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Detection of early stage damage in carbon fiber reinforced polymers for aeronautical applications using an HTS SQUID magnetometer

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Abstract. We present an experimental characterization of multidirectional fibre composites based on eddy current testing using HTS dc SQUID (Superconducting Quantum Interference Device) magnetometers. The correlation between the mechanical tolerance of CFRPs with different thickness and the phase gradient of the magnetic field generated by damage is shown. The eddy current based SQUID NDE is used to detect damage not visible to the naked eye and to study the effect of an impact far from the point of impact. The aim of this work is to demonstrate the capability of our technique to provide information on early stage damage due to an impact process in an unshielded environment.

PACS. 85.25.Dq Superconducting quantum interference devices (SQUIDs) – 07.55.Ge Magnetometers for magnetic field measurements – 81.05.Qk Reinforced polymers and polymer-based composites

1 Introduction

The growing use of composite materials, especially in the aerospace and aeronautical industries, has attracted much attention in engineering and technological fields. Composite materials, specifically Carbon Fibre Reinforced Polymers (CFRPs), offer excellent mechanical behaviour, good damage tolerance, high strength and rigidity with low weight, good corrosion resistance and suitability for the production of complex-shape components with reduced manufacture time. However, due to low inter-laminar strength, fibre composites are susceptible to delamination during processing or in service.

Delamination may be produced, for example, by runway debris, hail, maintenance damage (i.e. dropped tools) and bird strikes. Frequently, delamination between the layers develops in fibre fractures with no visible surface manifestation. CFRPs are capable of absorbing the energy of impact thanks to the presence of a polymeric matrix that distributes the energy in the material. In this way the impact doesn't produce a perforation of the composite structure but may cause internal damage such as delamination. The presence and growth of delamination may produce severe stiffness reduction in the structure, leading to catastrophic failure. The degree of damage depends on various factors, for example, the energy of the impact, the thickness of structures and the fibre orientation of layers in the composite.

A range of experimental results over the last decade has shown that the mechanical deformation and the electrical resistance of CFRPs are coupled. Both the mechanical properties and the level of damage of CFRPs are correlated to the electrical conductivity of the reinforcing carbon fibres. It was demonstrated that the variation of fibre distance or fibre breakage changes the resistivity of the reinforced composite [1,2]. In this way delamination and fibre breakage alter the electrical conductivity of the material manifested as a variation of current distribution in the composite. This produces a change in the corresponding magnetic signal. The low electrical conductivity and high anisotropy of CFRP composites generally doesn't allow conventional techniques, such as traditional ultrasound, thermography and eddy current with induction coils, to detect early stage damage in composite samples. In fact thermography was found to be unreliable when testing bonded joints with a narrow gap between the unbonded surface, or when the damage in the material is a few millimetres in depth [3]. On the other hand, ultrasound is not very sensitive when the material has a rough surface and a layered structure [4,5]. Moreover, the eddy current technique shows a reduction of the sensitivity of induction coils to evaluate deep flaws in structures characterized by a low electrical conductivity [6].

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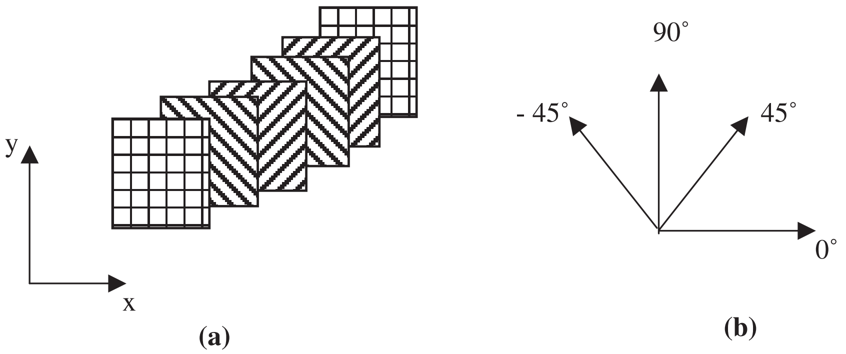

Fig. 1. (a) Stacking sequence of a multi-layer sample $[(0/90), \pm 45]_S$; (b) fibre orientations.

