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Rapid Determination of the High Cycle Fatigue Limit Curve of Carbon Fiber Epoxy Matrix Composite Laminates by Thermography Methodology: Tests and Finite Element Simulations

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Abstract

Self-heating measurements under cyclic loading allow a fast estimation of fatigue properties of composite materials. The tensile fatigue behavior of a high stress carbon fiber epoxy-matrix composite laminates is examined at room temperature. Tension-tension cyclic fatigue tests are also conducted under load control at a sinusoidal frequency of 5 Hz to obtain high-cycle fatigue stress curves (S-N). The fatigue limits of the different composite lay-ups tested were successfully compared with data resulting from the self-heating test method on the same laminates. This comparison reveals a good agreement between the two methods dedicated to stress fatigue limit determination. In addition, a tomographic analysis is used to perform comparisons at the microscale between both fatigue methods. The nonlinear heat transfer laminate theory is used for self-heating tests simulation. Self-heating simulations involving conduction, convection, and boundary radiation are performed with the Finite Element code Cast3M.

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Keywords: fatigue; self-heating; damage; thermomechanical behavior

1. Rapid determination of fatigue limit with self-heating tests

High cycle fatigue is a major criterion for the design of aeronautic or marine laminate composite structures. Rapid estimation methods of stress fatigue limits have recently been derived for several kinds of materials [1-5]. Thermal

effects associated with dissipation during cyclic loading are the key point of the so-called “self-heating tests” method. Results of this method show good agreement with those revealed by classical fatigue tests (Wöhler curves) for some metallic materials and rubber materials [3-4]. This “heating tests method” consists in applying successive sets of a given number of cycles for increasing stress levels. For each stress level, the temperature variation is recorded and the steady-state temperature is determined. Beyond a given limit, it is observed that the steady state temperature starts to increase significantly [3]. This change is correlated with the state where the fatigue limit is exceeded and can be related to the apparition of dissipation phenomena which occur with micro cracks sliding or viscous effects in the material and govern the fatigue properties [5-6]. In this work, the heating test method is applied in order to determine the fatigue property of a unidirectional high-stress carbon-fiber epoxy-matrix material. A correlation between the mean fatigue limit for composite laminates and the heat build-up is presented. Moreover, a damage model derived at the meso scale has been proposed to reproduce the heat build-up of the mechanical dissipation of self-heating tests. The composite laminate is classically described at the meso-level as a stacking sequence of homogeneous layers throughout the thickness and inter-laminar interfaces. Damage mechanisms of the composite structure are taken into account by means of internal damage variables [7-8]. Indeed, by using these models, it is possible to predict the Wöhler curve of the laminate structure [8-9]. A canonical base of four mechanical tests associated to finite elements simulations is used to determine all the fatigue mechanical properties of the elementary ply for the plane stress assumption.

2. Material and experimental procedures

Quasi-static, fatigue and self-heating tests have been conducted on carbon-fiber epoxy-matrix symmetric laminated specimens of dimensions 250 by 20 millimeters. The geometry is defined in ASTM D3039 or ISO 527 standards. Four stacking sequences have been tested: $[\pm 67.5]_s$, $[\pm 45]_s$, $[0/90/0/90]_s$, $[-45/45/90/0]_s$. Off-axis tests allow to determine in-plane shear properties. Tests on quasi-isotropic laminates are usually conducted with the aim of validating the meso-scale model. The number of plies is always 8 for all tested laminates. All lay-ups were manufactured by the oven forming technique. The prepregs were laid up by hand in a mold and then put into a vacuum bag for curing at 120°C. Specimens have been equipped with biaxial gages of 3 millimeters grid length (HBM XY91-3/350) at the specimen center. All the tests were carried out on a MTS 880-100kN servo-hydraulic machine at room temperature (RT, ~20°C). Temperature changes due to micro damages have been measured with a CEDIP infrared camera. To evaluate the temperature evolution on the specimen surface due to internal degradation phenomena and viscous effects, the temperature of a reference specimen was subtracted from that of tested specimen. The reference specimen was of same stratification. This method allows us to remove temperature fluctuations due to environmental conditions.

