HEAT BUILT-UP MEASUREMENTS AND ENERGETIC CRITERION USED TO EVALUATE QUICKLY THE FATIGUE LIFE OF PA66 GF50

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Keywords: Injection, SFRP, Heat build-up, Energetic fatigue criterion

Abstract
The goal of this paper is to apply a heat built-up protocol on a SFRP used for structural automotive applications (PA66GF50, a polyamide filled with 50% of glass fiber in mass) to predict quickly the fatigue properties from the temperature measurements. In order to provide a relation between the full heat build-up curve and the Wöhler curve, the dissipated energy is then evaluated from the thermal measurements and the parameters of an energetic fatigue criterion are identified from the results obtained from one single sample. The fatigue curve predicted from the heat build-up curve is compared to the one obtained from a classical fatigue campaign and the agreement is very good. The energy based criterion as well as the identification of the dissipation sources from the temperature measurements are finally challenged by an experimental campaign achieved on a sample with a different geometry.

1 Introduction

Designing short fibre reinforced plastic (SFRP) components against fatigue has become a major concern during the last years as these materials, filled up to 50% in mass with glass fibers, are now used for structural components [1-4]. A first difficulty comes from the thermoplastic and hydrophilic nature of the PA66 matrix, which leads to a strong environmental dependency [10] and a complex behavior exhibiting viscous, plastic and damage features [9]. A second difficult point arises from the very strong coupling between the microstructure on the one hand and the geometry and the process parameters on the other hand. The characterization of the influences of these numerous environment and process parameters on the fatigue properties therefore requires wide fatigue campaigns, which are even longer than for metallic materials as the test frequency has to be limited in order to reduce the influence of the temperature rise [7]. A way to speed up the characterization of the fatigue properties of these materials would be more than useful.

Thermal measurements to evaluate quickly the fatigue properties has been used for several years for metallic materials (see [18] and references therein) and are clearly reaching now maturity [14, 18]. For composite materials, following the temperature fields is usually a way to perform a non destructive evaluation or to identify the damage initiation along a fatigue test, earlier than from the stiffness drop [2, 16, 20].

The aim of the project is to investigate the relevancy of predicting the fatigue curve from heat build-up measurements for SFRP materials, as done recently on elastomers [15]. A first companion paper in this conference [19] details the specific heat build-up experiment, the results obtained on PA66-GF50 tensile samples are presented and the good ability of a first rough analysis based on the temperature measurements to predict the fatigue properties. Nevertheless, temperature is not an intrinsic material data and is dependent on the sample geometry and on the thermal boundaries. In order to provide a fatigue criterion intrinsic to the material, it is therefore important to evaluate the dissipated energy.

In this paper, a method to evaluate the cyclic dissipated energy from the temperature measurements is detailed. The parameters of a fatigue criterion based on the dissipated energy are then identified directly from the data provided by the heat build-up test from one single sample. The fatigue curve predicted by this criterion is compared to the Wöhler curve obtained from classical fatigue tests. Another validation is then performed on smaller samples: the dissipated energies are evaluated from the heat-build up curve and the fatigue curve is predicted using the energy criterion with unchanged parameters. This prediction is finally compared to the Wöhler curve obtained by a classical fatigue campaign.

2 Materials and testing methods

2.1 Material and specimen

The material used here is a short glass fibers reinforced polyamide 6,6 containing 50% by weight (PA66-GF50). Standard tensile test specimens were used (geometries reported in Fig. 1). The samples were weighted immediately after moulding then conditioned in a humidity ratio kept at 40% and weighted before the tests to insure the same water content.

