Heat build-up measurements on SFRP: fast determination of fatigue properties and validation of a fatigue criterion on automotive parts

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ABSTRACT

Designing short fibre reinforced plastic (SFRP) components against fatigue has become a major concern during the last years. This is a difficult task because they exhibit a complex mechanical response with a strong dependency on the service environment (temperature and humidity ratio) as well as on the complex microstructure induced by the process and the complex geometries of the parts. Speeding-up the characterization of the influences of these numerous parameters on the fatigue properties is of primary importance for the parts optimization and development.
In a recent paper, a heat built-up protocol was developed to predict quickly the fatigue properties from the temperature measurements: the dissipated energy is evaluated from the thermal measurements and the parameters of an energetic fatigue criterion are identified. Proven very efficient (the full deterministic fatigue curve can be predicted from one sample, within 2 days) the protocol and the energy based criterion are challenged in the present paper by several fatigue campaigns performed with variations of numerous parameters (sample geometry, humidity ratio, fibers orientation). The results obtained validate both the criterion and the fast determination protocol. A very good unification of the fatigue data is indeed obtained with the criterion.
Then, heat build-up and fatigue tests were achieved on structural automotive parts and the thermal fields were recorded. The localization of the hot spots were assessed both by thermo-elastic and dissipation fields. A specific analysis of the thermal fields allows for describing the fields of the dissipated energy. The energy based criterion obtained previously on samples is then applied to predict the fatigue lifetime from the local heat build-up curve measured on the parts. The agreement with the fatigue tests is very good, which validates both the energy based criterion and the use of thermal measurements to obtain quickly the fatigue curve for samples as well as for structures.

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. This is a difficult task because they exhibit a complex mechanical response with a strong dependency on the service environment (temperature and humidity ratio). Moreover, the industrial parts are injected, which induces a 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 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.

The first section decribes the material, the specimens and the approach used to predict quickly the fatigue properties from the temperature measurements. A so-called heat build-up protocol is applied to a classical injected sample. The dissipated energy is evaluated from the thermal measurements and the parameters of an energetic fatigue criterion are identified.

The second section investigates the ability of the approach (description of the dissipated energy from thermal measurements and energy based fatigue criterion) to describe the influences of first order parameters (humidity ratio, fibers orientation and length distribution) on the fatigue properties.

The last section aims at a difficult task, which is the application of the approach directly on an industrial part. The thermal fields are used to describe the dissipated energy fields using an original protocol. Then, the energy based criterion identified on samples is applied to predict the fatigue lifetime of the parts. At last, these predictions are compared to the experimental results.

EXPERIMENTAL AND NUMERICAL TOOLS

Material and samples

The material investigated here is a short glass fiber reinforced polyamide 6,6 containing 50% by weight (PA66GF50). The features of the microstructure (fibers length distribution, orientation tensors, cristallinity ratio) were obtained using classical microstructural techniques.Two geometries of tensile test specimens were used. The first one (called in the following ISO527) is as defined in ISO 527-2-1A standard [1]. This kind of sample is obtained by injection only. Some of these sample were injected using regrind pellets in order to modify the fibers length distribution. The second one (called in the following H2) is defined according to the ISO527-2-1BA standard [1]. These samples are either injection moulded or obtained from milling from injected plates in order to modify the fibers orientation tensor. All the samples were weighted in order to master as precisely as possible the subsequent water uptake, and conditioned in humidity ratios varying from 20 to 55% (referenced RH20 to RH55).

Mechanical testing devices and protocols

All the mechanical tests have been conducted on an INSTRON hydraulic testing machine equipped with a 100kN load cell. All the tests have been load controlled and were conducted at 1Hz in order to limit as much as possible the heat build-up (the coupling of the thermomechanical properties to the temperature can therefore be neglected). The strain is measured by an INSTRON extensometer (reference 2610-601, base length 12.5 ± 5 mm)

Fatigue tests were achieved at room temperature and the load ratio was set to R = 0. As observed commonly the number of cycles to initiation is very close (and will be taken equal) to the number of cycles to failure. The maximum rise of temperature encountered for high amplitudes was 10 °C.