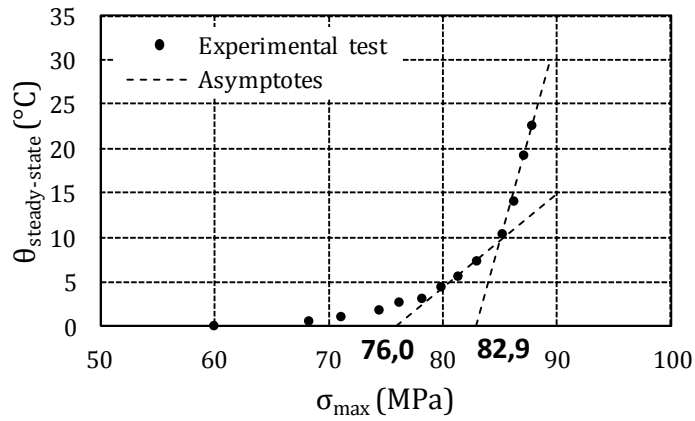
Fatigue tests were performed under tension-tension (T-T) cyclic loadings of constant stress amplitude. The loading frequency was 5 Hz in order to avoid any temperature influence on mechanical and failure properties. Fatigue tests were stopped if one of the following conditions occurred: the specimen broke out or the specimen was unbroken after 3 million cycles. Stress unloading stages have been planned during all fatigue tests to measure the stiffness decrease of specimens due to damage mechanisms.

The self-heating tests were performed under tension-tension cyclic loading with constant mean stress. Each loading block is made up of a first loading stage until reaching the mean stress, a cyclic loading stage of 3000 cycles at constant stress amplitude and a return stage to zero stress state. The first and third stages were displacement-controlled and the second stage was force-controlled. Each loading block contains 3000 cycles (number of cycles needed for stabilizing the temperature). After each loading condition, the stress has been entirely relaxed for 5 minutes to yield the thermal equilibrium again. The temperature on the specimen surface was measured with an infrared camera.

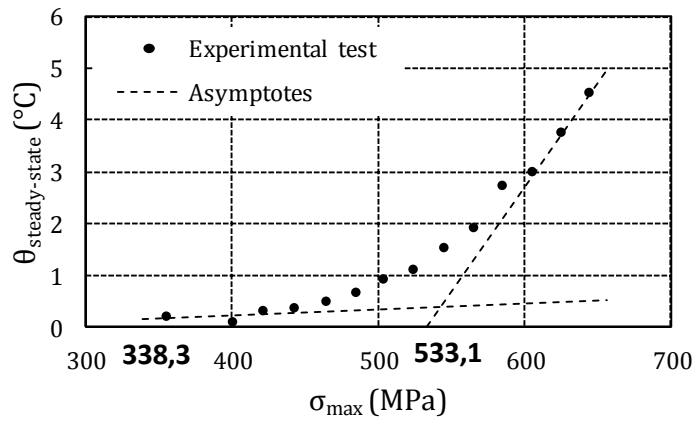
3. S-N fatigue relation-ships and comparison with results from self-heating tests

For several years, different research departments have been working on self-heating measurements for several kinds of materials [1-5]. The self-heating experimental method is based on the monitoring of the specimen's rising temperature under cyclic loadings. Successive series of stress loading with a given number of cycles (3000) at a given load ratio are applied to the composite specimen. We can consider that 3000 cycles is necessary to reach the temperature stabilization of the sample for a given stress level. Macroscopically, the multi-step stress level remains of the order of magnitude of the fatigue yield stress. From a micro scale point of view, micro-cracks appear in the microstructure after reaching the fatigue limit.

