HIGH CYCLE VIBRATION FATIGUE OF CFRP UNDER ELEVATED AMBIENT TEMPERATURES

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Abstract

Vibration Fatigue of Carbon Fibre Reinforced Polymers (CFRP) composite components couples both the thermal and the mechanical properties of the material. In fact, the fatigue life depends greatly on capacity of these properties to change according to both input load and environmental conditions. The mechanical properties are related to the change of the structural stiffness at a given input load while the thermal behaviour is associated to the dissipation of the input force either by hysteresis or by ply – by – ply friction forces in damaged regions. This paper will be primarily focussed on the experimental investigation of the coupling between the mechanical and thermal properties. Experiments focus on the relationship between response phase and the thermal life (self – heating) of composite specimens under different environmental temperatures up to early crack propagation. It will also explore the effect of the temperature during the early crack propagation.

1. Introduction

It is widely known that the fatigue behaviour, of polymer – based composites, is affected by various factors when it comes to in – service conditions, such as the environmental conditions as well as the material properties. Sudden change in the temperature and moisture severities due to in – flight conditions, can lead to rapid fatigue damage accumulation.

Several studies have agreed that temperature can influence the damage development of composite materials under static [1–7] or dynamic loading [8–13]. Surrounding temperature can alter the material resistance to damage. As a result, Fracture Energy shares a strong relationship with the ambient temperature. In accordance with this characteristic, studies shown that damage initiation Energy Release Rate (ERR) values are also affected by ambient temperature. Gregory & Spearing [7] examined the Intralaminar Fracture Toughness (IFT) of Carbon Fibre Reinforced Polymer (CFRP) at temperature levels up to material's glass transition temperature. The authors concluded that the significant increase in the delamination propagation IFT at elevated temperatures, is the result of fibre bridging. Furthermore, sub – zero temperatures can affect the Fracture Toughness of a material. Kalarikkal et al. [4] reported reduction in interlaminar fracture toughness due to the embrittlement of the matrix.

On the other hand, during fatigue a different behaviour is observed. Xiaopinga et al. [9] studied the Dynamic Fracture Toughness (FT) of Composite Laminates at different Temperatures. It was observed that the FT is decreased at elevated temperature. In addition to that, studies that took place in the University of Bristol [10], reported that delamination crack propagates two orders of magnitude faster at 80 ^{O}C in comparison to Room Temperature (RT). Cold conditions during fatigue are reported on [12] where the growth rate was significantly higher at – 30 ^{O}C and – 60 ^{O}C due to the matrix embrittlement.

The difference in the damage response under static and fatigue conditions is attributed to the conflicting micro-mechanisms governing the delamination growth according to [10]. The effect of temperature on these micro-mechanisms can be also dependent on the overall exposure time.

Polymer based materials experience a viscoelastic behaviour under cyclic loading due to the mismatch between strain and stress. Hence, the mechanical energy per cycle undergoes irreversible loading [14]. The internal energy, that changes in each cycle, gives rise to the "endogenous heating" or "self – heating" of the material, which is the cause of the laminate temperature rise in fatigue [15]. Self – Heating is a matter of great interest in composites, since it can influence the mechanical properties of the material [18]. A great piece of research was developed from Katunin et al. who have studied thoroughly the self – heating temperature of composites. He studied the self – heating of rectangular composite components which are subjected to Low Cycle Vibration Fatigue Testing, extensively He developed a heat dissipation function for self – heating from solving the heat transfer equations [16]. Then, he used it to implement Finite Element Simulations.

For the purpose of this study, the combined effects of fatigue and temperature conditions are being considered in order to accurately investigate the fatigue damage on composite components, using vibration testing.

2. Experimental Method

2.1. Specimen Preparation

The component is a rectangular specimen 185 mm x 50 mm, made with 20 pre – preg plies of IM7/8552, four of which are interrupted plies 110 mm x 50 mm. The stacking sequence is $[0, 0_{drop}, 90_{drop}, (0, 90)_3, 0]_S$. The ply – drop section acts as stress raiser and allocates the damage initiation region. Ply – drops are a common feature that many composite components may contain due to their non – uniform shape. Specimens were cut into shape with great accuracy ($\leq$ 1mm) since uneven dimensions, among specimens, can lead to different vibration shapes and therefore unpredicted strain distributions.