The samples were submitted to heat build-up tests. These tests consist in submitting a sample to a serie of cyclic tests of increasing stress (here) amplitude while recording the temperature. The number of cycles used for each loading condition is either the number of cycles needed for the temperature to stabilize (for example, 2000 cycles at 1 Hz are sufficient for the samples used) or a few cycles if the initial temperature rate of variation is to be used (see next paragraph). Between each cycling period of 2000 cycles, the sample is unloaded and a pause of 10 min 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 rate. This step is also used to evaluate the partial recovery of the strain reached at the end of the cyclic loading. Let us precise that the last loading step is left running until the failure of the specimen, giving a number of cycles to failure.

Thermal testing device and protocols

The infrared measurements were achieved with a FLIR SC7600BB camera equipped with a 50mm and G1 objectives. The focal plane array is 640*512 pixels and the distance between two detectors is 15µm. In order to get the best accuracy possible, a homemade calibration procedure was achieved (pixelwise calibration integrating the effects of the camera housing temperature) and gives acces to a thermal resolution of 10mK for differential measurements.

Accurate thermal measurements surely give precious data, using a mean evaluation or the temperature field description. Nevertheless, temperature depends both on time and space throughout the heat equation and is therefore not an intrinsic thermomechanical parameter. Relating the temperature to the dissipated energy is therefore mandatory to reach a reliable description of the thermomechanical response of samples and structures. In this study, two ways have been used to relate the dissipated energy to the thermal measurements. These protocols are detailed in companion papers [2, 3] and in former publications [4] and are only quickly recalled here. The first protocol solves takes advantage of the temperature stabilization after a given number of cycles, to work on a stationary state. The thermal exchange conditions are identified from the cooling kinetic once the mechanical solicitation is stopped. Then, solving the balance between the heat sources and the exchange terms gives acces to the cyclic dissipated energy. The second protocol takes advantage of the very low thermal conduction of these materials that allows neglecting the diffusion and exchange terms when comparing two close instants at the very beginning of the test. A substraction of the temperature fields obtained in the same mechanical configuration for two close instants therefore gives acces to the field of dissipated energy.

Principle of the identification of a fatigue criterion from thermal measurements

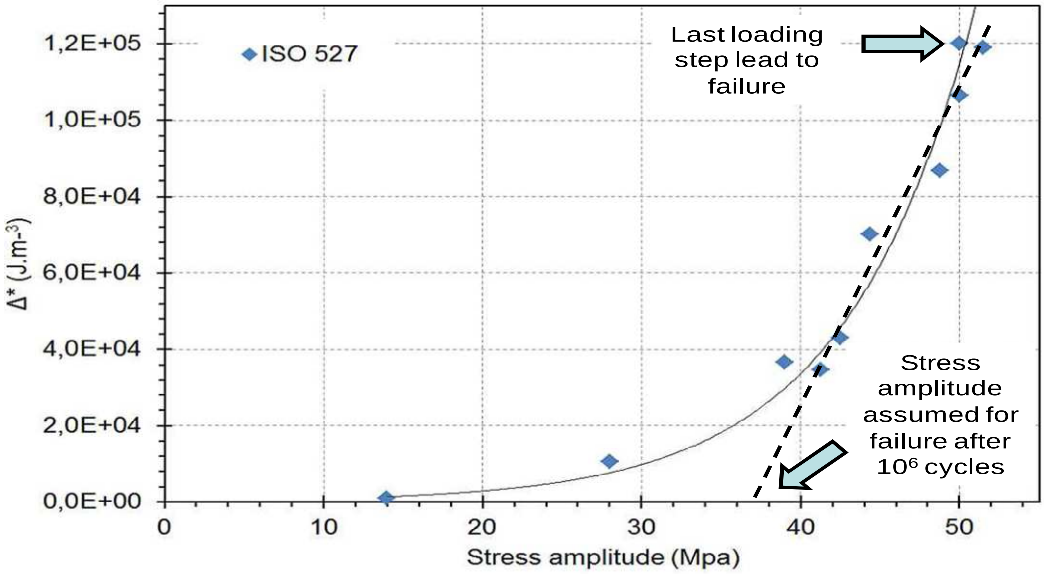

Figure 1. Evolution of the dissipated energy (mean analysis) during a heat build-up test.

