RAPID DETERMINATION OF THE FATIGUE PROPERTIES OF CARBON FIBER EPOXY MATRIX COMPOSITE LAMINATES BY SELF-HEATING TESTS

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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 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.*

1. Introduction

High cycle fatigue is a major criterion for the design of aeronautic or marine laminate composite structures. The standard determination method of fatigue properties requires about 100 specimens, for unidirectional, angle ply, cross ply and quasi isotropic laminates and fourth month of tests at a load frequency of 5 Hz for a given load ratio. This method, considered to be the reference, is time and specimen consuming. 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. Laminates 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 standard. Four stacking sequences have been tested: [±67.5]s, [±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. 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

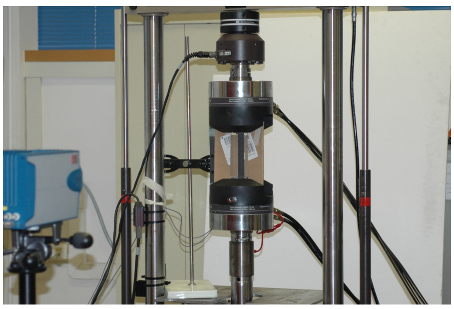

Figure 1. Laminate in grips of a universal test machine and CEDIP infrared camera.

3. Self-heating tests and finite element simulations

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 in loading block is necessary to reach the temperature stabilization of the sample for a given stress level (figure 2). 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 3). 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 3). Figure 3 presents the experimental self-heating curves obtained for the $[+45/-45/+45/-45]_S$ laminate and a proposal of empirical analysis for the mean stress loadings. Limit of fatigue is 69 MPa in global axis (σ_{12} = 34.5MPa). The self-heating curve is also obtained by heat transfer finite elements analysis with Cast3M (CEA). For this laminate, equation of transient heat transfer in a ply has the following form:

$$\rho C\,\dot{T} = div\left(-\bar{\bar{\lambda}}\,\overrightarrow{grad}\left(T\right)\right) + Y_{12}\dot{d}_{12} + 2\sigma_{12}\dot{\varepsilon}^{p}_{12} - R\left(\varepsilon^{p}{}_{12}\right)\dot{\varepsilon}^{p}_{12} + H\dot{h} \quad \text{in a ply} \tag{1}$$

Material density, heat capacity and Fourier’s law are experimentally identified for the carbon-epoxy under consideration. The inner heat-generation rate per unit volume is the experimental mechanical dissipation of the ply modelling [7]. It’s a sum of the products of forces variables or dual variables with the respective flux variables. The experimental heat-generation rate of the hysteresis loop is ($H\dot{h}$). Boundary conditions are temperature of grips (figure 1) and convection and radiation on the laminate surface. For angle plies laminates there is a visco-plastic effect combined with damage variations and for cross plies laminates visco-plastic effect are negligible. The limit of fatigue for laminate specimen is correctly determined by the proposed self-heating method (figure 5). 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 staking sequence for both classical fatigue test and corresponding self-heating level are equivalent.

