Impact Damaging of Carbon Fibre-reinforced Composites: a Comparison between Infrared Thermography and Ultrasonics

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Abstract
Carbon Fibre Reinforced Polymers (CFRPs) are increasingly used in aircraft primary structural components. A main weakness, when compared to metallic materials, is their vulnerability to low velocity/energy impact; in particular, important damage may arise inside the material thickness without any perception on the impacted side. The duration of a metallic component is dependent on the possible formation of a crack and its growth, which can be somehow predicted by the linear elastic fracture mechanics. On the contrary, CFRPs are strongly inhomogeneous and their behaviour under impact is complex and difficult to be modelled. Then, the use of effective non-destructive testing (NDT) techniques is fundamental to get information on the damage induced by low energy impacts. Generally, NDT techniques are asked for assessing the extension of delamination, but, often, one has to guess between sound and damaged material at the edge of the instrument background noise. To help fixing this problem, results obtained with either lockin thermography, or an ultrasonic phased array system, are analysed with the aid of thermographic data collected during impact tests.

Keywords: Carbon epoxy, impact damage, non-destructive evaluation, infrared thermography, ultrasonics,

1. Introduction

Composite materials, especially those made of carbon fibres impregnated of resin epoxy (CFRP), are ever more replacing metals in the aircraft industry because of their high specific stiffness and high specific strength, combined with a significant reduction of weight [1-3]. Besides the many advantages, there are also some disadvantages due to their willingness to include defects during fabrication. A weak point of CFRPs is their susceptibility to delamination, often resulting in considerable loss in strength, and possibly leading to catastrophic failures in-service. Delamination often arises also in the impact with blunt objects, which may occur during manufacture, service and maintenance.

The impact damage in CFRPs is a very complex mechanism involving matrix cracking, surface buckling, delamination, fibre shear-out and fibre rupture [4,5] and it is still not completely understood also because of the vast variety of composites, which can be created by simply changing an ingredient (type of matrix and/or fibre) and/or the stacking sequence. Moreover, most often, delamination occurs, under impact, without surface manifestation and, therefore, the great attention from both academic and industrial communities is justified. Generally, the scientific community is divided into two main groups: one mainly interested in detecting the produced damage (non destructive inspection), the other one is instead driven towards the dynamics of impact load. The latter was mainly addressed numerically with only few attempts to on-line monitoring. Being cheaper, computer simulation is normally preferred by industries for design and development, even if test validation is often compulsory.

The use of effective non-destructive testing (NDT) techniques is fundamental to get information on the damage induced by low energy impacts. Generally, NDT techniques are asked to evaluate the extension of delamination with the impact energy being a parameter to assess the material performance. Today, many different NDT techniques are available, but no technique 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, often, 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) [6] 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 but is gaining popularity mainly because of its possibility to inspect wide areas in a relatively short time.

UT is based on the principle that an ultrasonic wave, of a given frequency, is modified by passing through a material; in particular, the wave undergoes both amplitude variation and reflection at interfaces between parts of different acoustic impedance. This method is effective in the detection of most of the common CFRP defects, (such as porosity, slag inclusions and delamination) but has the disadvantage of the needed contact with the part to be inspected. This entails some problems since the surface must be smooth enough to assure good contact, a coupling medium is necessary and time is needed to scan large surfaces. In recent years the advent of phased array ultrasonics (PAUT) [7] has solved some of the problems of conventional ultrasonics. However, from one side, the PAUT allows for the inspection of complex geometries in a faster way, on the other side, it poses the problem of the custom-built reference blocks which must be fabricated, used and stored following specific rules [8].

