A Rapid Procedure to Reconstruct S/N Curve by Using Harmonic Components of Thermal Signal

R. De Finis, D. Palumbo, and U. Galietti

Abstract The use of thermal indexes assessed by monitoring rapid fatigue tests with infrared detectors as reliable damage parameters to reconstruct the S/N curve is currently a topic still presenting open points. First of all, the selection of the proper thermal index representing damage is a topic to be explored, and also the relationship between the damage from rapid stepwise tests and constant amplitude tests is another point of discussion.

In the present work, we deal with such an issue by investigating the first amplitude harmonic (FAH) of thermal signal related to thermoelastic phenomena and dissipative effects too. It has been demonstrated that FAH is related to stiffness degradation and stress-induced effects. Moreover, it provides a local analysis of specific effect related to the material fatigue damage without artefacts.

The results show that due to the relationship between stiffness degradation and FAH and specific material properties, it is possible to reconstruct the S/N curve by carrying out just one constant amplitude test and a stepwise rapid test. Moreover, the capability of temperature FAH to study fatigue behaviour and detect damage during any loading procedure is also presented.

Keywords S/N curve · Stiffness degradation · Stepwise loading · Temperature first amplitude harmonic · Thermoelastic signal

Introduction

The fatigue behaviour of composites is crucial for the structural analysis due to damage mechanisms that vary depending on layup, mechanical properties and technological process of constituents. As well known, the damage can be understood as mechanical property degradation that can occur in different stages leading to final material failure [1–6]. In this way, the damage analysis is essential to develop 'stiffness-driven' design procedures that are reliable to implement a damage-tolerant approach.

Several models for damage analysis have been presented in the literature [1, 5, 6]; each one is tailored on the specific composite and application (e.g. woven [7], FRP [6], etc.) and any type of damage [1]. However, to validate these models, classic experimental tests are required which involve experimental campaigns and analyses that are time-consuming and require a lot of resources for modelling and validation stages. These implications clearly affect the time-to-market of new components and materials. This problem has, in recent years, become the 'driving force' for the development of new test procedures for rapid and effective fatigue test campaigns, supported by experimental techniques such as infrared thermography [6–18].

Nowadays, the stepwise loading procedure, to induce a self-heating in the material, can provide an estimation of the material endurance limit using the thermographic method on a small number of specimens [14]. Even if the approach proved to be effective on metallic and non-metallic materials [6–8], as far as composites are concerned, the relationship between the thermal parameters from a stepwise test and those from constant amplitude tests is still a topic to be explored. Furthermore, the choice and evaluation of a correct damage parameter that takes into account the specific accumulation mechanisms during

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the rapid fatigue test are also a topic to be explored. Huang et al. [6], for example, proposed a damage parameter based on the stiffness degradation of composite specimens and the average temperature measured during rapid fatigue tests. The procedure required the assessment of material constants from the classic fatigue test campaign; therefore, it was in any case challenging from the point of view of tests and analyses. Montesano et al. [8] proposed a method based on the temperature continuously acquired during the steady-state stage of a loading block of stepwise fatigue tests, accounting for the procedure proposed by La Rosa and Risitano [14] on metals. The basic condition for the application of the procedure is the achievement of thermal steady state in the temperature evolution and also the hypothesis of energy conservation (constant energy parameter) which should be verified for composites. In this regard, in the last 10 years, more effective indices have been studied, such as the harmonic components of the temperature signal [12, 16], to carry out the analysis of the damage processes in composites.

In the works of De Finis et al. [12], the relationship between the mechanical work associated with the material (area under the hysteresis cycle) and the thermal energy dissipated during tests of constant amplitude was presented, and, in another work, [17], the ability of the thermoelastic signal to describe the degradation of the material stiffness was investigated. These indices have proved to be very effective for estimating the residual life of the composites, as they are directly linked to the damage.

The aim of present work is to obtain the fatigue life of a quasi-isotropic composite via the assessment of thermal indices acquired during a rapid fatigue test.