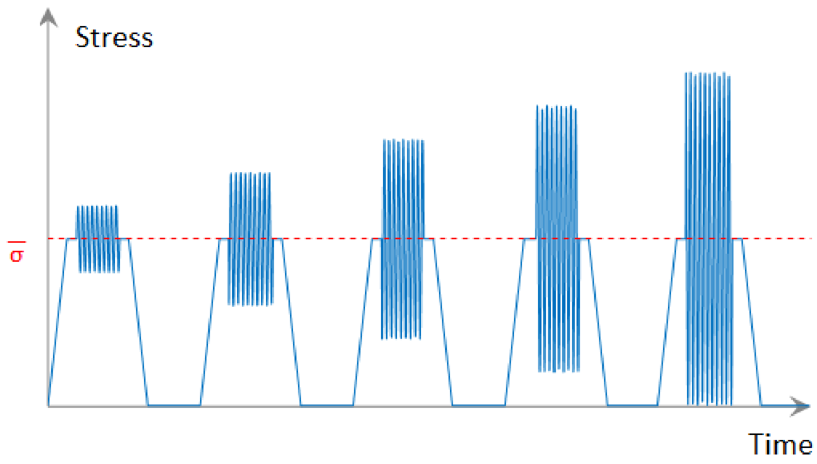

Figure 2. Self-heating loading blocs. 3000 cycles in a loading block

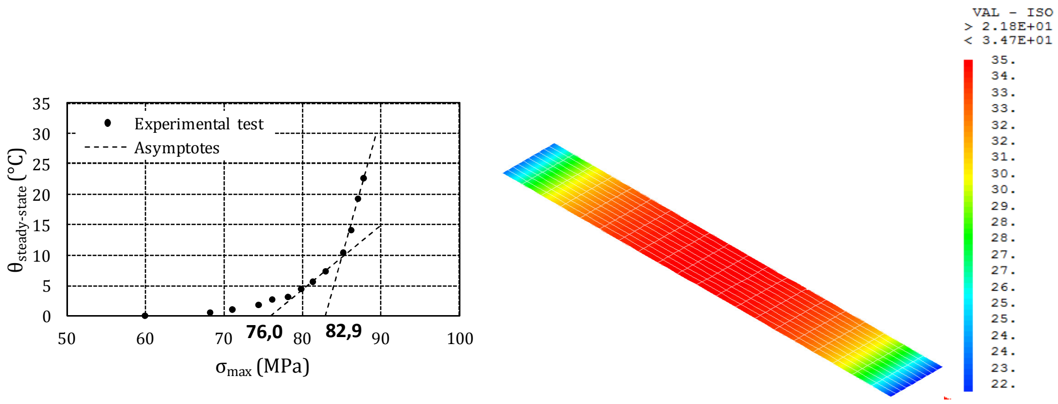

Figure 3. Limit of fatigue is 69 MPa in global axis. Experimental self-heating curves and FE prediction for carbon fiber epoxy matrix laminates $[+45/-45/+45/-45]_S$ loading $\overline{\sigma_{xx}} = 50\ MPa$, Maximum laminate skin's temperature (50°C) during self-heating tests

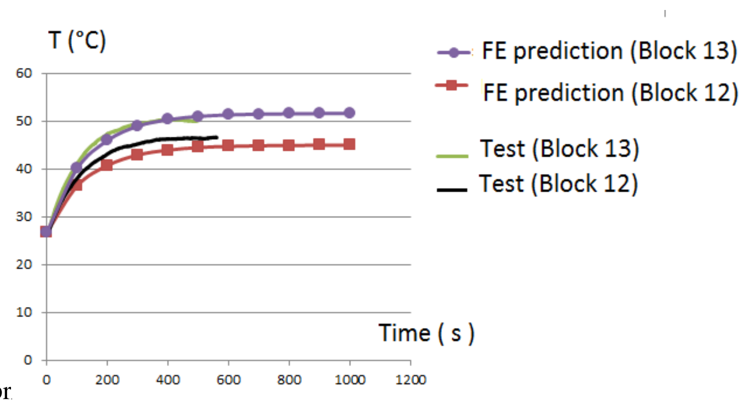

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Figure 4. Experimental and Finite Element transient thermal modelling for self-heating tests

$[+45/-45/+45/-45]_S$ loading $\overline{\sigma_{xx}} = 50\ MPa$, Maximum laminate skin's temperature (50°C)

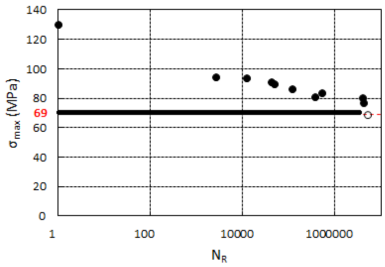

Figure 5. $[+45/-45/+45/-45]_S$ experimental Wöhler curve for ($\overline{\sigma_{xx}} = 50\ MPa$) and limit of fatigue from self-heating tests

4. 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 to take into account these influences. Only 2 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 [±45]s, [45/90/-45/0]s and [0/90/0/90]s stacking sequences.

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