For this reason an eddy current method utilizing an HTS SQUID magnetometer, thanks to its high magnetic field sensitivity ($\cong$100 fT/Hz$^{1/2}$ in unshielded environment), could be an effective technique to improve the non-destructive evaluation of CFRP materials.

Since it has already been demonstrated [7–10] that our technique allows us to detect damage in CFRP materials, the aim of this work is to show that the HTS dc SQUID magnetometer is capable of detecting impact defects at an early stage, immediately following an elastic response, i.e. impact energy less than 2 J in 4 mm thick CFRP composites, in an unshielded environment. This energy value can be taken as a threshold for early stage damage for a thickness of 4 mm. At the present time there are no published results involving conventional eddy current induction coil NDE for impacts at comparable energy. We demonstrate that a magnetic image of a damaged sample at low energy levels successfully localizes the impact area and internal defects, even when they aren't visible to the naked eye.

2 Experimental set-up and materials

Non-destructive inspection using a Superconducting QUantum Interference Device (SQUID) magnetometer was performed. A description of the eddy current NDE system, based on HTS SQUIDs, has been reported elsewhere [8]. Eddy currents were induced in samples by a wire-wound circular coil with a diameter of 5 mm positioned at 6 mm below the sensor. The feed current into the coil was 5 mA at the frequency of 15 kHz, allowing our NDE SQUID system to distinguish the defects due to different energy impacts. The magnetic field sensitivity of the system in an unshielded environment is less than 0.3 pT/$\sqrt{\text{Hz}}$-rms for frequencies above 100 Hz. The SQUID system has a slew-rate of $10^3\ \Phi_0$/s and a dynamic range of about 130 dB. The SQUID-sensitive area is oriented to measure the component of the magnetic field parallel to the plane of the sample. The specimens, positioned at 2 mm below the coil, were moved under the cryostat with a speed of 3 mm/s by a non-metallic and non-magnetic computer controlled x-y positioning system. Surface scans of the specimens have been acquired in a continuous mode at a rate of 6 points/mm. The output channel from the SQUID read-out electronics is synchronously demodulated using a dual channel lock-in amplifier. In this way we measure the magnitude and the phase of the magnetic field. The CFRP samples tested here were multidirectional composites 70 mm × 70 mm based on an epoxy-matrix (HMF 934) reinforced with prepeg[1] layers made of T400 carbon fibres fabricated by hand lay-up[2] and autoclave curing. The fibre content in the composite was 55% by volume. Each sample is made of six blocks of layers stacked together, and each block has a number of overlapping layers with the same fibre orientation, as shown in Figure 1. The number of layers in each block depends on the total thickness of the sample, which ranges from 2 mm to 4 mm.

The multidirectional specimens were loaded at the centre by a hemispherical steel indenter, having a diameter of 12.7 mm, and falling from different heights using a drop weight tower machine. Specimens with a thickness of 2 mm were impacted with an energy level up to 12 J, while 3 mm and 4 mm thick samples were damaged with impact energies up to 25 J. In particular, we focus our attention on 2 mm thick samples impacted at 2.4 J, 7.8 J, 12 J, and on 4 mm thick sample at 1.8 J. The variable depth of the damage, i.e. indentation, located at the centre of the sample was measured using a micrometer.