The novelties and outputs of present research are related to:

- Capability of temperature first amplitude harmonic (FAH) to detect fatigue damage
- Capability of temperature FAH to study fatigue behaviour
- Correlation between FAH and stiffness degradation during any loading condition
- An innovative procedure to reconstruct the S/N curve from FAH data acquired during a stepwise loading

Background

Damage and Stiffness Loss of Material

As discussed by several authors [1–3], for a composite subjected to uniaxial fatigue testing (constant amplitude), the actual damage parameter related to the i-th stress level, D_i, is:

$$D_i = 1 - \left(\frac{E}{E_0}\right)_i \tag{1}$$

where D_i of course varies also depending on loading cycles. During a cyclic loading test, the first damage mechanism that occurs is the appearance of transverse cracks in the layers where fibres are oriented in a direction different from the one of the loading [3, 4, 6]. From Eq. (1), it results that D_i can be defined as the Young's modulus loss (the actual value of longitudinal one in this specific case, E_i is referred to a reference value usually measured at the beginning of the test or evaluated from the static tensile tests, E_0). The stiffness degradation is related to the cycles to failure of the material via different analytical/semi-analytical/phenomenological models [1–7]. A very well-established model is the following one:

$$\left(\frac{E}{E_0}\right)_i = \left(\frac{E}{E_0}\right)_{i,\mathrm{CA}} = A\left(\frac{N}{N_\mathrm{f}}\right)^b_{i,\mathrm{CA}} \tag{2}$$

where the subscript CA refers to constant amplitude tests, N is actual loading cycle, N_f is the cycle to failure of the material and A and b are constants of the specific material.

Equation (2) allows the determination of the remaining life of the material once the degradation of the material is known and vice versa. It is interesting to note that the behaviour of the material during a constant amplitude fatigue test depends only on the life fraction [5]. Therefore, it can be assumed that during a generic test at a constant stress level, the decay of the elastic properties with respect to the life fraction is the same regardless of the type of test (constant amplitude (CA) or stepwise test (SW)). Considering, moreover, that the reduction of the stiffness of the material occurs prevalently in the first load cycles, the following relationship can be considered valid:

$$\frac{E}{E_0}\left(\frac{N}{N_{bc}^{\mathrm{SW}}}\right) = \frac{E}{E_0}\left(\frac{N}{N_{\mathrm{f}}^{\mathrm{CA}}}\right) \tag{3}$$

Equation (3) indicates that at constant load, independent on the kind of test procedure (CA or SW), the Young's modulus loss is the same and depends on the cycles performed. In particular, N_{bc}^{SW} are the cycles of each loading block of a SW test (usually 10,000 cycles), while $N_{\mathrm{f}}^{\mathrm{CA}}$ are the cycles to failure of a CA test.

Equation (2) can also be used to estimate the stiffness degradation of the material during each single load block of the rapid fatigue test.

To estimate $\frac{E}{E_0}$, data from an extensometer or those deriving from the digital imaging correlation (DIC) can be used. Naturally, the first method is useful for laboratory applications, while the DIC technique requires an ad hoc equipment and setup and the presence of a surface applied speckle pattern useful for detecting displacements. An indirect method for estimating the loss of material stiffness is the one proposed by some researchers [9, 18], based on the study of the small temperature variations induced by the thermoelastic effect [19].

The phenomena affecting material mechanical behaviour are related to the heat energy involved in fatigue process; hence, mechanical data can be related to thermal data by considering that the formation of a new off-axis crack is a problem involving both variations of elastic energy and dissipations [4, 15, 19]. Indeed, the occurrence of cracks leads to a reduction of the structural stiffness which is related to the thermoelastic signal [9, 12, 18]. Furthermore, the energy released during damage (proportional to the energy needed to produce new fracture surfaces) [20] determines a change of internal energy and of work done on the material. Micro-cracks, however, are potential sites for the development of delamination between layers [20], and friction due to rubbing of damaged/delaminated surfaces also leads to energy dissipation [21].

All these phenomena influence the behaviour of the material by determining a variation of the thermoelastic signal and an increase in the dissipated energy; therefore, approaches based on the detection of the dissipated heat through measurement of the temperature signal can be useful for studying the damage by detecting these phenomena [7–17].