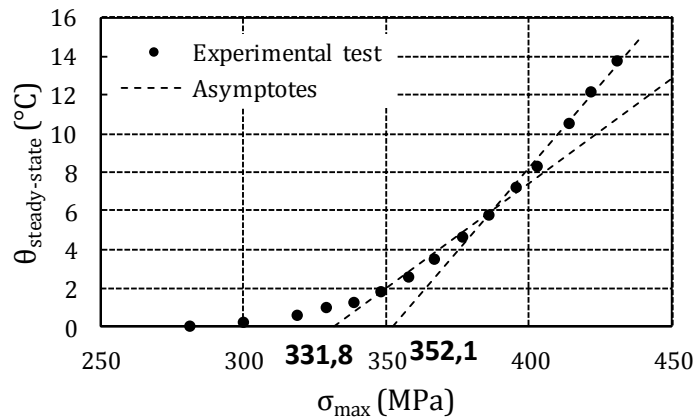
At a microscopic scale, micro-cracks, fiber/matrix debonding in plies lead to temperature variations. At each stress loading level, the steady state temperature elevation can be measured and a self-heating curve, relating the temperature elevation to the maximum stress level, can be plotted (Figure 1). To obtain this type of curve, only two hours are required for a carbon-epoxy laminate standard specimen test. With a deterministic approach, the mean endurance limit of the material can be determined considering the intersection between the abscissa axis and the asymptote of the self-heating curve (Figure 1). Figure 1 presents the experimental self-heating curves obtained for the $[+45/-45/+45/-45]_S$, $[0/90/0/90]_S$ and $[+45/-45/90/0]_S$ laminates and a proposal of empirical analysis for the mean stress loadings. The temperature rising is higher for $[+45/-45/+45/-45]_S$ than for the $[0/90/0/90]_S$ laminate. For angle plies laminates there is a visco-plastic effect combined with damage variations and for cross plies laminates visco-plastic effect are negligible. Figure 2 shows the limit of fatigue for the $[+45/-45/90/0]_S$ laminate specimen is correctly determined by the proposed self-heating method. Tomography analysis is used to verify the microcrack density in specimens for the fatigue limit and corresponding self-heating level. It must be highlighted that the state of micro cracks in the laminate stacking sequence for both classical fatigue test and corresponding self-heating level are equivalent. Figure 3 shows the cracks density of cross sections for $[+45/-45/+45/-45]_S$ specimen obtained by the self-heating method (figure 3 a) and the corresponding fatigue test. Crack density for both tests at a corresponding stress level is equivalent.



(a)



(b)



(c)

Fig 1. Experimental self-heating curves for carbon fiber epoxy matrix laminates. (a) $[+45/-45/+45/-45]_s$ loading $\overline{\sigma_{xx}} = 50$ MPa, (b) $[0/90/0/90]_s$ loading $\overline{\sigma_{xx}} = 335$ MPa, (c) $[+45/-45/90/0]_s$ loading $\overline{\sigma_{xx}} = 250$ MPa.

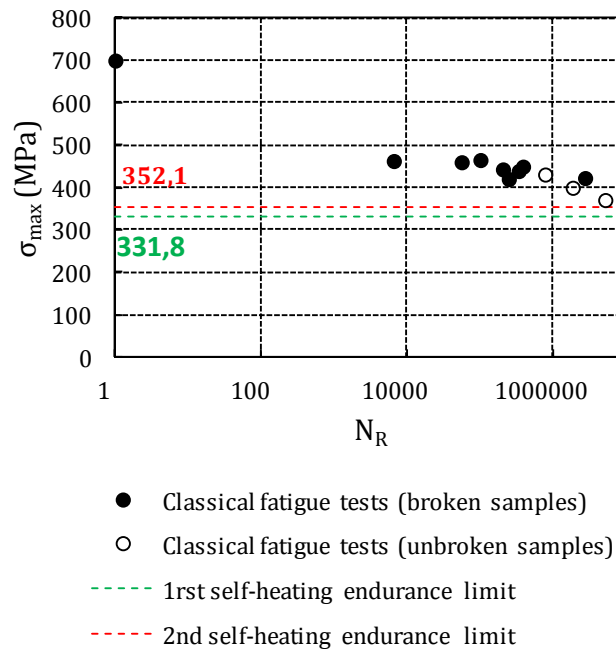


Fig 2. Experimental Wöhler curve and self-heating fatigue limit for $[+45/-45/90/0]_S$ under the average fatigue stress $\bar{\sigma}_{xx} = 250$ MPa

