Damage analysis of composites by means of thermography

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ABSTRACT. Composite materials are widely used for structural applications, thanks to their excellent mechanical properties combined with a low material density. It is difficult to perform a complete characterisation of these materials, due to the influence of several factors on their mechanical behaviour. Generally, the mechanical characteristics of composites are influenced by the manufacturing process parameters (i.e. curing time-temperature) and the experimental parameters (i.e. specimen shape, the use of tabs for testing, the test velocity, and the loading conditions). These materials show different failure mechanisms (i.e. interfacial debonding, delamination, fibre rupture, matrix cracking), which depend on the type and direction of the applied load. In this study, an E-glass/vinylester pultruded material is mechanically characterised by means of static tests, performed on specimens with different fibre orientations. Thermal analyses are also performed, by means of a Thermal imaging camera (FLIR Thermacam SC 3000), to determine the static damage parameters (i.e. Temperature). Thermal maps of the damaged area, evaluated from the experimental data, are used to get information related to the damage evolution and the failure mode. The aim of this work is the evaluation of composites damage under static loading conditions, by using the thermographic method.

KEYWORDS. Composites; Thermography; Damage parameters.

INTRODUCTION

Every body with a temperature higher than the absolute zero emits electromagnetic radiations in a spectrum which is in the infra-red (IR) region. These radiations depend on the surface temperature of the body; therefore, it is possible to measure the surface temperature of a material without any contact need, by detecting the emitted radiations. This is the base principle of the IR-thermography, a non destructive technique (NDT) for the evaluation, by image analysis, of the surface temperature of a body. This technique is used for non destructive inspections (NDI) on various types of materials and on large areas of engineering components [1].
Another field of application of the thermography is for the Thermoelastic Stress Analysis (TSA), a well established technique for the evaluation of stress in isotropic engineering components [2-5]. In TSA an IR-detector is used to measure the small reversible temperature change associated with the thermoelastic effect from a component subjected to cyclic load. For an isotropic material this temperature change is related to the change in the sum of the principal stresses on the surface of the material [7-8] as follows:

$$\Delta T = -K\Delta(\sigma_1 + \sigma_2) \tag{1}$$

where K is the thermoelastic constant,

$$K = \frac{\alpha T}{\rho C_p} \tag{2}$$

α is the linear thermal expansion coefficient, ρ is the mass density, and C_p is the specific heat. The Eq. (1) is modified for orthotropic materials such as fibre-reinforced plastics, as follows [7]:

$$\Delta T = -\frac{T}{\rho C_p}(\alpha_1 \Delta\sigma_1 + \alpha_2 \Delta\sigma_2) \quad (3)$$

where α_1 and α_2 are the coefficients of linear thermal expansion in the principal material directions. In the last decades, it has been demonstrated the usefulness of TSA as an experimental tool in damage and stress analysis of anisotropic materials too (i.e. complex composite components). [6-8]
As remarked by Risitano A. and other researchers, the temperature of stressed components is an important parameter to dynamically characterise the material [9-12]. A new methodology to determine the fatigue limit using thermal increments has been developed, allowing this limit and the whole fatigue curve to be evaluated in an extremely short time (Risitano method). This technique has also been applied to different types of materials, including composites (short fibre-SMC[1] composites) and polymers [13-14].
Damage analyses, by means of thermography, allow both qualitative and quantitative analyses. Many researchers have been studying in the last period, whether this method can also be applied to complex materials, such as fibre reinforced composites. This study aims to investigate the applicability of the thermographic method to evaluate damage in continuous fibre composites.