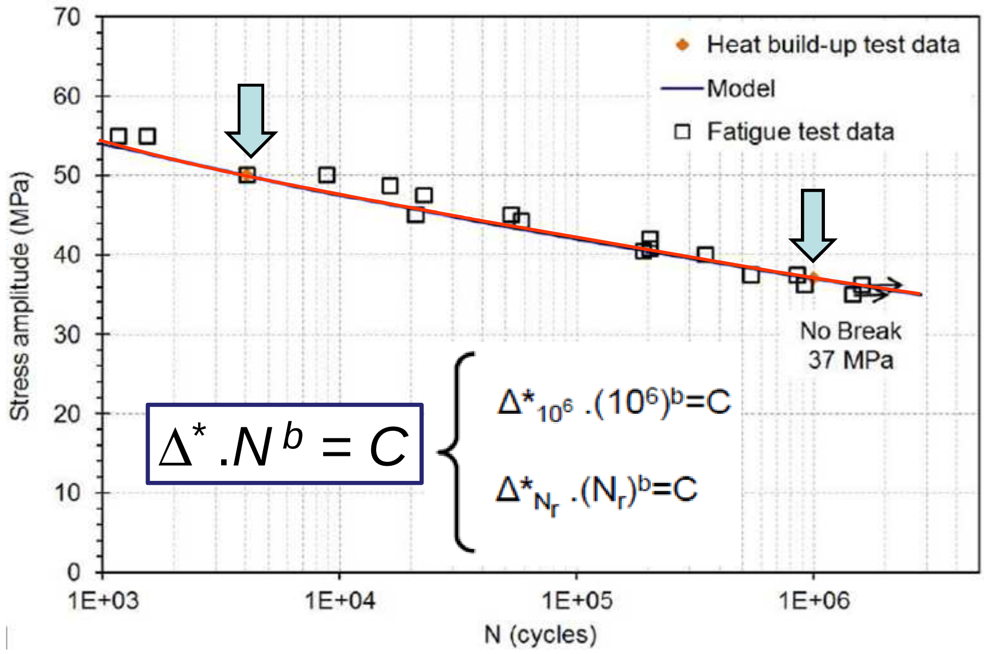

Figure 2. Analytical identification of the parameters of the energetic criterion and validation on the results obtained by classical tests (unfilled squares).

Figure 1 gives the evolution of the dissipated energy obtained on ISO527 samples from a heat build up test. This test gives acces to two numbers of cycles leading to failure. The first one is obtained from the last loading step which is left running to failure. The second one is given by a graphical evaluation illustrated on the figure 1. This fast evaluation is classically used for metallics and is based on the idea that a threshold can be observed in the energetic and fatigue behaviour of the tested material. For SFRP, no clear fatigue limit is to be seen, neither any clear change of the shape of the heat build-up curve. Nevertheless, this rough evalution was kept as a first try and seemed efficient.

Figure 2 illustrates the identification of the parameters of the energetic criterion from the two couples (mean cyclic dissipated energy Δ*,number of cycles to failure Nr) obtained from the analysis of the heat build up test. Then the comparison to the fatigue results obtained from classical tests on the same samples illustrates that the criterion and the approach suggested are very efficient. The deterministic Wöhler curve could therefore be obtained with only one sample and within 2 days (including the last step leading to failure).

RESULTS

Challenge of the approach to describe the influence of first order parameters

The influence of several first order factors on the fatigue properties have been investigated here: a change in the volume of the sample, a change of the average fibers orientation, and a change of the water uptake induced by conditionning in humid environement. Due to the limited format, the approach is illustrated here only for the influence of the water uptake and of the sample geometry.