3 Results and discussion

In electromagnetic non-destructive inspections based on an eddy-current technique an electrical model is generally used to describe the sensor and the sample. This model is based on a transformer in which the primary and the secondary circuits symbolize respectively the sensor and the specimen. In particular, the specimen is characterized by impedance in which the real part is linked to its conductivity and the imaginary part represents the leakage inductance of the specimen (i.e. structural variation of the sample) [11]. Consequently, it is possible to correlate the phase and the magnitude of the magnetic field to the

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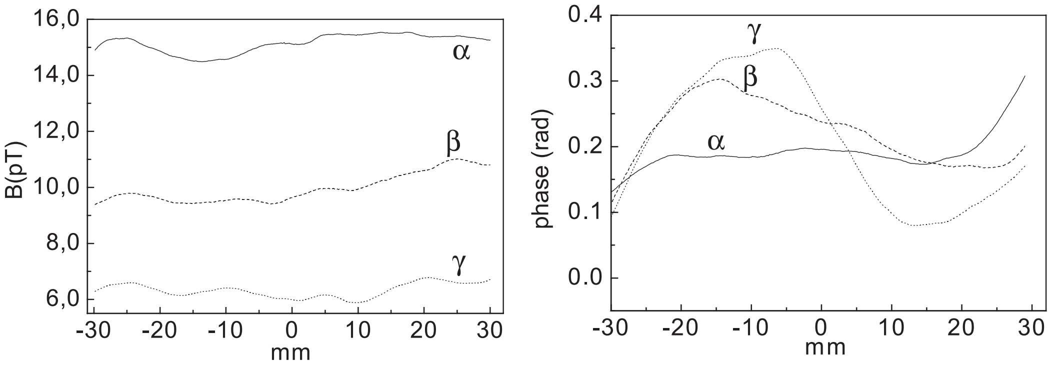
[1] A reinforced-plastics term for the reinforcing material that contains or is combined with the full complement of resin before the molding operation.

[2] Production of reinforced plastics by positioning the reinforcing material, such as glass fabric, in the mold prior to impregnation with resin.



(a) **(b)**

Fig. 2. (a) and (b) represent the magnitude and the phase of the magnetic field for 2 mm thick specimens. (α) is the line-scan related to the virgin sample, (β) and (γ) are the line-scans of the damaged samples impacted at 2.4 J and 12 J respectively.

structural integrity of the sample (i.e., delaminations and fibre ruptures) and the variation of the electrical conductivity of the composite material respectively.

In the following discussion we focus our attention on the phase rather than on the magnitude of the magnetic field. This choice depends on the capability of the measured magnitude and phase to give information about the damage.

In Figures 2a and b the magnitude and the phase of the magnetic field for the virgin (α lines) and the damaged (β and γ line) 2 mm-thick samples are presented. The β and γ line-scans were obtained moving the sensor across the center of the defects due to an impact energy level of 2.4 J and 12 J respectively. Each line represents a 60 mm scan over the sample.

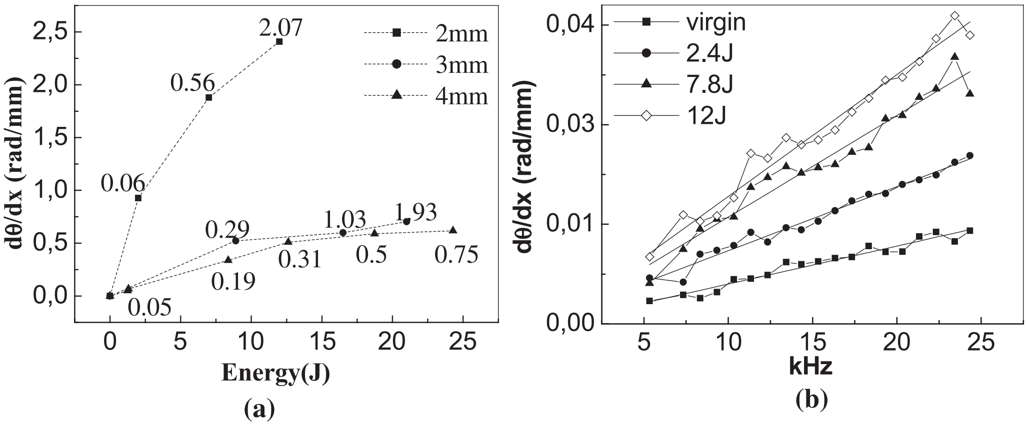
The magnetic field magnitude for the damaged samples (β and γ lines) in the vicinity of the defect center ($x = 0$) shows no significant variation. For this reason, their change in magnitude with distance looks quite similar to that for the virgin sample. Apart from that, the only difference that could be noted among the line-scans is the different value of the magnetic field amplitude. The magnitudes of the damaged samples are lower than the magnitude of the virgin sample; in particular, the higher the damage, the lower the magnitude of the magnetic signal. Therefore, considering only the magnitude of the magnetic field, the presence of the defect isn't obvious. This measurement gives only qualitative information about the conductivity of the samples. In particular, the experimental results indicate that increasing the damage decreases the conductivity of the specimen. The limited spatial resolution of our NDE SQUID system prevents us from revealing the local variation of the sample conductivity. For this reason the magnitude of the magnetic field only gives us information about the average conductivity of the sample.