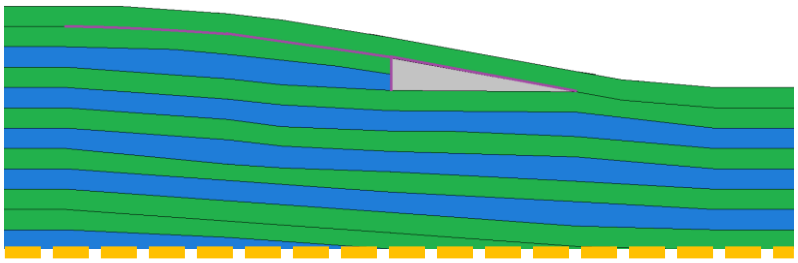

Figure 1. Specimen Lay – up & Ply Drop (Green: 0^O plies / Blue: 90^O plies / Grey: resin / Purple: Crack Propagation)

2.2. Experimental Procedure

An electromagnetic shaker was employed which dynamically excites the specimens while a laser vibrometer measures the vibration amplitude. The vibration response, measured by the vibrometer, is maintained at constant amplitude during the endurance testing. An accelerometer is installed at the fixture's base and acts as reference for the calculation of the response phase of the vibration during testing. In addition to these, a strain gauge is installed above the ply – drop to carry out a strain – displacement calibration curve used to estimate the severity level for each High Cycle Fatigue (HCF) test. The strain gauge is removed after the measurement of the calibration curve to avoid its failure

during the HCF testing. Finally, the specimen is positioned inside an Environmental Chamber which controls the surrounding temperature. Although, the Environmental Chamber has its own sensors to measure and control the temperature, two thermocouples are utilised to further inspect the temperature inside the Chamber at different locations. Hence, one thermocouple is attached on the specimen's clamp while the other is located close to the air outlet. A thermal camera is gathering information about the thermal properties of the specimens during the test, but the use of thermocouples was decided to eliminate variations in the thermal imaging data.

Figure 2. Experimental Set Up

A customised fixture was manufactured (Fig. 2) to enable the vibration of the first bending mode by imposing the minimum boundary constraints. The fixture is made as such to allow the environmental chamber to slide over and enclose the specimen. The vibration mode can be considered well isolated response mode. The thermal camera, the vibrometer and the accelerometer are positioned outside of the chamber at a safe distance for carrying out temperature and vibration measurements (Fig. 2). A small opening in the insulation material, on the top of the oven, permits the camera and the vibrometer to get the necessary vibration readings. Prior to the initiation of the test, an appropriate heat input value was selected in the chamber which maintains the inside temperature within a range of 0.5 ^{O}C for 1e7 cycles. A minimum of 1 hour and 30 minutes is required for the specimen to reach a thermal equilibrium with the ambient temperature. During this time, the temperature of the specimen was monitored by the thermal camera and the thermocouples. The experiment will only be initiated when thermal equilibrium is confirmed by the thermocouple and the camera.

The experimental method consists in exciting the first bending mode, close to the resonance frequency (≈ 400 Hz.) up to a desired level of strain/displacement and by keeping that vibration amplitude for the entire duration of the HCF test. The typical Phase Lock Loop (PLL) is replace by a Frequency Lock Loop (FLL) to trace the response phase rather than the resonance frequency. In fact, by fixing the excitation frequency one can observe how the dynamics of the specimen evolves due to the change of its internal stiffness distribution. The response phase traces a constant slope decay up to a sudden change, which is defined as the "critical event" and it describes the opening of a delamination. The HCF tests are interrupted if either this critical event or the 1e7 cycles are reached. This method is characterised by its high sensitivity to damage formation.

