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Mechanical damage assessment of Glass Fiber-Reinforced Polymer composites using passive infrared thermography

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ABSTRACT

This study deals with characterization of the damage and thermomechanical behavior of the Glass Fiber-Reinforced Polymer composite materials (GFRP), submitted to static tensile loadings, using a passive infrared thermography technique. During mechanical testing, thermal measurements are performed by means of an IR camera. The thermal data post-processing involves the analysis of both the thermal maps and the thermomechanical behavior of the material. The thermal maps analysis allows qualitative evaluation of the created material damage at high stress levels. While the thermomechanical analysis gave us a quantitative evaluation of the material damage, for both low and high stress levels, through definition of a new thermoelastic damage variable.

1. Introduction

GFRP composite laminate materials are largely used for structural applications, such as automobile, railway, and wind energy. thanks to their high strength-to-weight ratios, hence, an increasing need of studying their mechanical behavior in case of damage. Indeed, damage of composite materials is a very complex phenomenon due to their structural heterogeneity and anisotropy added to the inevitable internal defects originated from manufacturing process [1], such as porosity, and misalignment of fibers.

Under mechanical loadings (depending on type and direction of the applied load), these materials show different failure mechanisms, whose two or more can be occurred simultaneously: (i) matrix cracking, (ii) interfacial debonding, (iii) delamination, (iv) fiber rupture, (v) buckling (in compression). The unpredictable evolution of these mechanisms with applied loading, changing material states, and interactions with the overall structural design, create the need for the non destructive testing (NDT) methods for detection of damage initiation, as well as subsequent tracking of its evolution and accumulation [2].

Generally, two investigation steps are conducted on the composite components, the first one concerns the initial state integrity evaluation of structures [3] and the second one concerns permanent [4] or periodical [5] in-service structural health monitoring. Significant research works have been conducted in the last years in the composite-NDT field in order to develop new techniques or to increase efficiency of the conventional ones so as to improve the investigation quality in terms of accuracy and quickness. They include the use of acoustic-based techniques [6–10] or electrical potential/resistance approaches [11,12]. In addition to NDT, other methods have been used for monitoring the degradation of properties and the bulk mechanical behavior of composites using standard metrological devices, such as extensometers and strain gages [13–17] or non contact optical methods [18–23]. Although such efforts have had some success in characterizing the mechanical and damage behavior of composite materials, a non intrusive approach which could effectively and reliably detect and quantify, in situ conditions, both damage initiation and subsequent damage evolution is needed.

The InfraRed Thermography (IRT) can fulfill this need; it is a non contact technique and can be used easily in service conditions [24]. It allows a quick real-time imaging (traceability) inspection and can examine a relatively large area of a structure [25,26]. Most research works based in IRT techniques have been applied on composite materials for surface defect detection [27,28] and for damage or stress analyses under dynamic loading conditions (fatigue tests) [29–37]. However, very few works have it applied to static loading tests because the composite materials are not highly dissipative (low temperature variation) in these conditions [2,29,38,39]. This is the reason why the conventional heat data processing methods, based only on the heat images analysis, do not allow a reliable characterization of the material damage, especially for low applied loadings where the temperature variation is very

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small. Therefore, new pertinent descriptors of mechanical damage during static loading are needed; this is the goal of our paper.

This paper addresses the experimental procedure followed to analyze, by means of passive IRT technique, the mechanical damage created in GFRP materials submitted to uniaxial tensile test with a step-wise loading profile. The analyses is based on a thermo-mechanical approach, which allowed identification of the thermoelastic coefficient variation as an indicator of damage valid both in low and high applied stress levels.

2. Theoretical background

Under mechanical loading, assumed not affecting the material microstructure, and basing on the first and second principles of thermodynamics, the heat equation can be written as

$$\rho C\dot{T} - k\nabla^2 T = r + S_{the} + d \tag{1}$$

where ρ is the material density, C is the specific heat (at constant pressure) and k is the thermal conductivity (which is assumed to be isotropic). The second term represents macroscopic heat sources, which are cumulated in the terms of external source supply "r", the thermoelastic source "S_{the}" and the intrinsic dissipation source "d". Some hypotheses are assumed to simplify Eq. (1): (i) the mass density and specific heat are material constant, (ii) due to low temperature gradients and displacement velocities, the convective terms associated with the particular time derivative of the temperature field are neglected [40], (iii) the external sources are time independent and give the equilibrium temperature of the specimen (T_0). Thus, the simplified heat diffusion equation is:

$$\rho C\Delta T - k\nabla^2 \Delta T = S_{the} + d \tag{2}$$

where $\Delta T = T - T_0$ is the instantaneous temperature variation (commonly known as "contrast"). It could be considered that the rate of temperature change (ΔT) is much important than the Laplacian term ($\nabla^2 \Delta T$). That condition is usually expressed when the temperature variations are low (static loading + absence of external heat source) to assure that the equation can be written as:

$$\rho C\Delta T = S_{the} + d \tag{3}$$

For low level of stress, the dissipated energy is negligible compared to the thermo-elastic production of heat. So Eq. (3) is simplified to:

$$\rho C\Delta T = S_{the} \tag{4}$$

For linear isotropic material, under plane stresses, the thermo-elastic energy can be written as:

$$S_{the} = -\alpha T_0 \Delta\sigma \tag{5}$$

where α is the linear expansion coefficient and $\Delta\sigma$ is the variation of the sum of principal stresses.

Finally, Eqs. (4) and (5) lead to the equation of thermo-elasticity described by Thomson [41]:

$$\rho C\Delta T = -\alpha T_0 \Delta\sigma \tag{6}$$

Eq. (6) is valid for linear isotropic, homogeneous material if adiabatic conditions prevail. The change of temperature is proportional to the variation of the sum of the principal stresses according to Eq. (7):

$$\Delta T = -\frac{\alpha}{\rho C} T_0 \Delta\sigma = -K_m T_0 \Delta\sigma \tag{7}$$

where K_m is the thermo-elastic coefficient.

For solid media submitted to mechanical loading, the thermo-elastic effect predicts, subject to adiabatic transfer, that their temperature decreases (respectively increases) proportionally to the applied load in the case of tensile (respectively compressive) loading. Typical values of K_m for epoxy and polyester resins are respectively 2.88×10^{-5} (MPa^{-1}) and 4.13×10^{-5} (MPa^{-1}) [42].

3. Experimental procedures

3.1. Material and mechanical loading

The tested material is a cross-ply GFRP laminates with lay-ups of [0°/90°]S. It was made from unidirectional sheets of E-type glass fibers pre-impregnated with uncured epoxy. Compression molding process of the GFRP plates was used in this study to obtain, as far as possible, planar plates with uniform thickness. Heels were added to the mechanical testing samples (integrated on both ends of the stack according to NF EN ISO 527-5) through twill tape 2/2, where the fibers are oriented at 45°. All specimens are cut from the same plate, in order to reduce the variability of the material properties, and five samples were tested for each tensile test. Dimensions of these tensile specimens are shown in Fig. 1 and detailed in Table 1.

Fig. 2 shows profile of the applied mechanical loading, which consists in a step-wise static tensile test of 50 MPa each time (6 levels and 7 ramps). The tensile test, controlled in displacement, is carried out at cross-head speed of 0.5 mm/min for the all ramps to achieve the desired stress level using an INSTRON electrical tensile machine with a capacity of 100 kN. The holding time at each stress level is fixed to four minutes, during which the last attained temperature remains approximately constant. The variation of the surface material temperature under loading is acquired from the beginning to the end of the tensile test using an IR camera.

3.2. Thermographic procedure

A CEDIP JADE III (MW) IR camera was used to measure the variation of the test specimen surface temperature. Its pixel resolution of 320(H) × 240(V) and temperature sensitivity of 0.01 °C were sufficient for accurately measurement. The IR camera was placed at a distance of 68 cm from specimen and the thermal scene was isolated using an obscuring insulator curtain to avoid external disturbance that can alter the temperature measurement (Fig. 3). The acquired thermographic movies can be represented by a 3D matrix composed by 240 rows, 320 columns and n elements in the third dimension (time), which corresponds to the number of images (Fig. 4). For a given image, $p(i, j) \in [0, N_g]$, where N_g is the maximum gray level, is the gray level of the pixel located at i (row) and j (column) whose values are integers.

4. Results and discussions

4.1. Evaluation of the thermoelastic part

Five monotonic tensile tests up to failure, monitored by the IR camera, were conducted on the material in order to evaluate its thermoelastic behavior. Also, it is possible to get additional information on damage evolution during the tests. Fig. 5 shows a typical result of these tests in terms of time temperature evolution associated to the applied tensile stress. An inversely proportional rela-

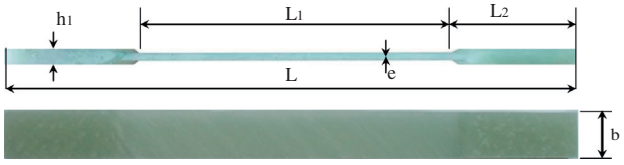

Fig. 1. Representation of GFRP tensile specimen.