On the other hand, the phase of the magnetic field related to the damaged samples shows significant variation along the line-scan. The difference between the signal of virgin and damaged specimens can be seen in the slope of the phase signal along the $x = 0$ coordinate. An inflexion corresponding to the presence of damage characterizes the lines of impacted samples.

Moreover, for specimens with visible damage the variation of the magnetic phase is correlated with the damage location. In particular, we have checked that the defect center coincides with the center of the inflexion ($x = 0$).

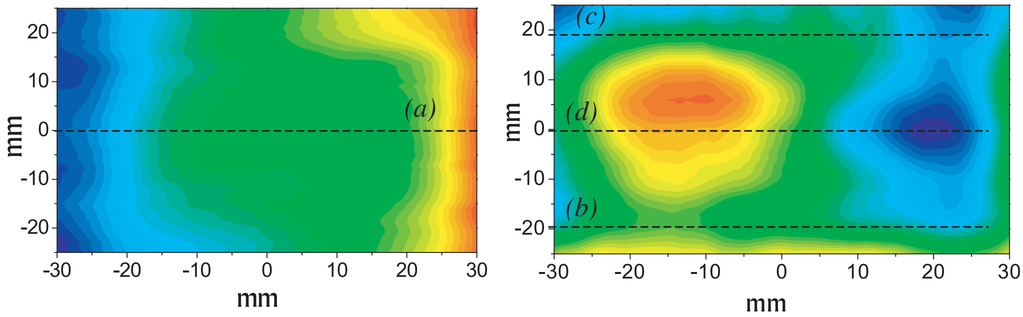
It should be noted that the decreasing and increasing phase value, at the beginning and the end of the scan is purely caused by edge effects. This is due to the comparable dimension of the specimen and the line-scan length. Experimental results demonstrate that the slope of the magnetic phase ($d\theta/dx$) is correlated with the damage severity. In other words it is possible to discriminate the different damage using the slope value; the greater the slope value of the magnetic phase, the more visible the damage and the greater the defect depth [10].

In Figure 3a the trend of the slope value against the impact energy levels is shown. For each thickness, increasing the impact energy increases the slope value. In the case of 2 mm thick samples there are not slope values for energies higher than 12 J because the specimens are already perforated, as is evident from an inspection of the sample. Comparing the slopes for each impact energy, the values for the 2 mm thick samples are always higher than those for the 3 mm and 4 mm thick samples. It is reasonable that specimens with small thickness are more brittle than samples with a bigger thickness. For this reason also comparable impact energies produce higher indentations in the 2 mm thick specimen. The slope is similar at different value of indentations in the case of the 3 mm and 4 mm thick samples. In other words composites with smaller thickness have a lower mechanical tolerance than specimens with bigger thickness. Probably a threshold value of the thickness exists between 2 mm and 3 mm that discriminates the mechanical response of the loaded CFRPs, and for this reason in specimens with a thickness above this threshold the magnetic response became similar. It should be noted that the experimental results shown in Figure 3a do not depend on the particular frequency chosen for the excitation coil. As shown in Figure 3b the slope of the magnetic phase measured by the NDE SQUID based system follows a linear behaviour versus the frequency of the excitation coil in the range 5 kHz–25 kHz.



