a the crack length, b the specimen width and m the power parameter identified from the power compliance law. The FCGR vs ERR curves can then be plotted according to equation 2.

$$\frac{da}{dN} = k.(G_{max})^n \tag{2}$$

Where $\frac{da}{dN}$ is the propagation rate in mm/cycle, k and n are parameters.

FCGR vs ERR curves for materials G947 and NC66 are presented on Figure 3 and 4. Regarding G939 given its low flexural modulus, dynamic tests did not allow the crack to propagate. Indeed the imposed displacement required for crack propagation leads to the specimen fracture near the clamping before the crack propagation.

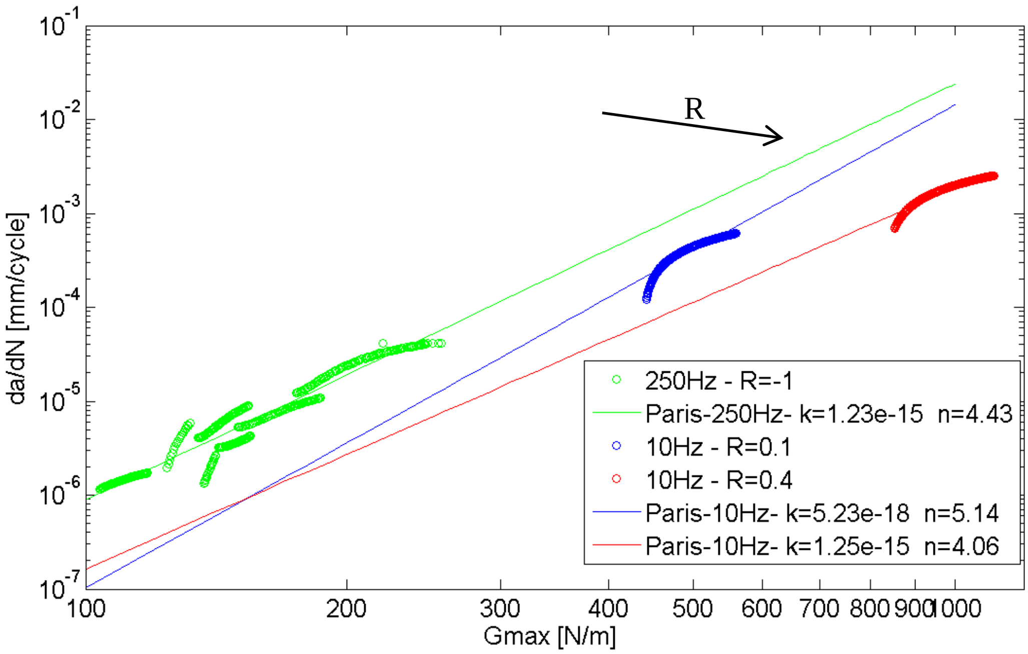

Figure 3. Evolution of FCGR vs ERR in mode II
for material G947 for dynamic and classical fatigue tests

For the G947 the curves slopes are nearly equal, regardless the frequency or the load ratio R values.

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As regards load ratio, its increase implies a “shifting” of Paris’ law curves on higher Energy Release Rate values : the propagation rate is lower for the same ERR value.

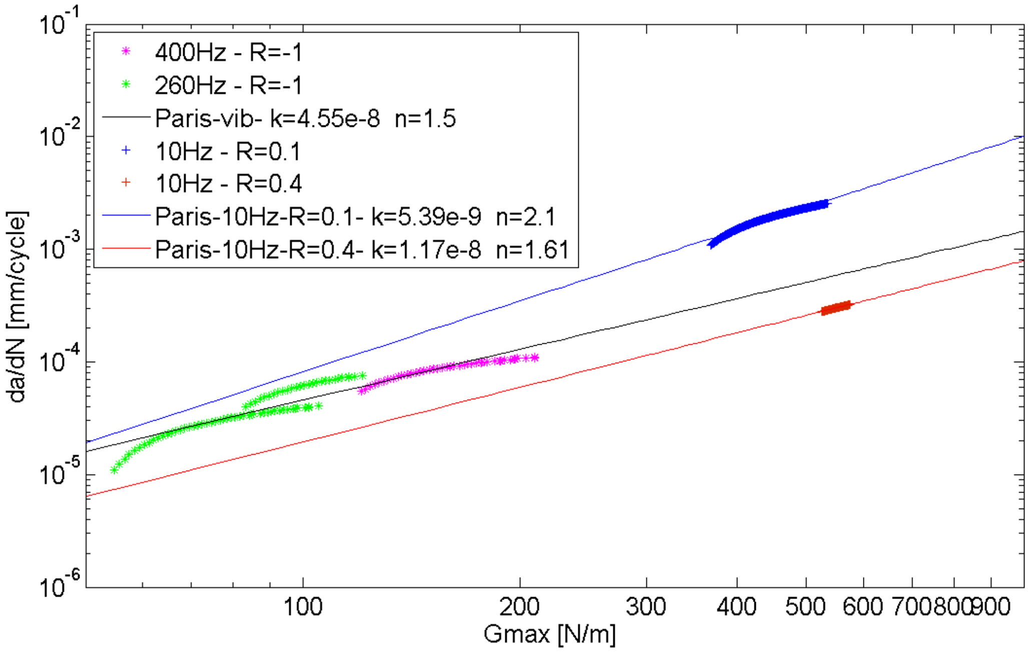

Figure 4. Evolution of FCGR vs ERR in mode II
for material NC66 for dynamic and classical fatigue tests