Infrared thermography bases its principle on the thermal energy radiated from objects in the infrared band of the electromagnetic spectrum. It is very attractive since it offers noncontact and fast inspection of wide areas. Non destructive evaluation (NDE) with IRT can be performed with different approaches which allow for detection of defects and reconstruction of their position in plane and in depth within the thickness of the inspected component. As an example, flash thermography [9] has emerged as the most valuable method to account for the presence of porosity in composites. IRT has also proved usefulness within the impact damaging of composites as used for online surface thermal mapping, when the specimen is being impacted, and for non destructive evaluation of impacted panels [10-12]. In particular, Meola and Carlomagno [10] supplied information on the onset and propagation of impact damage in glass fibres reinforced polymers (GFRP) through the analysis of thermal signatures appearing during an impact event. Recently, they demonstrated the important role played by manufacturing defects, like porosity and fibres misalignment, in the behaviour of GFRP to impact load [12].

In the present work the thermal signature, visualized by an infrared imaging device during the impact event, is used as reference to compare and understand results obtained with ultrasonic phased array and lockin thermography, as well as to fix problems about the boundary between sound and damaged materials. And then, infrared thermography is used to create the reference (used as technique of temperature measurement) and to evaluate its use as NDT technique.

2. Experimental

2.1 Description of specimens

The used material is a thermoset matrix reinforced with carbon fibres, which is mainly used in the aeronautical field. Indeed, two types of materials are considered owing to their fibres arrangement.
• The first type includes pre-impregnated unidirectional fibres arranged following the stacking sequence [0, 45, 90-45]. A panel 300x300 mm$^2$, 2.4 mm thick, is prepared by the hand lay-up technology and cured in autoclave. Several specimens about 150x100 mm$^2$ are cut and are named CFRPu.

• The second material is a CFRP panel, 485 by 485 mm with a thickness of 7.8 mm that is named CFRPF. It includes Non-Crimp Fabrics (NCF) Multiaxial Reinforcements (MR) and 5 Harness Satin Weave (HSW). It is fabricated by the hand lay-up technology and appropriate curing cycle in autoclave.

Specimens are first nondestructively evaluated by LT and PAUT, then they are impacted with a modified Charpy pendulum from one side while an infrared camera views the rear side and again nondestructively evaluated with both LT and PAUT.

2.2 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 larger plates with a window 15 cm x 7.5 cm to allow for the contact with the hammer from one side and optical view (by the infrared camera) from the other side. The hammer has hemispherical nose 12.7 mm in diameter. 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 640x512 pixels full frame with the pixel size 25 µm x 25 µm and with a windowing option linked to frequency frame rate and temperature range. The camera is equipped with the Lockin option and the IRLockIn© software for performing lockin thermography tests.

![Figure 1. Setup for impact tests with the modified Charpy pendulum](image)

The impact energy E is chosen as to produce only barely visible damage without perforation and is set by suitably adjusting the falling height of the Charpy arm. In particular, E = 5 and 10 J for the CFRPu specimen and in the range 50-70 J for the CFRPF one. Sequences of thermal images are acquired during impact tests at 96 Hz for CFRPu and 84 Hz for CFRPF. To allow for a complete visualization of thermal effects evolution with respect to the ambient temperature, the acquisition starts few seconds before the impact and lasts for some time after. To better analyze the material’s thermal behavior, the first image (t = 0 s) of the sequence, i.e. the specimen surface (ambient) temperature before the impact, is subtracted to each subsequent image so as to generate a map of temperature difference $\Delta T$ [13]:

$$\Delta T = T(i, j, t) - T(i, j, 0)$$ (1)
i and j representing lines and columns of the surface temperature map. Some examples of $\Delta T$ images are shown in the following figures 2 and 3.