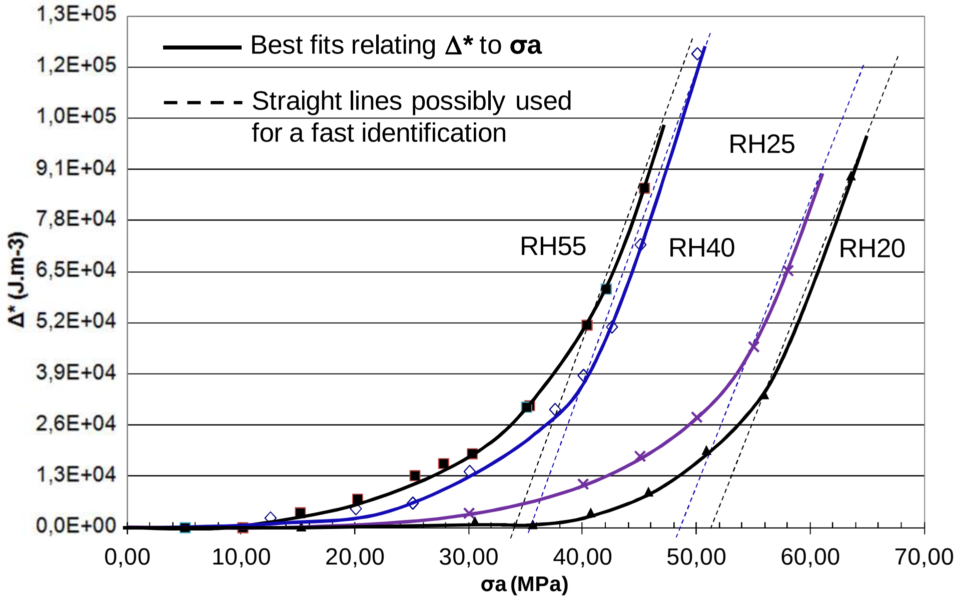

Figure 3. Illustration of the influence of the water uptake on the heat build-up curves.

The heat build up curves obtained for the samples conditioned for various humidity ratios (ranging from RH20 to RH55). One can see an expected ranking, as the water uptake leads classically both to an increase of the dissipation associated to a shift of the glass transition [5] and to a reduction of the fatigue lifetime. On this figure, we plotted dotted and plain lines. The dotted straight lines illustrates the graphical evaluation of the stress amplitude assumed to lead to a fatigue duration of 1 million cycles. The plain lines give the fit suggested to relate the dissipated energy to the stress amplitude applied.

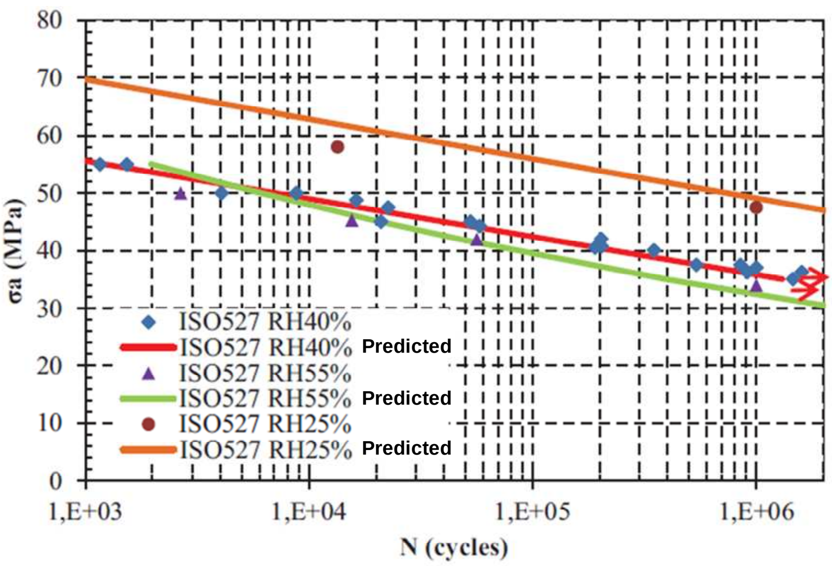

Figure 4. Illustration of the influence of the processing strategy to the identification of the thermal heat sources based on the estimation of the heat build-up variation.