MATERIALS AND METHODS

In this study, specimens made of pultruded material and cut from a corner profile of a bus cabin were tested. The pultruded material is made of 30% of E-glass fibres and 70% of random mat impregnated into a vynilester matrix. The volume fraction of fibres and mat is 0.5.
In order to characterise the material and evaluate the different types of failure, static tensile tests were performed on specimens with different fibre orientations with respect to the load direction. The static tests were performed by means of a universal tensile testing machine (MTS Alliance RF150). The specimens were rectangular, as provided by the standard ASTM D3039/D 3039M-08 [14]. To avoid local damage in the grip area and to guarantee a correct load transfer, bond tabs were put at the end of the specimen, in the grip areas, which were clamped into the machine grips during the tensile tests. Tabs of the same material of the specimen were chosen and glued by means of an acrylic adhesive. The tests were performed in displacement control mode by choosing, according to the standard [14], a cross-head speed of 1 mm/min, which allowed constant displacement increments along the gage length. A frequency of 1 Hz was used for data acquisition.

Figure 1: Testing set up (tensile tests and thermal analyses).

During these tests, thermal analyses were performed by means of an IR camera and an RTD (Resistance Temperature Detector) to obtain a comparison of the mechanical behaviour also from the energetic point of view.
The type of used camera is a FLIR Thermacam SC 3000, with macro lens 34100. This camera, designed to meet demanding thermal analyses for scientific applications and NDI, has a high sensitivity and high speed data acquisition

[1] *Sheet Moulding Compound*

capabilities. It uses an advanced photo detector sensor that provides extremely high sensitivity of less than 20 mK at 30 °C. This photo detector absorbs the radiations emitted from the observed body, converting them into an electric voltage. The adopted RTD is a PT100, installed into a clamping system directly placed at the bottom of the specimen (far from the scanning area of the IR camera) before testing. This resistance was calibrated by using an object with a known temperature, to obtain a correct output signal (voltage).
Two series of specimens were tested: 1) specimens with the orientations of 30°, 45° and 90° were tested with the aid of only the IR camera; 2) specimens with the orientations of 0° and 30° were tested with the aid of both the IR camera and the RTD. During the tests, the machine components close to grip areas of the specimens were covered with an insulating tape, to avoid that the scattering of the electromagnetic rays would reduce the accuracy of the results. In addition, the direction of the camera objective was not normal to the specimen surface, to avoid the detection of the scattered rays. A MATLAB routine was then used to reorganise the data and obtain the thermal images. The testing set up is shown in Fig. 1.

Results and Discussion

The results showed different types of failure, dependent on the fibres orientation and on the real amount of fibres and mat. The various failure modes are clearly visible from the thermal images, shown in Fig. 2. The failure of the specimens with fibres at 45° happened along the fibres orientation, without fibre/mat debonding. In specimens with fibres at 30°, failure happened mainly due to fibre/mat debonding, which was followed by the mat failure, normally to the applied load, as shown in Figure 2-b. In this case, the increase in temperature, due to the rupture, was higher than the case 'a' because of the higher mat ratio, which absorbs more energy of rupture. This was confirmed by a following analysis of the surface of fracture, by means of a computed tomography (CT). In the specimens with normal fibres, failure occurred, as expected, in the direction orthogonal to the applied load, both for matrix cracking and mat rupture. In the longitudinal specimens, the failure mode included fibre/mat debonding, followed by fibre failure. In this case, the temperature variation was small; this was due to a progressive damage, caused by a progressive fibre/mat debonding followed by fibre rupture, which gradually release the energy absorbed before the breakage. This was visible only by means of a local thermographic analysis, where sudden increases in temperature, due to the rupture of some fibres, are shown.