As shown in the recent work [22], during cyclic loading, a certain amount of energy supplied to the material is dissipated. In accordance with the first law of thermodynamics, the rate of mechanical energy supplied to an isolated system can be stored internally in the material or converted into heat [23, 24]. The latter contribution produces the temperature increase of the material or component [10–15].

Based on the total energy balance in terms of power per unit volume:

$$\dot{W} + \dot{Q} = \dot{U} = \dot{E}_{\mathrm{rev}} + \dot{E}_{\mathrm{irrev}} = \dot{E}_{\mathrm{s}} + \dot{E}_{\mathrm{d}} + \dot{E}_{\mathrm{rev}} \tag{4}$$

where $\dot{W}$ is the rate of mechanical energy supplied, $\dot{Q}$ is the rate of heat exchanged and $\dot{U}$ is the rate of internal energy variation. The rate of change of internal energy is composed of both a reversible part ($\dot{E}_{\mathrm{rev}}$) and an irreversible part ($\dot{E}_{\mathrm{irrev}}$). In particular, $\dot{E}_{\mathrm{rev}}$ represents the term due to the thermoelastic source which is related to the volume variations of the material induced by the imposed load, while $\dot{E}_{\mathrm{irrev}}$ can be divided into the contribution from intrinsic dissipations ($\dot{E}_{\mathrm{d}}$) and stored energy portion which is not converted into heat ($\dot{E}_{\mathrm{s}}$).

Focusing on the thermoelastic component, the energy can be determined with the following formula:

$$\dot{E}_{\mathrm{rev}} = f\ E_{\mathrm{rev}} \tag{5}$$

where f is the mechanical frequency of the tests. Instantaneous value of energy is:

$$E_{\mathrm{rev}}(t) = \rho c_p T_{\mathrm{the}} \sin(\omega t + \varphi) \tag{6}$$

where T_{the} is the amplitude of the thermoelastic signal and φ is the phase between the temperature and the reference load [9, 10] while ρ and c_p are, respectively, the density and the specific heat at constant pressure and ω is the pulsation which depends on the mechanical frequency. As presented in several papers [10–12], the monitoring of the thermoelastic signal can be correlated to the stiffness degradation of the material and can be used as a parameter to study the damage induced by fatigue processes and to estimate the failure cycles of the material. However, the thermoelastic signal is also influenced by the damage processes linked to the material stiffness loss (reduction of the normalized longitudinal elastic modulus) [9].

Considering that damage in composite materials begins once the load is applied so from the very first cycles and continues throughout the life of the material [25, 26], it is clear that a signal will be generated immediately, regardless of the type of load. This consideration is especially valid for the outer layers that are those monitored by the infrared camera detector.

For highly imposed stress values, the increase in the load leads to an increase in the thermoelastic signal as well. In this case, the effect of stress is more important than the reduction of stiffness. This is certainly true if the material presents a plateau in the stiffness degradation curve [12] as reported in [22]. Naturally, under these conditions, a dissipative thermal component is added to the thermoelastic signal in the first amplitude harmonic component [22]. Therefore, the amplitude of the first harmonic of the thermal signal, therefore, includes both effects related to the thermoelastic effect (also induced by dissipative processes) and effects deriving from irreversible processes. Moreover, since during a rapid fatigue test, the thermal signal does not depend only on cycles but also on the applied stress; under these conditions, the term representing the first harmonic component can be expressed as a function of the following sub-components:

$$T_1 = f\left(T^r_{\frac{E}{E0}}, T^r_\sigma, T_{1d}\right) \tag{7}$$

where $T^r_{\frac{E}{E0}}$ refers to the thermoelastic signal induced by the elastic properties loss, T^r_σ is the thermoelastic component linked to the increase in stress and T_{1d} is linked to fatigue dissipative processes.

Due to the variety of fatigue mechanisms that occur in the material and their random appearance affecting certain regions locally, one advantage of using thermal signal analysis is to locally 'inspect' the material for an effective and efficient monitoring of the damage.