For the NC66, curves slopes values are similar for all loading frequencies. For 10Hz tests, the load ratio has the same effect as seen before. However, taking high frequency curves into account, curves do not follow that phenomenon since vibration curve at R=-1 is located between curves at R=0.1 and R=0.4. This could be due to NC66 glass transition temperature which is lower than that of G947 and implies more viscoelastic effects.

A second objective is to study the unicity of the FGCR vs ERR curves. Considering the definition of ΔG_{eq} given by Rans [7] (Eq. 3), curves are plotted again (Fig. 5 and 6).

$$\Delta Geq = (\sqrt{G_{IImax}} - \sqrt{G_{IImin}})^{2(1-\gamma)} {G_{IImax}}^{\gamma} \tag{3}$$

Where coefficient gamma is the shifting coefficient, allowing superimposing curves, provided that they have the same slope. Coefficient values used here are 0,7 for G947.

And using the following Paris’ law formulation:

$$\frac{da}{dN} = k(\Delta Geq)^n \tag{4}$$

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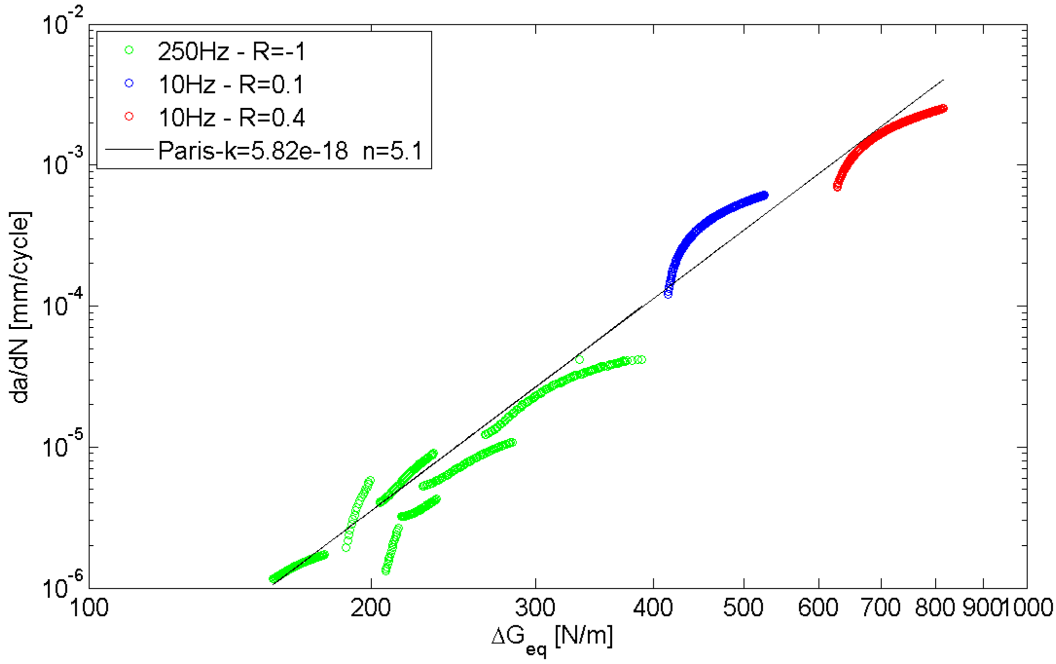

Figure 5. Evolution of FCGR vs ΔG_{eq} for material G947
for dynamic and classical fatigue tests, $\Upsilon = 0.7$

Rans' definition gives the Paris' law unicity for G947, where k=5.82e-18 and n=5.1. As for the NC66, unicity could not be obtained using the same value of gamma for both vibration and classical tests.

3. Conclusion

Fatigue tests have been conducted on two different materials giving similar results in terms of Paris' law slope for low and high frequency tests.
Load ratio effect for mode II has been demonstrated for low frequencies fatigue tests: Paris' law is "shifted" to higher Energy Release Rate values with the increase of the load ratio. However, taking into account high frequency tests, this phenomenon is observed for G947 but not for NC66, maybe due to the low glass transition temperature of this material. This needs to be confirmed by conducting tests at 10Hz at another load ratio. The coefficient gamma value will then be determined.

Finally, a master FCGR vs ERR curve has been plotted for G947, independently of the frequency and the load ratio.

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