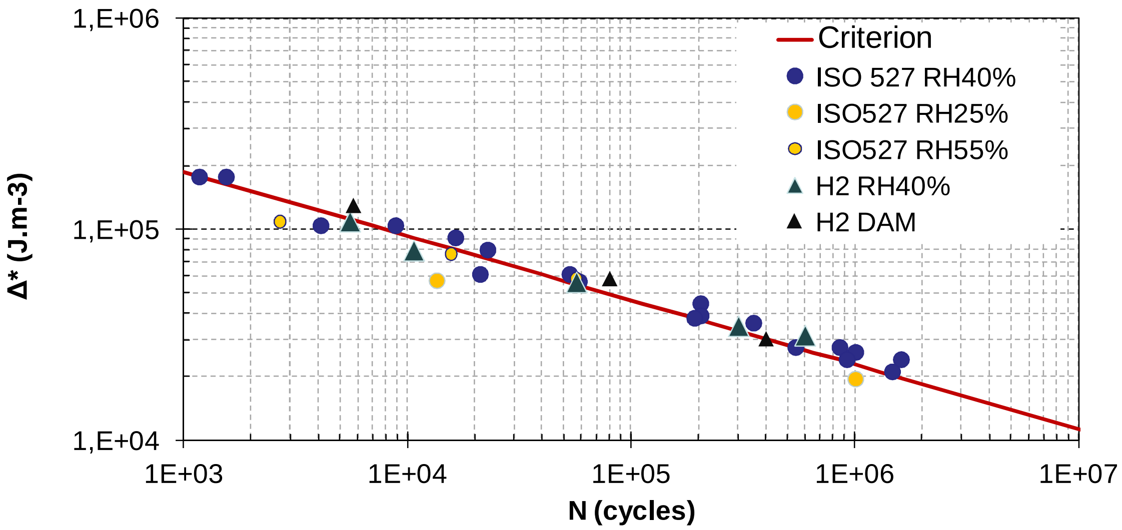

Figure 5. Illustration of the influence of the processing strategy to the identification of the thermal heat sources based on the estimation of the heat build-up variation.

Figure 4 illustrates the comparison between the fatigue results (obtained from classical tests) and the analysis provided by the heat build up curves. A first point is the efficiency of the graphical evaluation to give the stress amplitude leading to 10^6 cycles. The second point, more interesting, is that if one applies the energetic criterion identified previously to the curves identified on figure 3, the predicted fatigue curves are in very good agreement with the experiments, whatever the conditionning. It therefore seems natural to plot all the fatigue results according to the cyclic dissipated energy, instead of the stress amplitude. The figure 5 illustrates that this plot unifies very well the different fatigue data obtained for several conditioning and samples geometries (ISO 527 and H2 samples) and that the criterion identified (from one single sample) gives a very good correlation to the experimental results.

The results of this section have been obtained on classical samples and the analysis of the dissipated energy was based on the hypothesis of homogeneity in the sample section and along the sample tensile direction. The energy based criterion could therefore also be identified from a more classical evaluation, i.e. computing the hysteretic loop from the stress/strain data obtained with the machine force and an extensometer. This was actually checked and the difference between the evaluations from the mechanical and thermal data never exceeds 15 %. Nevertheless, the major advantage of identifying the dissipated energy from the thermal fields is that it can be applied also to identify the local dissipated energy when it comes to heterogenous loading cases like structural samples or parts. This is what is illustrated in the next section.

Challenge of the approach on an industrial part

In this section, the heat build up protocol is applied on an automotive part (prototype engine mount) developed by TrelleborgVibracoustic (see figure 6). The determination of the fields of dissipated energy is achieved according to the second protocol recalled in the introduction and detailed in companion papers [2, 3].