Materials, Methods and Data Processing

The samples were made of carbon fibre-reinforced epoxy type resin and exhibited a nearly isotropic lamination sequence. Samples were made by the automated fibre placement (AFP) process. They were extracted from a 560 × 695 × 2.93 mm^3 plate composed by 16 layers. The rectangular cross-section specimens have the following dimensions: 250 × 25 × 2.93 mm^3 [22, 27]. The test campaign included static tensile tests, constant amplitude tests to construct the S/N curve and rapid fatigue tests (stepwise tests involving incremental loading blocks until material failure). The tests were performed on an INSTRON 8850 servo-hydraulic loading machine with a capacity of 250 kN.

The tensile tests, performed on five specimens (traverse speed of 1 mm/min), allowed the evaluation of the mechanical properties of the material: UTS 825 [MPa] (standard deviation 85 Mpa) and longitudinal Young's modulus 66 GPa (standard deviation 0.3 GPa). Constant amplitude fatigue tests (runout set at 2 * 10^6 cycles) were performed at $R = 0.1$ and load frequency of 7 Hz. The detail of the CA tests is reported in the reference work [12].

The rapid fatigue tests were performed on three specimens under load control according to the procedure indicated in [10] at the same load ratio and mechanical frequency of the CA tests. The imposed loads ranged from 30%UTS to 85%UTS with a variable increment between one loading block and another.

During each loading block (whose duration was 10,000 cycles), three thermal sequences were acquired for each load block, i.e. in the first load block, thermal acquisitions were carried out at 3000/6000/9000 cycles. Thermal sequences were acquired by a FLIR X6540 SC cooled In-Sb sensor camera (640 × 512 pixel matrix array, NETD thermal sensitivity <30 mK) positioned in front of the loading machine (Fig. 1). The camera was set up to acquire sequences at 177 Hz. The test setup was set to obtain a spatial resolution of 0.35 mm/pixel. The equipment also included an extensometer with a measuring base of 25 mm for measuring the small deformations. The extensometer was connected to the data acquisition system integrated in the loading machine, with data acquired at a frequency of 100 Hz. The thermal signal acquisitions were simultaneous with those performed by the data acquisition system integrated in the loading machine.

In order to obtain the mechanical data (in terms of Young's modulus loss), the procedure for analysing data from the extensometer was similar to the one presented in [12]. Young's modulus was calculated as the average of the load/unload phase of a hysteresis cycle. Finally, that value, as described in [12], was referred to the first value of the data set for each stress level. The procedure for evaluating Young's modulus was identical for data obtained from classical fatigue tests (CA) and from tests at incremental loads (SW).

As for thermal signal, it was analysed using IRTA software that it is based on thermal signal reconstruction via least square method [10, 16]. The reference thermal model is:

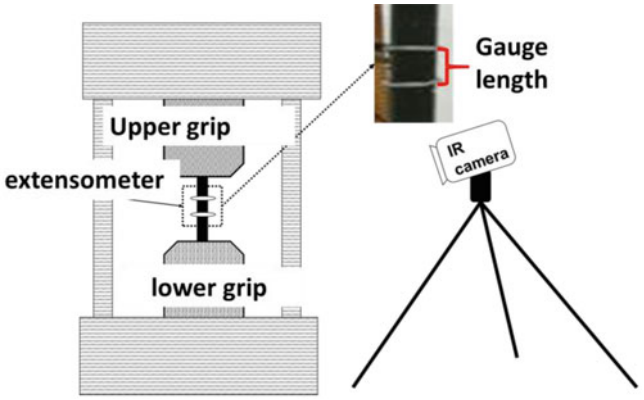
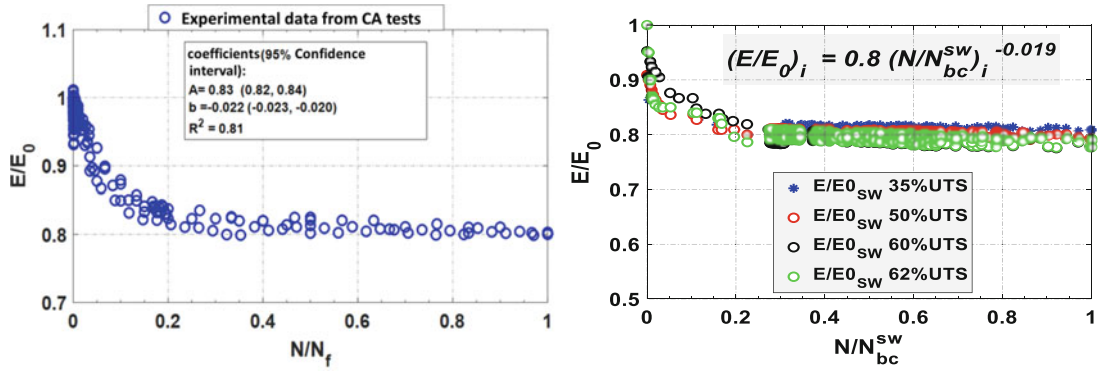