3. Relation between Stiffness and Temperature

Magi et al. [17] reported that the response phase (φ) of a single degree of freedom prismatic beam with length L and section S subjected to longitudinal natural vibration, can be described as:

$$\varphi = \tan^{-1}\left(\frac{m\omega}{c}\right) + \frac{m^2\omega(k - m\omega^2)}{c^3 + cm^2\omega^2} + O((k - m\omega^2)^2) \quad (1)$$

Where the *k* is the stiffness, *m* is the mass of the beam, *ω* is the natural frequency, *c* is the damping ratio and higher order terms from the Taylor expansion, which can be neglected. Therefore, it can be assumed that the phase is directly proportional to the stiffness for sufficient small stiffness variations at constant excitation frequency; both the mass and the damping are assumed constant. In this case and by taking into account that k = ES/L, Eq. 1 can be formulated as:

$$\varphi = \mathrm{A} \times \mathrm{E} + \mathrm{B} \quad (2)$$

Where E is the Young's Modulus and A and B are constants that correspond to:

$$A = \frac{S\,(m^2\omega)}{L\,(c^3 + cm^2\omega^2)} \quad (3)$$

$$B = \tan^{-1}\left(\frac{m\omega}{c}\right) - \frac{m^3\omega^3}{c^3 + cm^2\omega^2} \quad (4)$$

Viscoelastic materials differ from elastic material for their characteristic phase lag between an applied stress and its strain response. The strain energy, introduced at loading, cannot be the same to the strain energy during unloading. As a result, there is an energy loss in the form of heat during each cycle of oscillation [15]. The increase of a composite specimen's temperature (self – heating temperature), subject to cyclic loading, is the direct effect of the generation of heat on viscoelastic materials. The energy loss is related to the reversible strain energy (U_{max}) with a loss (damping) factor (∅). Lahuerta et al. [18] reported that the self – heating temperature can be approximated as follows:

$$T_s = \left[f \cdot \emptyset \cdot \frac{\sigma_2^2 - \sigma_1^2}{E} \cdot \left(\frac{t^2}{4k} + \frac{t}{2h}\right)\right] + T_a \quad (5)$$

Where σ_2, σ_1 are the maximum and minimum tension, *f* is the frequency, *k* is the thermal conductivity, *t* is the object's thickness and T_s, T_a are the object's temperature and the surrounding temperature respectively. Therefore, for a composite beam subject to vibrations of fixed frequency and severity level Eq. 5 can take the form of:

$$T_s = \frac{C}{E} + D \quad (6)$$

Where *C*, *D* are constants that correspond to:

$$C = f \cdot \emptyset \cdot (\sigma_2^2 - \sigma_1^2) \cdot \left(\frac{t^2}{4k} + \frac{t}{2h}\right) \quad (7)$$

$$D = T_a \quad (8)$$

Although, certain assumptions are required; Eq. 2 and 6 imply that stiffness is proportional to the response phase and reverse proportional to a testing coupon's temperature, during fatigue testing. In other words, while the stiffness of a specimen decreases its temperature increases but the response phase decreases. One could assume that the phase is reverse proportional to the self – heating temperature.

4. Experimental Results

4.1. Stiffness and Self – Heating Temperature

Experimental investigation revealed that the response phase and the thermal life of specimens during testing follow a similar trend that is independent of the strain level and the ambient temperature. Fig. 3 demonstrates this pattern. More specifically, the typical behaviours of the response phase and self – heating of specimens are presented. It can be observed that the graphs can be separated into three regions.