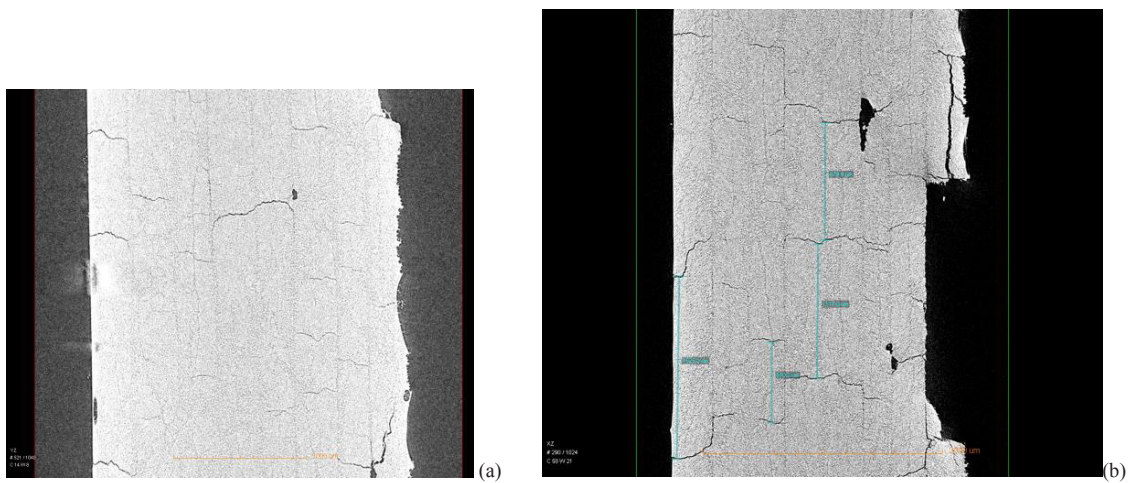


Fig 3. (a) Tomography analysis of the crack distribution in a cross section of a $[+45/-45/+45/-45]_S$ specimen for the last point of measure of the self-heating test (stress is greater than the limit of fatigue). (b) Corresponding state of stress for the classical fatigue test ($\sigma_{max}=82$ MPa).

4. Finite Element heat transfer predictions of self-heating tests

A finite element methodology is developed to precisely analyze the sources of dissipation occurring in a self-heating test of a laminated stacking sequence. The Finite Element code Cast3M (CEA) is used for heat transfer analysis. Heat transfer boundary conditions are constant and uniform temperatures imposed on the lines corresponding to the grips. For each Finite Element simulation, the temperature corresponding to the hydraulic grip is higher than the other one. Convection and radiation boundary conditions are also applied on the upper and lower faces of the composite laminate (figure 4). The steady state rising temperature due to damage mechanisms and visco-plastic effects is obtained by the introduction of the experimental dissipated energy in the finite element model (figure 5). Equations 1 and 2 correspond to the continuum heat transfer equations. Steady state heat transfer equations are presented in equation 3. From an experimental point of view, the dissipated energy Δ is obtained cycle by cycle during the self-heating test. For each level of stress loading the corresponding heat transfer finite element prediction is conducted in order to obtain the temperature field. From an experimental point of view, the dissipated energy is measured and split in four main contributions: the viscoelastic part, the damage part, the irreversible strain part and the stored part. Dissipated energy is composed by the measured of areas of the hysteresis loops, irreversible strain and damage variation (variation of the slope of the hysteresis loop). By using the theoretical thermodynamic framework and according to Clausius-Duhem inequality, dissipation modeling is the product of flux variables $\dot{V}_K$ (damage, inelastic strain...) with associated thermodynamic forces A_K . Generally speaking, the heat transfer mechanisms are convection and radiation, on the surfaces of the laminate and dissipated energy and conduction inside elementary plies. Heat conduction coefficients (eq. 2, $\bar{\lambda}_L$) and the specific heat capacity for the elementary ply were experimentally identified at the LTN Laboratory. Figure 5 shows the temperature prediction of the experimental self-heating test for the $[\pm 45/90/0]_S$ composite laminated specimen. It corresponds to the temperature responses of the steady state finite element simulations corresponding to each 3000 loading block boundary conditions. For each block of 3000 cycles there is a steady state of dissipation Δ_B leading to the corresponding stationary temperature T . In order to obtain the experimental self-heating curve, the Finite Element temperature prediction is adjusted by a unique factor ξ on the global dissipation $\xi \Delta_B$. This factor is a constant value for successive loading block, for a given type of laminate. Values obtained for tests conducted in this study fall in the range $[1.5 - 2]$. This factor indicates that there are energy mechanisms which are not identified. These aspects are still under consideration. It must be highlighted that from a damage model point of view [8, 9], it is possible to obtain a similar stress strain curve response with two behaviour models with only a difference on the dissipated energy.