Fig.2 shows some $\Delta T$ images taken, on a CFRP$_u$ specimen, at different instant during the impact at $E = 10$ J. The temperature scale is not maintained constant for all the images because the interest is focused mainly on the spatial evolution of thermal signatures rather than on the temperature rise. As can be seen the specimen surface, which is initially (before the impact) at an almost constant $\Delta T = 0$ K (Fig.2a), displays at the impact sudden temperature variations. In particular, a hot oblong structure (about 11 mm long and 3 mm wide) appears sudden at the impact (Fig.2b) surrounded by a colder (dark) zone. More specifically, the hot stripe is composed of two tracts that are equally spaced with respect to the center which coincides with the tip of the hammer nose. Fractions of a second later (Fig.2c) the colder zone disappears and the hot stripe warms up consistently ($\Delta T \approx 20$ K, not visible in Fig.2c that is in saturation) accounting for large amount of energy dissipated in fibres breakage along the horizontal direction.

![Figure 2. Some $\Delta T$ images taken on the CFRP$_u$ specimen impacted at $E = 10$ J.](image)

It is suggestive to see the spiky ends of the hot stripe in Fig.2c which let to imagine the damaging way through fibres breakage and delamination. On the other hand, the thermal stain
that is depicted in Fig.2d supplies indications on the delamination on the deeper layer with fibres oriented at 90° (vertically). The successive evolution of the warm zone is depicted in Figs.2e and f. In general, by considering two diameters, \( D_H \) and \( D_V \), along horizontal and vertical directions and by relating to two different conditions \( \Delta T \geq 2 \text{ K} \) and \( \Delta T < 2 \text{ K} \) it is possible to distinguish between severe damage and overall delamination. Owing to Fig.2b, values of 11 and 3 mm are obtained for \( D_H \) and \( D_V \), while, going to Fig.2c, the two diameters stretch to 20 mm and 14.75 mm and are indicative of the overall delamination.

Some of the most significant \( \Delta T \) images for the CFRP specimen impacted at \( E = 70 \text{ J} \) are shown in Fig.3. It is worth noting that the frame rate is 84 Hz and the acquisition starts before the impact, then the image in Fig.3a is the first that shows signs of the impact. Indeed, this image is plenty of information since it is possible to have a quick idea of both the most important damage and of the overall delamination. In fact, it is possible to clearly distinguish the most important damage accounted for by the hottest fibres in the centre. On the other hand, the darker zone nearby accounts for the material bending under the pushing impact force, while the lighter contour may act as boundary to the delaminated area, even if, due the simultaneous subsistence of thermo-elastic and thermoplastic phenomena, adverse effects tend to cancel. From a quantitative point of view, \( D_H \approx 40 \text{ mm} \) and \( D_V \approx 35 \text{ mm} \) for the lighter contour in Fig.3a, while the entire warm area in Fig.3d has a diameter of about 36 mm.

![Figure 3. Some \( \Delta T \) images taken on the CFRP specimen impacted at \( E = 70 \text{ J} \).](image)

### 2.3 Non-destructive evaluation

#### 2.2.1 Lockin thermography

The test setup includes the specimen, the infrared camera (the same SC6000 used to monitor the impact) and halogen lamps (1 kW each) for thermal stimulation of the specimen [10]; in particular, one lamp is enough for the CFRP specimen, while two are necessary for the larger CFRP. The infrared camera is equipped with a Lock-in module that drives the halogen lamp to generate a thermal wave of selectable frequency \( f \). 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 (inhomogeneities). The reflected wave interferes with the surface wave producing an oscillating interference pattern, which can be measured in terms of either temperature amplitude or phase angle $\phi$, and represented as amplitude, or phase, images, respectively. The basic link of the thermal diffusion length $\mu$ to the heating frequency $f$ and to the material thermal diffusivity coefficient $\alpha$ is via the relationship:

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

(2)

The depth range for the amplitude image is given by $\mu$, while the maximum depth $p$, which can be reached for the phase image, corresponds to 1.8 $\mu$. 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.2, the knowledge of the thermal diffusivity is fundamental to evaluate the depth at which any detected anomaly is located, or to chose the frequency value to check the material conditions at a given depth. To this end, the overall thermal diffusivity $\alpha$ is evaluated with the lockin technique itself; the procedure is described in a previous work by Meola et al. [14].