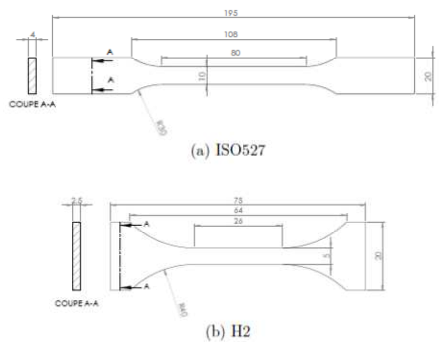

Figure 1. Samples geometries. The dimensions are given in mm

2.2 Mechanical testing and thermal measurements

2.2.1 Thermal measurements

The temperature measurements were performed with a MWIR 9705 FLIR infrared camera and a 20mK precision is obtained on relative measurements. The calibration details and experimental details are given in [3]. The temperature variation is computed from measurements performed on 3 zones, located in the middle of the specimen and on the upper and lower grips which permits to compute the temperature difference with no influences of the ambient temperature or the servo-hydraulic machine.

2.2.2 Heat build-up protocol

A heat build-up experiment can be defined as a succession of cyclic tests of increasing stress or stain amplitude while the temperature of the specimen is measured. The number of cycles used for each loading condition is the number of cycles needed for the temperature to stabilize. These tests were achieved at room temperature, on an INSTRON 1342 hydraulic machine, equipped with hydraulic grips. The frequency of the tests was 1 Hz in order to limit the heat build-up effect and the experiments were stress controlled with a load ratio set to *R*=0. The strain is measured by an extensometer. Between each cycling period of 2000 cycles, the sample is unloaded and a pause of 10 minutes is performed, in order to let the sample cool down and to get back to thermal equilibrium with the ambient. The temperature drop during the cooling is used to evaluate the convection kinetic. Let us precise that the last loading step is left running till the failure of the specimen, giving a number of cycles to failure.

2.2.3 Fatigue tests

Fatigue tests were achieved at room temperature, on an INSTRON 1342 hydraulic machine, equipped with hydraulic grips. The frequency of the tests was 1 Hz in order to limit the heat build-up effect and the experiments were stress controlled with a load ratio set to *R*=0.

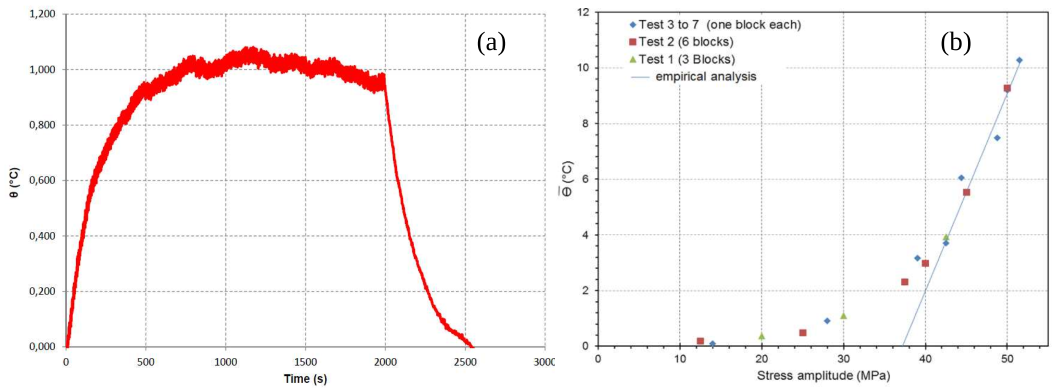

Figure 2. Evolution of the temperature along one loading step (a) and evolution of the stabilized temperature versus the applied stress amplitude (b).

3 Results and analysis of the heat build-up curve

3.1 Heat build-up curve

Figure 2a shows a typical result obtained for a loading step. A stabilization of the temperature increase was always observed, revealing that the dissipation source is nearly constant: equilibrium between what is lost by conduction and convection and induced by cyclic loadings is reached. Figure 2b presents the evolution of the stabilized temperature with respect to the applied stress amplitude imposed. It should be underlined that the repeatability of the measurements and the low influence of the loading sequence were checked [19].

3.2 Estimation of the cyclic dissipated energy from temperature measurements

Estimating the dissipation sources from thermal measurements requires solving a coupled thermo-mechanical problem, defined both by mechanical and thermal equations. In this paragraph, the hypothesis and the method used to identify the thermal sources from the temperature measurements are detailed.