Fig. 1 Schematic of the setup and equipment



(a) (b)

Fig. 2 (**a**) $\left(\frac{E}{E_0}\right)_{i,\mathrm{CA}}$ and (**b**) $\left(\frac{E}{E_0}\right)_{i,\mathrm{SW}}$ curves versus cycle fractions [22]

$$T(t) = T_0 + at + T_1 \sin(\omega t + \varphi) + T_2 \sin(\omega t + \varphi_2) \tag{8}$$

where $T_0 + at$ represents the linear part of the model that influences the mean temperature increase while T_1 and T_2 are, respectively, the first and second amplitude harmonics (FAH, SAH) of thermal signal. The present work is focused only on FAH. The FAH acquired three times per loading block is under the form of 2D matrix of pixel, where each pixel represents at a specific location the value of the first harmonic component. All the maps were addressed to a spatial smoothing to reduce the noise in the measurement of FAH.

As reported in the work of Emery [9], and as found in different researches [12, 22], the minimum value in a map of FAH (usually referred to the gage length of the specimen) is directly related to stiffness loss. So, in the present research, the minimum values of T_1 were extracted from each map and normalized by the first value of the T_1 data series through the loading blocks. This ratio is represented by the parameter ζ_i [22].

Analysis

In this paragraph, the results in terms of mechanical and thermal data are reported. In Fig. 2a, it is possible to observe the evolution of the longitudinal Young's modulus E normalized by the reference value E_0. The data of all the tests were represented as a function of the fraction of life $\left(N/N_{\mathrm{f}}^{\mathrm{CA}}\right)$. As can be seen, a single power law (Eq. 2) can represent all the data. The model fitting coefficients of the data (A, b) are reported in the same figure together with the 95% confidence interval.