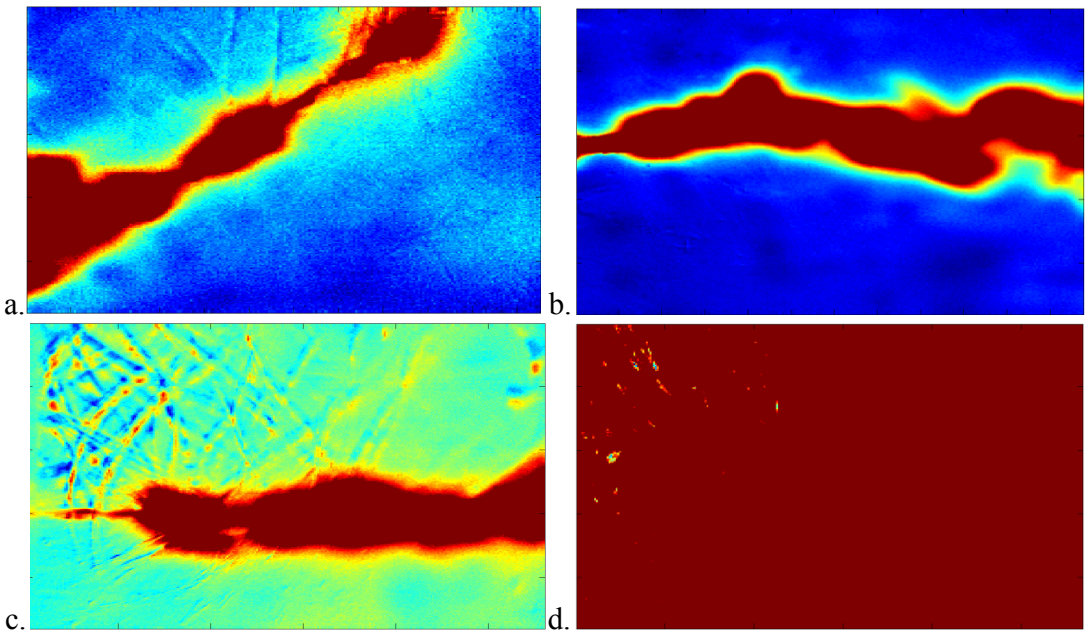

Figure 2: Thermal images of different type of failure with different fibre orientation (a. 45°, b. 30°, c. 90°, d. 0°).

In the various tests, it was possible to analyse the temperature trend of a point located in the area where the failure has occurred. It should be stressed that the temperature trend is strictly dependent on the chosen pixel. However, in general it

was found a similar temperature-time curve for the analysed specimens. A general decrease in temperature was found at the beginning of the test, followed by a plateau and a sudden increase immediately before the final breakage. This is clearly visible for specimens with fibres at 45° and 30°, whereas for longitudinal and transversal specimens the results are not so clear, as the curves are not so smooth. The initial temperature reduction is due to the elastic increase in volume. The change in the slope happens at the end of the elastic phase, when the damage starts. The final increase in temperature represents the energy, previously absorbed to deform the material, released at breakage.
Another comparison, between the results obtained from the camera and those obtained from the RTD, was made. Only one test was not considered to be valid due to tabs debonding before failure of the specimen. There is no agreement between the results obtained from the two instruments. This was due to that the thermal resistance was placed at the bottom of the specimens, far from the middle area, where the failure has usually occurred and its measurements were averaged on the detected area. Rather, the IR-camera lens was directed to the middle area. Another reason could be that the thermal resistance has a lower speed data acquisition than the camera, so the two instruments are not synchronised. In fact, the RTD is designed for fatigue test monitoring, where the temperature changes are not sudden as in a static test. Also, the thermal resistance has a clamp system in contact with the specimen; this might have affected the results too.

CONCLUSION

This study confirms the different failure mechanisms that can happen in composites, depending on the fibre orientations with respect to the applied load (interfacial debonding, delamination, fibre rupture, matrix cracking). A non destructive technique, the thermal image analysis, was used to study damage in composites under static load. This is a powerful technique to detect damage on large areas without the need of contact; it can also be used for damage monitoring on mechanical components under working conditions. Thermal analyses also provide the identification, at the beginning of static or dynamic tests, of the hottest point of the specimen; this allows detecting the area where the failure is likely to occur. It is important to locate this point to make previsions on the failure of component under working conditions.
This work has shown that the static tests, coupled with the thermographic analysis, for composite materials, can give reliable information about the type and the development of damage under static loading conditions.
Future research aims to investigate, through IR-thermography, the fatigue behaviour of composites giving a step forward in the research of fatigue damage in composite materials.

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