Each specimen is inspected by viewing both sides, the impacted and the opposite one, and by varying the heating frequency $f$; some of the most significant phase images are reported in the following figures 4 and 5.

![Phase images taken for varying $f$ on the rear side of the CFRP specimen impacted at $E = 10$ J](image)

Figure 4. Phase images taken for varying $f$ on the rear side of the CFRP specimen impacted at $E = 10$ J.

Fig.4 shows phase images taken for varying the heating frequency on the rear to impact side of the specimen CFRP impacted at $E = 10$ J. It is possible to see, for $f = 0.88$ Hz a lighter stripe along the horizontal fibres over the external layer, which well complies with what observed during online monitoring (see Fig.2b). Such a stripe has the same dimensions of about 11 mm x 3 mm already measured from Fig.2b (note that images in Figs.2 and 4 are not in scale) and represents the cut occurred during impact which caused large release of energy and, in turn, abrupt rise of temperature. From Fig.4b it is possible to see two lobes appearing along the fibres at 45° underneath; this is in good agreement with Fig.2d. From the successive phase images it is possible to see a change of shade due to the blind frequency [15] and other
structures which are well visualized by changing f. The overall damage, with maximum extension of 13.9 mm and 11 mm along horizontal and vertical directions, is displayed by the phase image in Fig.4e. No damage is found from tests performed by viewing the impacted side because the damage is close to the opposite surface and get masked within the fibres.

Phase images taken from both sides (impacted and rear) of the specimen CFRP impacted at E = 70 J are shown in Fig.5 and 6. Starting from the impacted surface (Fig.5), it is possible to follow the evolution of the damage at the different layer depicted by the white stain. In particular, considering that $\alpha = 0.03 \text{ cm}^2/\text{s}$ (measured with LT), for $f = 0.88 \text{ Hz}$ it is visible the indentation on the surface, going more in depth, for $f = 0.53 \text{ Hz}$ ($p = 2.4 \text{ mm}$), the white stain enlarge and strengthens accounting for some damage there, while a two-lobed structure appears surrounded by a lighter elliptic-shaped one for $f = 0.36 \text{ Hz}$ ($p \approx 3 \text{ mm}$). Such a lobed structure becomes well consolidated for $f = 0.15 \text{ Hz}$ ($p = 4.6 \text{ mm}$), while it tends to vanish going further deep. On the other hand, if tests are carried out by viewing the rear side (Fig.6), the two-lobed structure appears well consolidated for $f = 0.36 \text{ Hz}$ ($p \approx 3 \text{ mm}$). However, $p$ has been calculated considering $\alpha = 0.03 \text{ cm}^2/\text{s}$, which applies for the sound material, while the thermal diffusivity is affected by material degradation. Most probably the two-lobed structure corresponds to the oblong hot zone displayed by Fig.3c, which appeared later because it was located deeper and not over the external layer. Of course, the sequence of phase images allows for the reconstruction of the impact damage through the thickness. On the whole the damaged area takes $D_H \approx 34 \text{ mm}$ and $D_V \approx 25 \text{ mm}$ as maximum extension.

Figure 5. Phase images taken for varying $f$ on the side of the CFRP specimen impacted at $E = 70 \text{ J}$

Figure 6. Phase images taken for varying $f$ on the rear side of the CFRP specimen impacted at $E = 70 \text{ J}$
PAUT tests are performed with an Olympus OmniScan SX flaw detector with a 16:64PR phased array unit also equipped 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 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 [8].