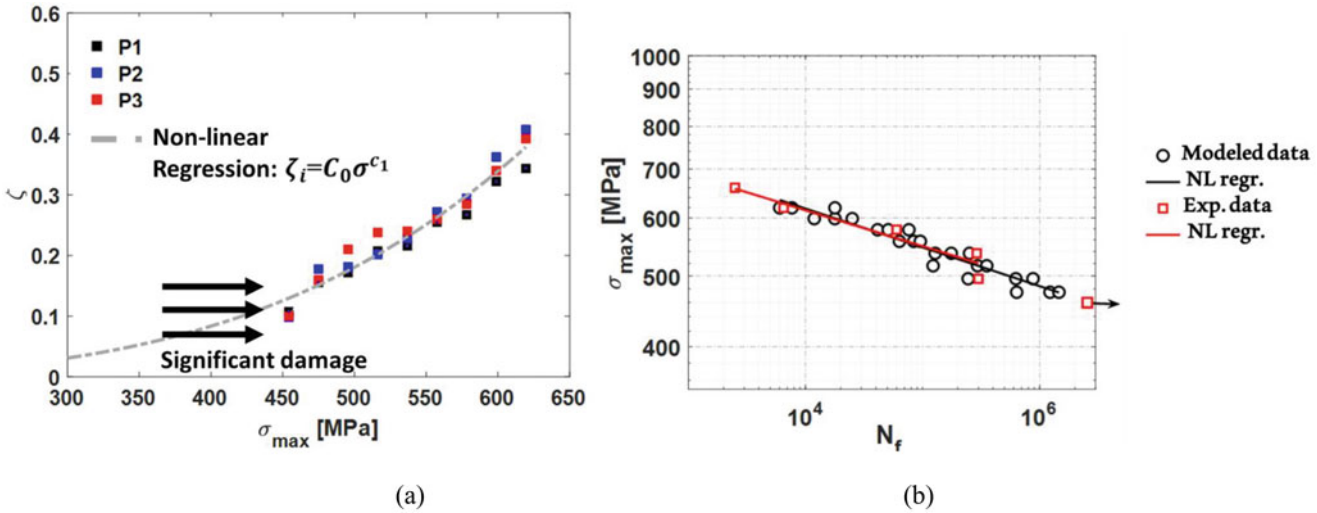


Fig. 3 (**a**) Non-linear regression model of ζ_i data depending on the stress. (**b**) S/N curve obtained by model, compared to experimental data (double logarithmic axes)

Figure 2b instead represents the same quantities (E/E_0) relating to single load blocks of the test at incremental loads. The data in this case have been represented as a function of the fraction of life spent at a given load block ($N_{bc}^{SW} = 10^4$ cycles). As can be seen from Fig. 2b, the curves of the stiffness reduction for tested specimens at different stress levels show a similar trend which can be represented by a power law with the same fitting parameters of Eq.(2) and represented in Fig. 2a.

Referring to thermal data, it is possible to approximate the relationship between the thermal parameter based by FAH of thermal signal (ζ_i) and the stress (Fig. 3) with a power function whose coefficients and relative 95% confidence intervals are $C_0 = 8.439\text{e}^{-11}$ (-1.189e^{-10}, 2.877e^{-10}) and $c_1 = 3.457$ (3.077, 3.837). The coefficient of determination R^2 is 0.94. In Fig. 3a, the thermal considered data are related to higher stress levels where the damage is significant.

Since the relationship between $E/E_0 - \sigma$ is of the same type of the one that approximates $\zeta_i - \sigma$, one can assume that the relationship between $E/E_0 - \zeta_i$ is the same for all the tested samples, so it can be represented by the following model:

$$\left(\frac{E}{E_0}\right)_{i,\text{SW}} = C_4(\zeta_i)^{c_5} \tag{9}$$

where C_4, c_5 are the constants depending on material.

Considering the validity of (3), as confirmed by Fig. 2a, b, using Eq. (9) to obtain the $\left(\frac{E}{E_0}\right)_{i,\text{SW}}$, accounting for Eq. (2), it is easy to obtain the cycles to failure of a CA test from the following formula:

$$N_f^{\text{CA}} = N / \left(\left(\frac{c_4}{A}\zeta_i{}^{c_5}\right)^{1/b}\right) \tag{10}$$

The comparison between the experimental data (red square markers) and data modeled with the presented procedure (black circular markers) is shown in Fig. 3b. In the Figure are also reported the data regression 'lines' and coefficients of the fitting. As can be seen from Fig. 3b, the adopted model approximates well the data deriving from calibration with a thermal parameter. In particular, the coefficients are almost the same, and furthermore the acquisition of thermal features from rapid tests allows for much more data to be available compared to a classic test, and this is advantageous both for the consistency of the results and for the definition of the S/N curve with more points.

Conclusion

In the present research, a new rapid procedure to evaluate the failure cycles of a quasi-isotropic CFRP was presented, based on FAH data and stiffness loss (longitudinal modulus) measurements. In particular, the thermal parameter used was the amplitude of the first harmonic of the thermal signal normalized with respect to the value of the first load block (ζ).

Finally, in this research:

- A new procedure has been presented to derive the S/N curve quickly.
- A damage parameter has been proposed which reflects the decay of the elastic properties of the material regardless of the type of test (classical or rapid test).
- Thanks to the calibration between thermal and mechanical data, it would also be possible to obtain maps of the 'stiffness degradation' of the material, which shows the decay of the material locally.

The disadvantage is that the procedure is currently valid for specimens and tests performed under laboratory conditions. As further development, the proposed procedure will be applied on a component during operating conditions in order to carry out structural health monitoring.

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