The heat equation can be classically written as follows [14, 21]:

$$\rho c\dot{T} + div(\vec{q}) = \rho c S_t = \Delta + r + \rho T \frac{\partial^2 \Psi}{\partial V_k \partial T} : \dot{V}_k + \rho T \frac{\partial^2 \Psi}{\partial \varepsilon^e \partial T} : \dot{\varepsilon^e} \quad (1)$$

With ρ the mass density, c the specific heat capacity considering the internal variables V_k as constants, S_t the thermal sources, Δ the intrinsic dissipation, r the external heat supply, Ψ the Helmholtz free energy and ε_e the elastic strain tensor. Some classical hypothesis can be applied: the external heat supply is not time dependant, the temperature variation (under 10°C here) are low enough to neglect the couplings between temperature and internal variables and to neglect the variation of ρ and c. In this study, only cyclic tests are considered. As the external heat supply is considered constant and as the thermo-elastic coupling terms compensate over a mechanical cycle, solving the heat equation over a mechanical cycle reduces to solve:

$$\rho c\dot{T} + \lambda\Delta T = fr\,\Delta^* \quad (2)$$

With Δ^* the intrinsic dissipation over a cycle and *fr* the loading frequency *fr*.

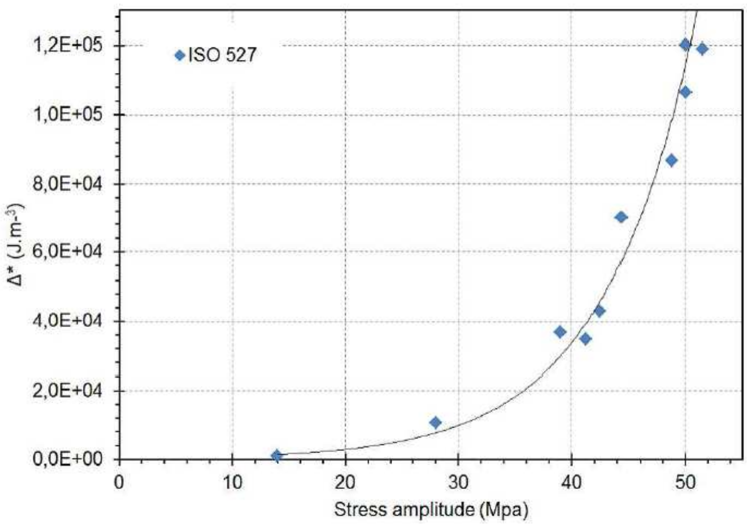

Figure 3. Evolution of the cyclic dissipated energy with the stress amplitude applied.

Considering that the mechanical variables and the temperature are homogeneous in a given section, with this geometry [21], this equation can be conveniently written:

$$\dot{\theta} + \frac{\theta}{\tau_{eq}} = \frac{fr\,\Delta^*}{\rho c} \quad (3)$$

with θ the mean temperature variation and $\tau_{eq}$the characteristic time (depending on the thermal boundary conditions). The identification of τ_{eq} is achieved thanks to the cooling period between the cyclic steps (no thermo-elastic coupling, no mechanical dissipation). Knowing τ_{eq}, the next step is of course to solve equation 3 for the cyclic loading block which leads to the following expression:

$$\theta = \frac{fr\,\tau_{eq}\,\Delta^*}{\rho c}\left[1 - \exp\left(-\frac{t}{\tau_{eq}}\right)\right] \quad (4)$$

The average cyclic dissipation therefore writes:

$$\Delta^* = \frac{\rho c\,\bar{\theta}}{fr\,\tau_{eq}} \quad (5)$$

With $\bar{\theta}$ the stabilized temperature at the end of the loading step. The values of the specific mass ρ and specific heat c are taken from the datasheet of the material supplier, i.e. ρ = 1560 kg/m^3 and c = 1300 J/(kg.K). This expression therefore enables to plot a heat build-up curve linking the cyclic dissipation to the stress amplitude, as illustrated on figure 3. It is crucial to underline that this evaluation of the dissipated energy is perfectly correlated to the one evaluated from the mechanical hysteresis (obtain from strain-stress stabilized curves).