(a) (b)

Fig. 3. (a) Slope of the phase of the magnetic field versus the impact energy level for 2 mm, 3 mm and 4 mm thick specimens. Alongside each slope value, the defect depth or indentation (in mm) is reported; (b) slope of the phase of the magnetic field versus frequency of the excitation coil for the 2 mm thick samples impacted at different energy levels. The error bars related to the slope value are about 2%.



(a) (b)

Fig. 4. Image of the magnetic field phase (rad.) for cross-ply composite: (a) 4 mm thick virgin sample; (b) 4 mm thick sample impacted with an energy level of 1.8 J.

We have already demonstrated that different steps characterize the damage in CFRP samples with a thickness of 4 mm [8]. CFRP materials behave elastically up to an impact energy level of about 1.6 J; above that matrix failure and delamination takes place. For impact energies higher than 12 J fibre failure occurs in the layer opposite the impact point. Increasing the energy, perforations and penetrations are clearly visible on the sample surface. It is important to detect the initial delaminations because when they occur, a reduction in the stiffness and the strength of the composite components appear. Obviously the threshold energy related to early stage damage depends on the thickness of the specimen. Previous mechanical tests and optical analyses of the cross section of the damaged sample area [8], demonstrated that 4 mm thick samples for energies above about 1.6 J are susceptible to early internal delamination. For this reason in the following investigation, we have considered an impact energy level of about 1.8 J for a 4 mm thick specimen.

In Figures 4a and b we show the image of magnetic phase for a 4 mm thick virgin and impacted sample with an energy level of 1.8 J respectively. The image of the damaged sample (Fig. 4b) is obtained without any data processing. The dipole-like image is related to the non-homogeneous eddy-current distribution around the center of the impact located at the position (0,0).

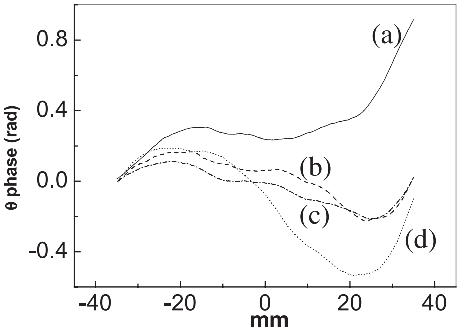
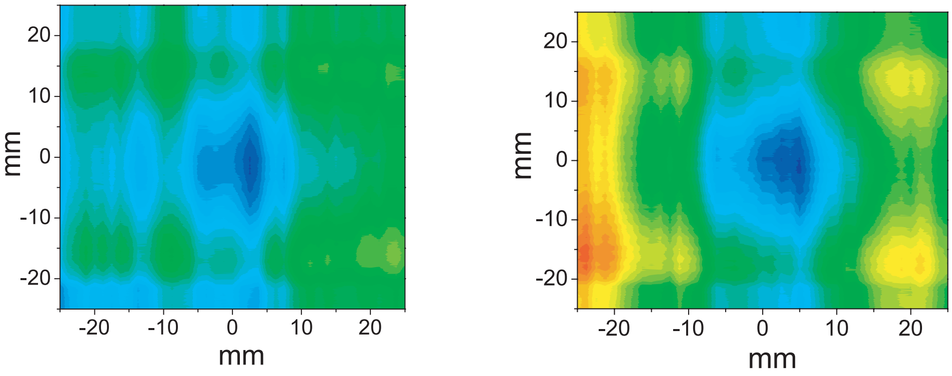


Fig. 5. Line-scans taken from the map in Figure 4b. (a) is the line of virgin sample 4 mm thick, (b) and (c) are the line-scans located at ±20 mm from the center of impact point, (*d*) is the line-scan at impacted point.