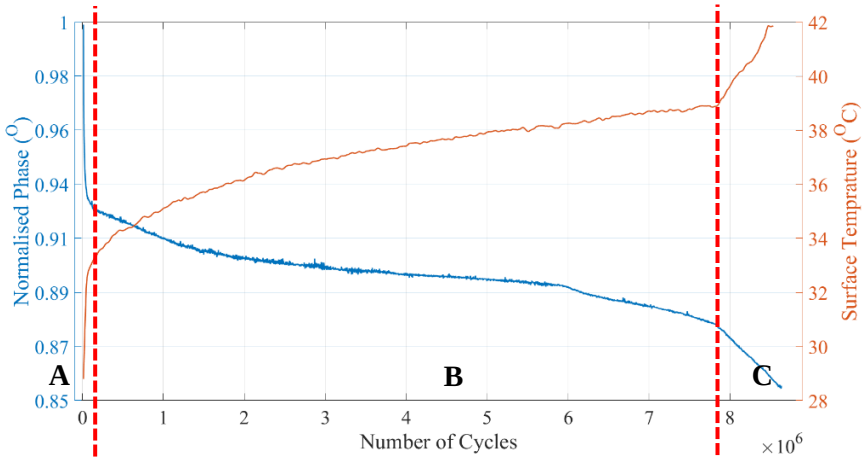

Figure 3. Phase / Specimen's Surface Temperature change during endurance testing

Region A corresponds to the settling period of the experiment, due to the initiation of the test. At this stage, specimen's temperature increases rapidly, until equilibrium is reached (point A). This behaviour is associate to a rapid change of the response phase, which was not investigate in this study. As soon as the thermal equilibrium is reached (Region B); the phase and the specimen's temperature experience an almost linear increase and decrease, respectively. The description of this behaviour was attempted in the previous section by correlating the change of response phase to the change of temperature as result of change of the Young's modulus. The critical event occurs at point C. At this stage, delamination has been developed. As a result, the surface temperature of a specimen increases rapidly due to the ply by ply rubbing. More specifically, the specimen undergoes a common behaviour for pry drops where delamination initiates after transverse matrix crack. This phenomenon was described in [19]. The newly formed delamination leads to a rapid deterioration of the specimen's stiffness, as described by the response phase measurement.

4.2. Before Critical Event

Each region of Fig.3 can be approximated by a quasi – linear relationship. Therefore, the functions corresponding to each line can be extracted and replotted against other lines from different specimens. This process can accommodate the in – depth analysis of experimental data. However, only the regions B and C (Fig. 3) were investigated because the region A seems to describe a settling behaviour of the specimen and was not investigated further. For this reason, the data acquired at region A is neglected in this analysis. On that account, the following graphs can be plotted.

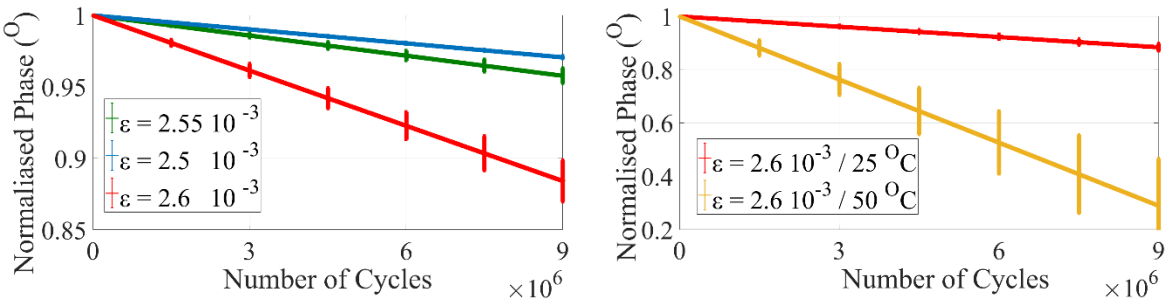

Figure 6. Phase Change during endurance testing at region B at different strain (Left / 6a) and at different Ambient Temperature (Right / 6b)

Fig. 6a presents the linear line approximation of regions B for three strain levels. The blue line indicates the strain level at which specimens did not experience the critical event up to the 1e7 cycle considered a stop criterion for the HCF test. The effect of increasing strain is apparent on these graphs as higher strain leads to acceleration in the rate of change of the response phase. This deterioration in the stiffness of testing coupons must emerge due to the accumulation of microdamage during testing. This can be further supported by the thermal imaging analysis, which suggests that no substantial delamination appeared as hotspots. The self – heating temperature of specimens decreases in this region (Fig. 3) and, qualitatively, the thermal behaviour has an inverse relationship with the stiffness as describe in Eq. 6. Figure 6b shows that ambient temperature can play an important role in the fatigue life of composite coupon. For the same strain load and two different ambient temperatures the time to degradation is much quicker for high environmental temperature. More specifically, the phases decays about 3 times faster when the ambient temperature is increased by 25 ^{O}C.

A different method, to read the data presented in Figure 3, is to plot phase against the self – heating temperature for both regions B and C. One can notice in Figure 7 that for an environmental temperature of 25 ^{O}C, the three curves overlay for the three different levels of strain load applied during the test. The same can be observed for the for 50 ^{O}C, whereas one test data is present for 75 ^{O}C. It can be noticed that their relation is independent of the strain level. On the other hand, the ambient temperature has a great effect on the trend. The rate of change of the lines is sharper. This implies that the fatigue life is shortened with increasing ambient temperature. The characteristics of the relationship between phase and self – heating temperature seems to correspond to the analytical approximation of the phenomenon; as it was presented in eq. 2 and 6. It can be assumed that higher self – heating and ambient temperatures accelerate the structural degradation of a testing coupon.