Any ultrasonic instrument typically records two fundamental parameters of an echo: how large it is (amplitude), and where it occurs in time with respect to a zero point (pulse transit time). The most basic presentation of ultrasonic waveform data is in the form of an A-scan, or waveform display, in which echo amplitude and transit time are plotted on a simple grid with the vertical axis representing amplitude and the horizontal axis representing time. Another way of presenting this information is as a cross sectional B-scan which provides a detailed end view of a test piece along a single axis. Successive A-scans are plotted over elapsed time, or actual encoded transducer position, so as to draw pure cross-sections of the scanned line. This allows visualization of both near and far surface reflectors within the sample. Linear Straight Scan (S-scan) is an electronic scanning along the length of a linear array probe to create a cross-sectional profile without moving the transducer. As each focal law is sequenced, the associated A-scan is digitized and plotted. Successive apertures are "stacked" creating a live cross sectional view. Another presentation option is a C-scan, a two dimensional presentation of data displayed as a top or planar view of a test piece, similar in its graphic perspective to an x-ray image, where colour represents the gated signal amplitude or depth at each point in the test piece mapped to its position. The probe is typically moved physically along one axis while the beam electronically scans along the other one, according to the focal law sequence. Signal amplitude or depth data is collected within gated region of interest and plotted with each focal law progression, using the programmed beam aperture.

In the present work, tests are carried out using an encoded 5 MHz, 64 elements linear array probe with a straight wedge and by using a specific gel as coupling medium. No calibration blocks are used, the measurement of the thickness being used as reference; it is worth noting that it is difficult to fabricate reference blocks reproducing the specimen CFRP, while the other one is relatively small and can act itself as reference. B, S and C scans in amplitude view are presented in Fig.7 for the CFRP specimen and in Fig.8 for the CFRP specimen. In particular, only the first specimen has both surfaces smooth enough to allow for measurements on both sides. From the C-scans by considering the yellow/brown colour as boundary between sound and damaged materials it is found $D_H \simeq 11$ mm, $D_V \simeq 12.34$ mm for the CFRP specimen and $D_H \simeq 35$ mm, $D_V \simeq 27$ mm for the CFRP specimen as overall damage extension. The
and S scans images instead supply information about the position of the damage through the thickness owing to the indicated axes. It is possible to recognize the characteristic truncated-conical path with apex in the impacted zone. In particular, the TOFD C-scan (Fig.8) displays presence of lenticular delaminations; of course, for a complete reconstruction of the position of such lenticular structures along the impact cone, many scans are necessary with varying the position of the probe along B-scan and S-scan directions.

![Figure 7. C, B and S scans on both sides of the CFRP_u specimen impacted at E = 10 J.](image1)

![Figure 8. C, B and S scans on both sides of the CFRP_f specimen impacted at E = 70 J.](image2)

**3. Data comparison and concluding remarks**

From the comparison with data coming from LT and PAUT, a general agreement is found. At first sight the damage shape displayed by the C-scans in Fig.7 seems different from that in Fig.4e, but for a direct comparison one of these images must be rotated by 180°. As main differences: PAUT fails to detect the shallow (from the rear side) damage in the specimen CFRP_u that is well resolved by LT (Fig.4); conversely, it is more successful in detecting the deeper damage from the impact side. More difficult is the comparison of Fig.8 with Figs.4
and 5 due to the superposition of all the damage structures at any depth in the PAUT images. Nevertheless, the two central ovals, which appear brown in the C-scan and white in the TOFD images, well match the two-lobed structure already observed in some phase images (e.g. Fig.4e and Fig.5a-c), also the lenticular structures over the border in the C-scan and in the TOFD can be recognised in the phase image of Fig.5c-e. In addition, the C-scan shape resembles the lighter contour in the thermal image of Fig.3a.

As a final remark, both techniques seems effective to detect the impact damage; LT is fast and more effective to detect shallow damage, conversely PAUT is better to inspect thick parts, and so an integrated use would be advantageous. However, both techniques are characterized by some uncertainty in the discrimination of very thin delamination in comparison with the thermal signature visualized during monitoring of the impact event especially in presence of composites with complex stacking sequence. Then, if the investigation regards the material performance for design purposes, the use of an infrared imaging device for monitoring the impact event is a viable and advantageous alternative and should be preferred.

References