It should be noted that in the picture of the damaged sample Figure 4b the edge effect, which characterizes the virgin map in Figure 4a, is negligible compared with variations of the phase of magnetic field due to the damage inside the specimen.

Though the impact energy is very weak, the magnetic signal reveals the presence of the defect even when it is not visible to the naked eye. It appears more evident in Figure 5, where we compare the line-scan (taken from the maps of Fig. 4) at the center of impact point (line (d)),



(a) **(b)**

Fig. 6. Eddy current image for (a) 4 mm thick virgin sample and (b) 4 mm thick sample impacted with an energy level of 1.8 J.

at ±20 mm from it (lines (b) and (c)), and the line-scan of the virgin sample with the same thickness (line (a)). The slope variation between the lines (a) and (d) means that, although the sample surface appears to be intact, the sample has internal damage such as delamination.

We next focus our attention on the comparison between the virgin line-scan and the line-scans collected at ±20 mm from the center of the impacted area. Even though the 4 mm thick sample is damaged with a very low energy level, $U = 1.8$ J, the damage propagates 20 mm away the center, as shown from the non negligible slope variation of the magnetic phase with respect to the virgin one. It means that the variation of the magnetic phase along the line-scan expressed by the slope $d\theta/dx$ is a suitable parameter to investigate at an early stage not only the severity of the damage but also its extension inside the laminates. It is worth noting that the detection of damage due to very low values of impact energy considered in this work generally fails using conventional eddy current techniques with induction coils. The maps shown in Figure 6, where we show the image for the same samples considered in Figure 4, demonstrate this statement. The eddy current analysis shown in Figure 6 was performed using an Elotest B300 instrument supplied by Rohmann GmbH. The maps were obtained using an absolute ferrite core probe with an excitation frequency of 580 kHz. It should be noted that the conventional eddy current technique based on the induction coils is not able to distinguish the virgin sample from the damaged one at 1.8 J. This result highlights the difficulties of the conventional eddy current impact inspection at low energy levels (lower than 2 J). In other words the comparison between the images in Figures 4 and 6 stress the high sensitivity of the NDE system based on HTS SQUID magnetometer to detect early stage damage in complex structure like CFRPs.

In our opinion it is possible to improve the results obtained with our NDE system by substituting the SQUID magnetometer with a SQUID gradiometer. In this way the signal to noise ratio could be improved, thereby permitting the detection of small magnetic field variations with higher sensitivity in an unshielded environment. This could be of great interest for the study of the structural characteristic and the mechanical behaviour of the CFRP material and their development for aerospace applications at a research level.

4 Conclusions

Eddy-current techniques using an HTS-SQUID magnetometer have been successfully used to detect damage at an early stage in composite structures impacted at low energy in an unshielded environment. From experimental analysis obtained, the main results are summarized.

The gradient of the magnetic phase reveals that laminates with smaller thickness have a lower mechanical tolerance than specimens with bigger thickness. An increasing indentation in the specimens corresponds to a high slope of the magnetic field phase.

The phase magnetic image of a damaged sample allows us to localize the defect and the impacted area even if they are not visible to the naked eye. Moreover the magnitude of the magnetic field can give information about the average conductivity of the sample. The former method enables us to investigate damage due to impact energies less than 2 J and the propagation of matrix micro-failure at least 20 mm away from the impact point.

Above all the experimental results demonstrate that non-destructive evaluation using HTS-SQUID magnetometers is a suitable technique to analyse CFRP structures affected by early stage damage. The detection of structural defects, not visible to the naked eye and not detectable by conventional techniques, is very important for the research and development of these materials. These results are also interesting for the aerospace industry at a maintenance level to improve the flight safety of the aircraft components. In the quality control inspection of aircraft components it is very important to locate defects with a high degree of accuracy, and for this reason we plan to improve the defect localization and classification using an Artificial Neural Network model.

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