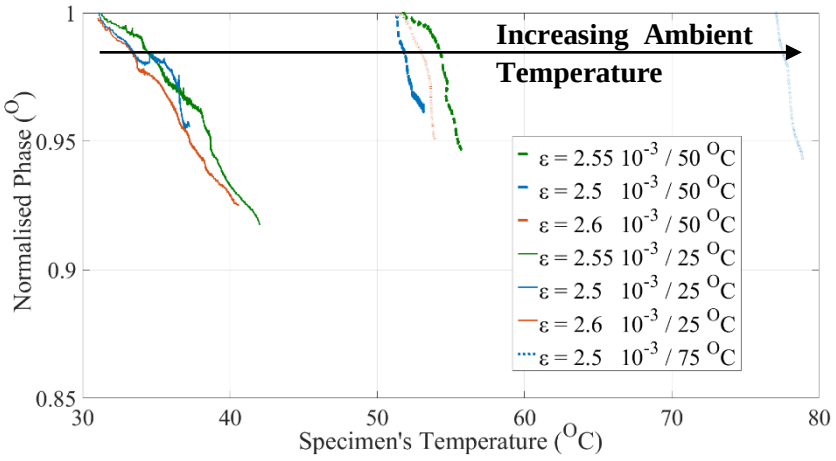

Figure 7. Typical Phase Change against Self – Heating Temperature during endurance testing at different ambient temperatures

4.3. After Critical Event

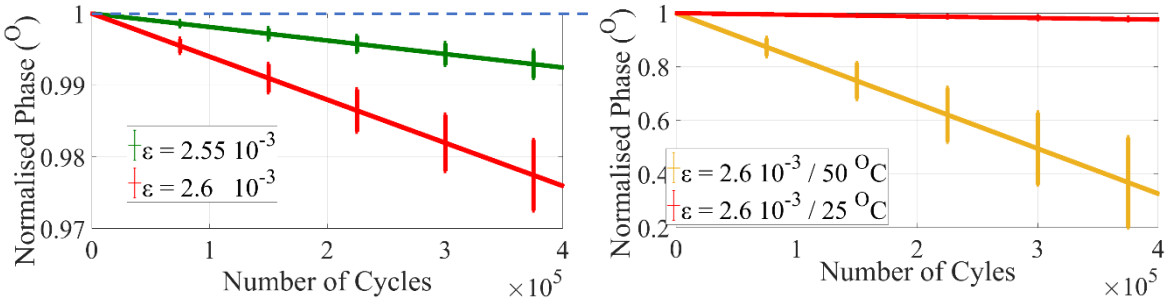

Figure 8. Phase Change during endurance testing at regions C at different strain (8a / Left) and at different Ambient Temperature (8b / Right) at 25 ^{O}C and 50 ^{O}C

This section deals with the part of test data relative to the appearance of the critical event that is in Region C (Fig. 7a). Again, the time of behaviour can be approximated to a *quasi* – linear trend within a limited amount of cycles. Figure 7a shows that for two different strain levels the opening of the delamination depends on the strain load imposed, as it might be expected. Figure 7b, instead, shows that the environmental temperature will play an important role in terms of crack opening. In fact, for a given strain load the rate of opening at 50 ^{O}C is much higher than at 25 ^{O}C. Thermal imaging revealed that the hot spot temperature increases as the crack opens, as visible in Figure 3 while its rate of change is reversely proportional to that of the response phase. This is understandable as the larger the opened delamination the higher is the friction caused by the ply rubbing for every cycle of oscillation.

5. Conclusion

A method for carrying out vibration fatigue testing, in different ambient temperature levels, was introduced and the data was analysed. Data analysis revealed a close connection between the ambient temperature and the stiffness deterioration during endurance testing. In fact, fatigue failure arises earlier at harsher temperature conditions. In addition to this, it was observed that elevated temperatures lead to higher crack opening rates. Furthermore, it was qualitatively showed by analytical examination that the self – heating temperature and the response phase are related to the stiffness of specimen. Experimental results seem to support this property and introduce a further relation between the phase and self – heating temperature (Fig. 7).

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