4 Coupling thermal measurements to an energetic criterion to predict the Wöhler curves

4.1 Identification and first validation of the parameters of an energetic criterion

Numerous approaches to predict the fatigue of SFRP can be found in the literature [11-13, 17]. Here a criterion based on the dissipated energy is chosen for several reasons: this criterion is computed from a stabilized cycle that is reached during the loading blocks of the heat build-up protocol; the dissipated energy is of course easy to link to the temperature evolution under cyclic loading; this kind of model was found very efficient on numerous tests and material [11].

The energetic criterion chosen aims at relating the number of cycles leading to failure or initiation (N) to the dissipated energy during the stabilized cycle (Δ*). This relation is usually written:

$$\Delta^{*}.N^{b} = C \quad (6)$$

With b and C the model parameters.

Replacing the expression of the cyclic dissipation, it comes:

$$\frac{\rho c\,\bar{\theta}}{fr\,\tau_{eq}}.N^{b} = C \quad (7)$$

In this expression ρ and c are material constants, frequency fr is a test constant, $\tau_{eq}$is a thermal constant (evaluated previously from the cooling test), $\bar{\theta}$ is dependent on the stress amplitude, according to the heat build-up curve.

A heat build-up test affords two data: the dependency of the temperature on the stress amplitude, and the number of cycles to failure on the last loading block. As explained in the companion paper [19], a fast analysis of the heat-build up curve gives a reasonable value of the stress amplitude leading to 10^6 cycles. Two couples of data (Δ*;N) can therefore be obtained from the heat build-up test. Knowing these two couples, the parameters b and C of the energetic criterion can be identified analytically. The values obtained for ISO 527 samples are b= 0.221 and C= 638026 J/m^3.

Using the heat build-up curve to link the stress amplitude to the dissipated energy and the identified energetic criterion to predict the number of cycles to failure, it is possible to predict the fatigue curve. As illustrated on Figure 4, a very good agreement is observed between the experimental data and the predicted curve.

This result validates that the heat build-up curve can be used in a very efficient manner to provide a good prediction of the deterministic Wöhler curve, throughout an energetic fatigue criterion. This is a very interesting result in order to speed up the characterization of the influence of the numerous factors on the fatigue properties of SFRP because this evaluation can be performed using only one sample, with a test lasting less than 2 days (including the failure on the last heat build-up block).

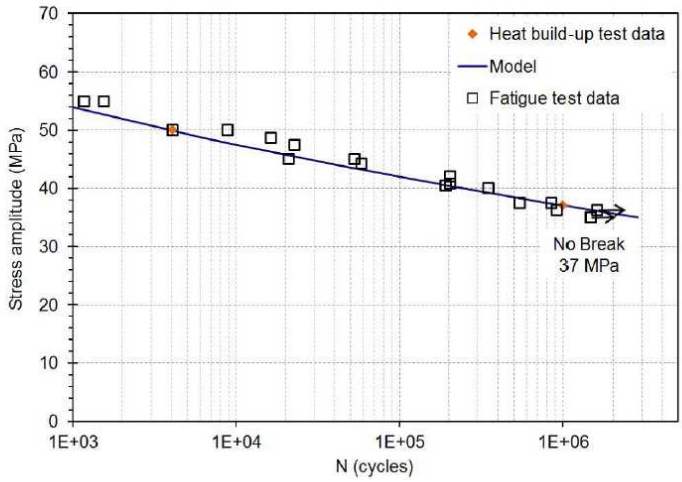

Figure 4. Comparison between the model prediction and the Wöhler curve for ISO527 samples

4.2 Prediction of the Wöhler curve from thermal measurements: application to H2 samples

To identify the evolution of the cyclic dissipation with the stress amplitude a heat build up test is performed, allowing plotting the evolution of the stabilized temperature versus the applied stress amplitude. Figure 5 shows this curve and illustrates that the shape is similar to the one obtained for ISO527 samples, but with lower temperatures, which is consistent with the fact the volume of H2 samples is smaller.

