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Nondestructive evaluation of carbon fibre reinforced composites with infrared thermography and ultrasonics

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ABSTRACT

Infrared thermography and phased array ultrasonic are used to detect defects and impact damage in carbon fibre reinforced composites. Apart from its use as non-destructive evaluation technique, infrared thermography is also employed to record a video during the impact event. The visualization of thermal signatures, caused by local dissipation of impact energy, allows gaining information which is useful for understanding the material response to impact. In particular, the two techniques allow for estimation, in a reliable way, of the overall delamination extension which is of utmost importance for material design purposes.

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1. Introduction

Carbon fibre reinforced composites, mainly known as CFRPs, are increasingly used in aircraft primary structural components [1]. They are light and stiff but exhibit different problems, which require attention. In fact, they are susceptible, during fabrication, to formation of defects and slag inclusions which may affect their performance in service. Besides, their main weakness is their vulnerability to low velocity/energy impact because important damage may arise inside the material thickness without any perception on the impacted side. Their behaviour under impact is still not completely understood due to the multitude of CFRPs that can be obtained by varying stacking sequence and manufacturing procedures. Moreover, impact damaging of CFRPs is a very complex mechanism involving matrix cracking, surface buckling, delamination, fibre shear-out and fibre rupture [2,3] which are difficult to simulate numerically. Therefore, the availability of effective non-destructive testing (NDT) techniques is fundamental to getting information on the damage induced by low energy impacts.

NDT techniques are used in different stages of the life of a composite material. First, in conjunction with impact/fatigue tests, to estimate its performance under load, then before assembly, to assure the material it is free of manufacturing defects and, later on, to detect in service deterioration. Given the susceptibility to impact events, the impact damage resistance properties of composites are one of the major design concerns. Often, this feature is assessed through specific impact tests, which are intended to identify the energy that causes delamination of a given extension. More specifically, such tests consist of impacting the laminate at a given energy, evaluating, in a non-destructive way, the induced damage extension and go on to increasing impact energies until the preset delamination has been reached. Generally, delamination is detected with ultrasonic testing. Of course, this operation is time consuming and, sometimes, not very accurate depending on the surface under exam and on the employed instrument, so demanding for alternative methods.

Today, many different NDT techniques are available, but none can be considered as superior and very effective; in fact, every technique has its inherent limitations and, often, one has to guess between sound and damaged materials at the edge of the instrument background noise. A good practice is to choose the most adequate technique to the specific application but, frequently, an effective routine may be to use more than one method in the light of a data fusion approach. It is worth noting that Ultrasonic Testing (UT) [4] is a well standardized technique and the most commonly used in the aeronautical industry; instead, infrared thermography (IRT) has been only later recognized amongst the standardized techniques even if is gaining popularity, mainly because of its possibility to inspect wide areas in a relatively short time.

Recently [5,6], it has been demonstrated that the use of an infrared imaging device directly during the impact may be advantageous to getting information on the extension of the occurred delamination. In fact, the damage caused by the impact is related to the warm area which develops, and can be visualized on-line, on the laminate surface opposite to the impact. This approach is fast and accurate being able to identify also thin delaminations and disbands; these give rise to the so called kissing bonds, which are difficult to detect

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with conventional NDT methods, once the impact event is finished and the surface returns to its unloaded position.

In the present work, the thermal signature, visualized by an infrared imaging device during the impact event, is used to get more information about the impact damaging of a CFRP and as a reference to be compared with results obtained with either ultrasonic phased array or lock-in thermography, having the aim to fix the phenomenology about the boundary between sound and damaged material.

2. Experimental investigation

The impact damaging of carbon fibre reinforced polymer is evaluated in a non-destructive way with both infrared thermography and ultrasonic testing. However, infrared thermography is used with the twofold function of NDT technique and of monitoring tool to account for the material behaviour during the impact event.

2.1. Description of specimens

Two CFRP specimens are considered.

- One includes 24 unidirectional carbon/epoxy pre-preg laminas M21/IM7 (provided by HEXCEL®) and is 113 mm long and 63 mm wide with an overall thickness of 4.59 mm. This specimen, that is named CFRP_A, is fabricated with the hand layup technology and with curing in autoclave. It includes a kapton® disc, 20 mm in diameter, made of two overlapped foils, each 0.0625 mm thick, to simulate a thin local delamination; the kapton® disc is located under 4 plies starting from one (smooth) specimen side.
- The other specimen is a panel of square side 500 mm and nominal thickness 5 mm. It is a multilayer laminate with fibres oriented at 0/90°/+45/−45° alternatively; fibres are of both fabric and unidirectional types. This specimen, which is named CFRP_B, is used to perform multiple impacts at different energies.