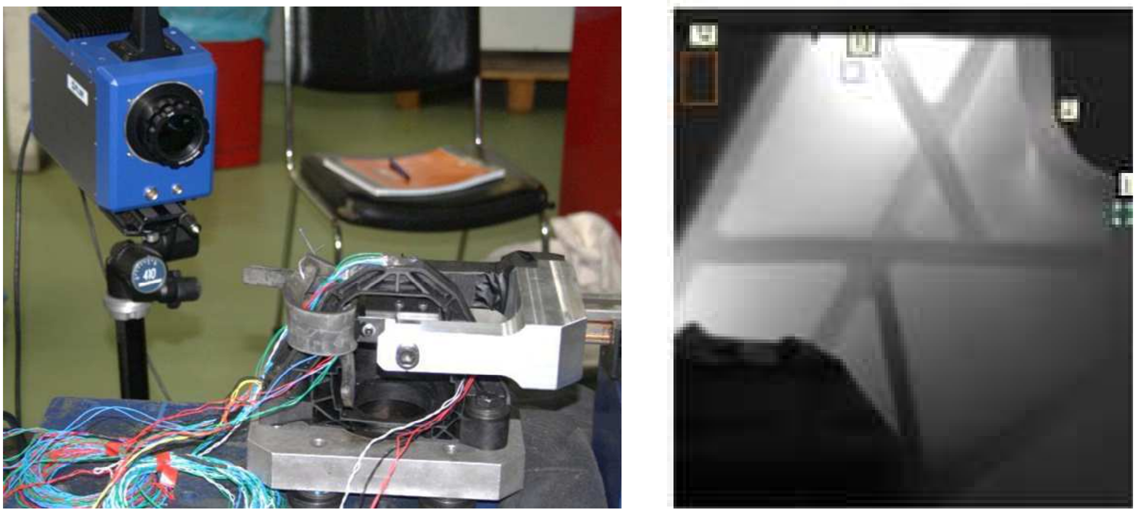

Figure 6. Tests on parts: experimental set-up(left) and example of thermal fields (right).

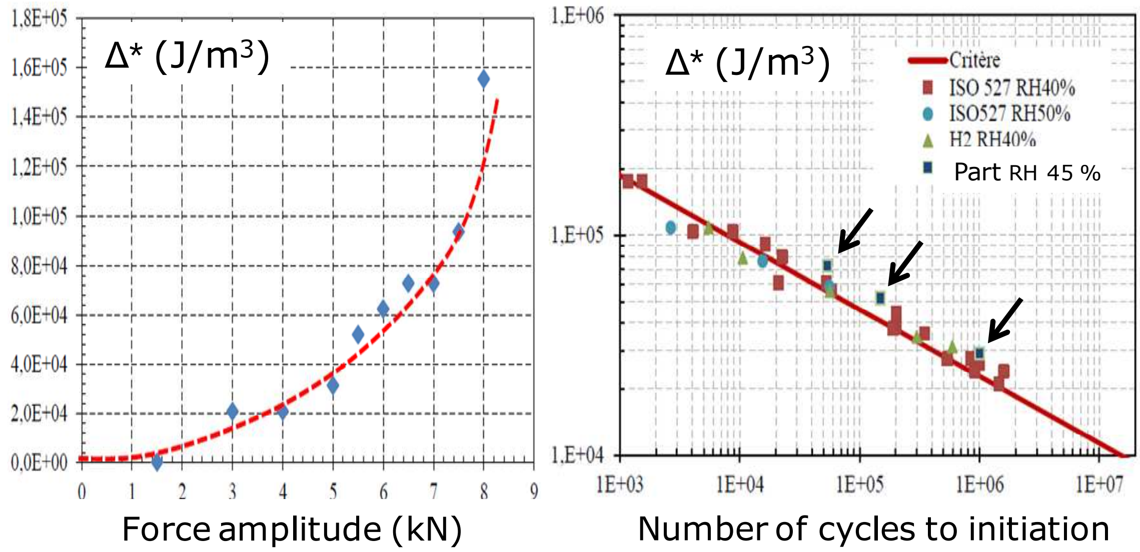

Figure 7. Heat build-up curve obtained at the hot spot leading to initiation and comparison to the fatigue energetic criterion identified on samples.

Figure 7 presents the evolution of the dissipated energy along the testing force applied on the structure. This measurement is performed locally, on the critical location where the first crack iniates (identical for all the tests). Then, the number of cycles to initiation ar plotted according to the dissipated energy mesasured and a very good correlation can be observed between the fatigue ecriterion identified on samples and the results obtained on parts.

CONCLUSION

In this paper, a protocol suggested recently to identify quickly the fatigue properties of SFRP has been applied and the parameters of the fatigue criterion, based on the cyclic dissipated energy, have been challenged. First the effect of several first order parameters have been identified and well unified throughout the criterion. Then, the application to a real automotive part turned out to be very promising, opening the way to further investigations.

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