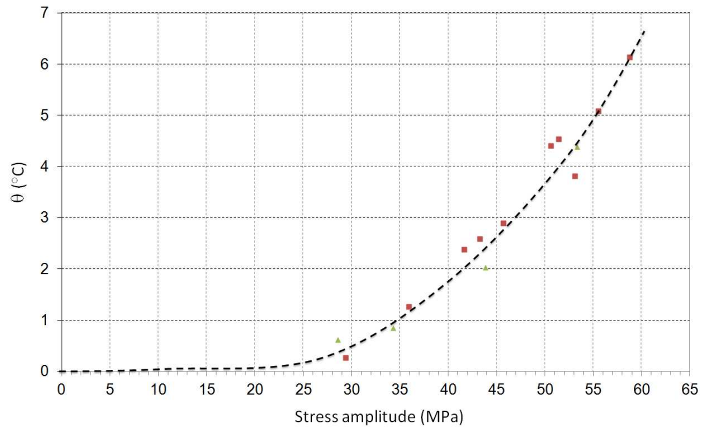

Figure 5. Heat build-up curve measured for H2 samples

Then, as the geometry of the sample is different, the characteristic time τ_{eq} (depending on the thermal boundary conditions) is different and has to be evaluated from the cooling steps. A good correlation is obtained for value of 95 s. It is worth noting that identifying a lower characteristic time for H2 samples than for ISO527 samples is consistent with the faster stabilization of the temperature rise (around 800 cycles for these samples instead of 2000 previously, using the same loading frequency).

Considering now equation 7, frequency fr is a test constant, $\tau_{eq}$is a thermal constant evaluated from the cooling test, the dependency of $\bar{\theta}$ on the stress amplitude has been characterized by the heat build-up curve, ρ and c are material constants and are kept the same than for ISO527 samples. The number of cycles to failure can therefore be calculated with the parameters b and C identified previously on ISO527 samples. The experimental and predicted Wöhler curves are plotted on Figure 6. The correlation is actually very good, which validates both the criterion based on the dissipated energy and the identification from the heat build-up tests of the evolution of the dissipated energy with the stress amplitude. It should be underlined that no identification of a given lifetime from the heat build-up curve has been done for the validation of the criterion.

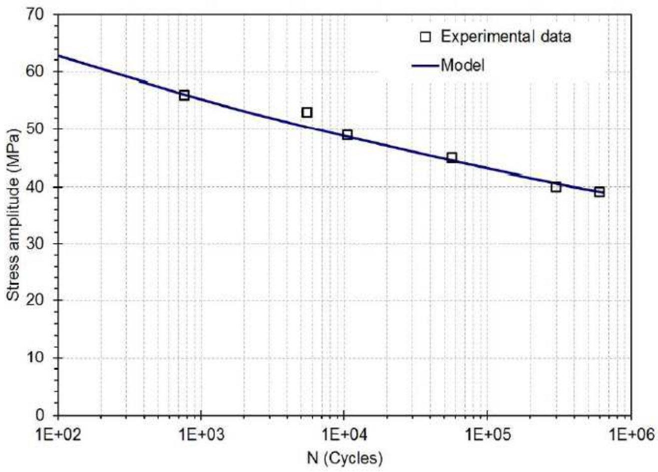

Figure 6. Comparison between the model prediction and the Wöhler curve for H2 samples

4 Conclusions

In this paper, the ability to use thermal measurements to determine the fatigue properties of SFRP was evaluated. In order to use an intrinsic variable (temperature is dependent on the geometry and on the thermal boundaries), the cyclic dissipated energy was evaluated from the temperature measurements. The heat build-up data issued from ISO527 samples were then used to identify an energetic criterion and to predict the Wöhler curve. A very good correlation to a Wöhler curve obtained from classical fatigue measurements can be observed. The criterion parameters identified on ISO527 samples were also successfully used to predict the deterministic Wöhler curve from the heat build-up data measured on H2 samples. This result validates both the energetic criterion and the evaluation of the dissipated energy from the temperature for a change of the sample geometry. It furthermore illustrates that the full deterministic Wöhler curve as well as a relevant energetic criterion can be evaluated from a heat build-up test using one single sample and lasting 2 days.

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