2.2. Non-destructive tests

Non-destructive evaluation is performed with both lock-in thermography (LT) and phased array ultrasonic testing (PAUT).

2.2.1. Lock-in thermography

The test setup includes the specimen, the infrared camera and halogen lamps (1 kW each) for thermal stimulation of the specimen [5]; in particular, one lamp is enough for the CFRP_A specimen, while two are necessary for the larger CFRP_B. The used infrared camera is the SC6000 (Flir systems), which is equipped with a QWIP detector, working in the 8–9 μm infrared band, NEDT < 35mK, spatial resolution of 640 × 512 pixels full frame, pixel size 25 μm × 25 μm and with a windowing option linked to frequency frame rate and temperature range. The camera is equipped with the Lock-in module that drives the halogen lamp to generate a sinusoidal thermal wave of selectable frequency f and the IRLock-In© software for performing lock-in thermography tests. The thermal wave, delivered to the specimen surface, propagates inside the material and gets reflected when it reaches parts where the heat propagation parameters change (in-homogeneities). The reflected wave interacts with the surface wave producing an oscillating interference pattern, which can be measured in terms of either temperature amplitude or phase angle ϕ, and represented as amplitude, or phase, images, respectively. The basic link of the thermal diffusion length μ to the heating frequency f and to the mean material thermal diffusivity coefficient α is via the relationship:

$$\mu = \sqrt{\frac{\alpha}{\pi f}} \tag{1}$$

The depth range for the amplitude image is given by μ, while the maximum depth p, which can be reached for the phase image, corresponds to 1.8μ. In general, it is preferable to reduce data in terms of phase image because of its insensitivity to both non uniform heating and local variations of emissivity over the monitored surface. The material thickness, which can be inspected, depends on the wave period (the longer the period, the deeper the penetration) and on the material thermal diffusivity. According to Eq. (1), the knowledge of the mean thermal diffusivity is fundamental to evaluate the depth at which any detected anomaly is located, or to choose the frequency value to check the material conditions at a given depth. To this end, the overall thermal diffusivity α can be evaluated with the lock-in technique itself [7], or with flash thermography [8].

2.2.2. Ultrasonic testing

PAUT tests are performed with an Olympus OmniScan SX flaw detector with a 16:64PR phased array unit equipped also with a conventional UT channel for pulse-echo, pitch-catch or TOFD inspection. Phased array elements are pulsed in such a way as to cause multiple beam components to combine with each other and form a single wave front travelling in the desired direction. Similarly, the receiver function combines the input from multiple elements into a single presentation. Because phasing technology permits electronic beam shaping and steering, it is possible to generate a vast number of different ultrasonic beam profiles from a single probe assembly, and this beam steering can be dynamically programmed to create electronic scans. Phased array ultrasonic instruments utilize high frequency sound waves to check for the internal structure of a test piece, or measure its thickness, and rely on the same basic laws of physics that govern sound wave propagation. The ability to generate multiple transducer paths within one probe adds a powerful advantage in the detection and naturally increases the ability to "visualize" an inspection by creating an image of the inspected zone. Phased array imaging provides the user with the ability to see relative point to point changes and multi-angular defect responses, which can assist in flaw discrimination and sizing [9].

In the present work, tests are carried out by exploiting an encoded 5 MHz, 64 element linear array probe with a straight wedge and by employing a specific gel as coupling medium. No calibration blocks are used, the measurement of the specimen thickness being taken as reference; it is worth noting that it is difficult to fabricate reference blocks reproducing the specimen CFRP_B, while the other one is relatively small.

In any case, the smaller specimen with the enclosed insert of known diameter, which is inspected with both LT and PAUT, may serve as reference. In addition, the same warm area which is visualized during the impact and which helps following the damage extension [5,6] may function as reference.

2.3. Impact tests

Impact tests are carried out with a modified Charpy pendulum, which, as shown in Fig. 1, allows enough room for positioning of the infrared camera to view the rear specimen surface (i.e., opposite to that struck by the hammer). Specimens are placed inside a special lodge which includes two large plates having a window 12.5 cm × 7.5 cm to allow for the contact with the hammer from one side and optical view (by the infrared camera) from the other

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