$$\Delta = \sum_k -A_K \dot{V}_K \quad (1)$$

$$\rho c \dot{T} = \text{div}(\vec{q}) + \sum_k -A_K \dot{V}_K \quad \text{with} \quad \vec{q} = -\bar{\lambda}_L \overrightarrow{\text{grad}}(T) \quad (2)$$

$$\text{div}\left(-\bar{\lambda}_L \overrightarrow{\text{grad}}(T)\right) + \Delta_B = 0 \quad (3)$$

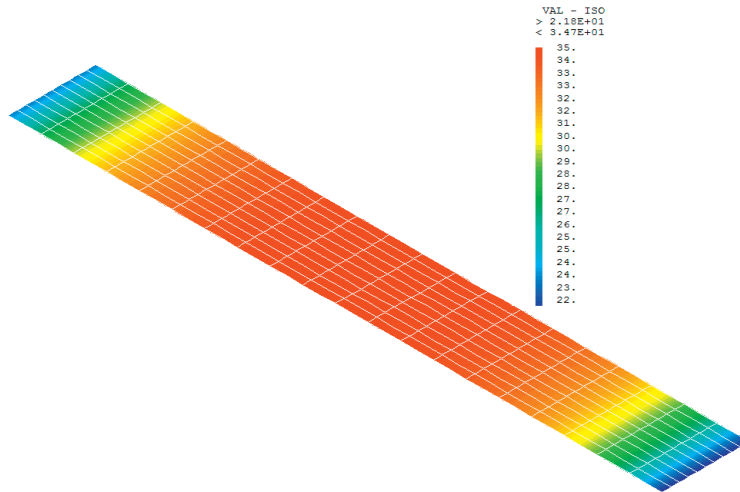


Fig 4. $[\pm 45/90/0]_s$ laminated plate. Skin's temperature (35°C). Initial temperature T_i is 23°C

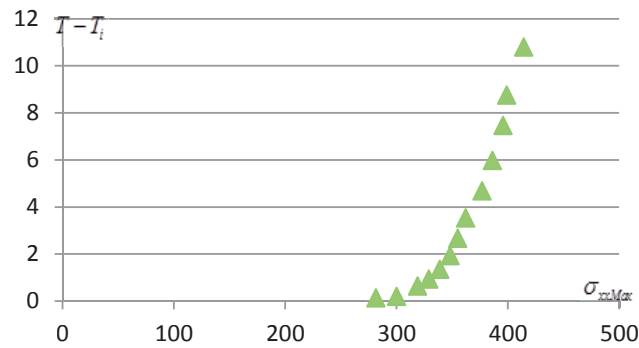


Fig. 5 Steady-state predictions of the self-heating curves of the $[\pm 45/90/0]_s$ laminate . Temperature variation $T - T_i$ as functions of the maximum apparent stress amplitude σ_{xxMax} .

5. Conclusions

This paper deals with the fast determination of fatigue limit of carbon fiber epoxy matrix laminated composites under cyclic loadings by self-heating measurements. Traditional fatigue test campaigns are time consuming and require a large number of specimens for the determination of the fatigue properties. Self-heating measurements represent a good alternative. Only two hours are necessary to obtain a self-heating curve of carbon/epoxy laminated composites. The fatigue limit resulting from self-heating tests and estimated limit based on classical Wöhler curves were found to be in good agreement for the carbon/epoxy laminates of $[\pm 45]_s$, $[45/90/-45/0]_s$ and $[0/90/0/90]_s$ stacking sequences. New experiments and simulations are currently in progress to compare both methods at other stress levels and for other stratifications. The ultimate goal is to introduce a non-isothermal damageable nonlinear model at the ply level in order to simulate the complete thermomechanical self-heating tests. Nevertheless the proposed self-heating test method combined with tomography and finite element simulations confirms that the fatigue limit of composite materials could be measured in few hours without classical fatigue test campaigns.

Acknowledgement : Multiplast Composite Yachts, www.multiplast.eu

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