Complementary methods for nondestructive testing of composite materials reinforced with carbon woven fibers

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Abstract. This paper presents complementary methods used in nondestructive evaluation (NDE) of composite materials reinforced with carbon woven fibers as two electromagnetic methods using sensor with orthogonal coils and sensor with metamaterials lens as well as ultrasound phased array method and Fiber Bragg gratings embedded instead of a carbon fiber for better health monitoring. The samples were impacted with low energy in order to study delamination influence. The electromagnetic behavior of composite was simulated by finite-difference time-domain (FDTD) software, showing a very good concordance with electromagnetic nondestructive evaluation tests.

1. Introduction
Carbon fiber reinforced plastics composites have been started to be used at large scale in aerostructures and automotive industry. Majority of structures have been manufactured using carbon-fiber-reinforced polymers (CFRP), which are thermoset pre-impregnated carbon fibers in the form of unidirectional tape or woven fabric. But, in order to reduce the costs, to increase the production rates and avoid the impact on environment, it requires new manufacturing processes and materials, as for carbon-fiber-reinforced thermoplastics (CFRTP). Despite the fact that thermoplastic composites are more expensive, they have been preferred, due the advantages of thermoplastic matrix as recyclability, aesthetically finishing, high impact resistance, chemical resistant, hard crystalline or rubbery surface option, eco-friendly manufacturing, making the entire process costless [1]. Woven carbon fiber is most suitable for applications requiring a high strength-to-weight ratio. Polyphenylene sulfide (PPS) has excellent properties [2], framing into the advantages described above. Woven carbon fibers/PPS laminates are characterized by reduced damages but are susceptible to impacts with low energies, leading to delaminations, desbonding of carbon fibers and/or matrix cracking [3]. The aerospace industry has the requirement for the highest quality control and product release specifications [4]. The raw material standard, prepreg materials, require mechanical property testing (e.g. interlaminar strength and tensile strength) from specimens. Final parts also require NDE [5] and structural health monitoring (SHM) [6]. Alternative techniques based on phenomenological changes on the composite materials were developed during the past several decades, to measure damage due to impacts: acoustic emissions [7], infrared imaging [8], electrical resistance [9] or non-contact techniques such as digital
image correlation [10] and X-ray tomography [11], but these methods have their limitations, being complementary. Nowadays, NDE methods are developed for post-damage inspection and assessment as thermography [12], ultrasonic C-scan [13], and eddy current [14] offering quantitative results. Other techniques, such as piezoelectric sensor [15], optical fiber [16], can be used for on-line health monitoring of CFRP structures, embedding external sensors or additional fiber input in CFRPs.

This paper presents complementary methods used in NDE of composite materials reinforced with carbon woven fibers as two electromagnetic methods using sensor with orthogonal coils [17] and sensor with metamaterials lens [18] as well as ultrasound phased array method [19] and Fiber Bragg gratings embedded instead of a carbon fiber [20]. The studied samples were impacted with low energy in order to determine the damage inside the composite and provide more advanced imaging system and image of impacted area reconstruction. The electromagnetic behavior of composite was simulated by finite-difference time-domain (FDTD) software, the samples being CAD designed following textiles features, showing a very good concordance with electromagnetic NDE (eNDE) tests.

2. Studied samples
Plates of CFRTP made by Tencate, the Netherlands [2] having the dimensions 150 mm × 100 mm × 4.2 mm have been taken into study. The composite plate contains 12 layers of carbon fibers, 5 Harness satin woven type as reinforcement and the matrix is PPS–CETEX. The carbon fibers volume ratio is 0.5±0.1. The carbon fibers are T300JB type. This composite has been used in the construction of Airbus and Boeing aircrafts. In figure 1 are presented the studied samples and the layout of the 5 Harness satin woven. The samples were impacted with energies of 2 J, 4 J, 6 J, 8 J, 10 J, and 12 J, using equipment FRACTOVIS PLUS 9350-CEAST-Instron USA with a hemispherical bumper head having 20 mm diameter and 2.045 kg weight, in order to induce delaminations.

![Figure 1. Studied samples: a) composite plates; b) 5 H satin layout.](image)

Under impact, the CFRPT suffer delamination that is usually accompanied by a dent. The dent causes a reduction in the spacing between fibers in the thickness direction and this causes an increase in fiber contact leading to decrease of electrical resistance in the thickness direction. This situation modifies the electrical conductivity local both in the plane of the fibers and perpendicularly on fibers so that eNDE methods can be applied.

2.1. Ultrasound Phased array
The US measurements were effectuated with Phasor XS-General Electric, which can work both in conventional mode (pulse-echo or emission-reception) as well as in phased array mode, classic or top view. A linear phased array type with 32 elements and pitch of 0.5 mm, working at 5MHz central frequency. The Phasor XS equipment allows the selection of the domain for the angular scan in terms of refracted angles in the examined material after that its properties were input in the program. Usually, phased array sensor is fixed on a wedge (figure 2) [19].
2.2. Fiber Bragg gratings

The principal problem of CFRTP is the desbonding of fibers near subsurface during the impact leading to exfoliation of underskin that cannot be “seen” with US method. Therefore, CFRTPs with FBG sensors embedded were monitoring in order to emphasize their behavior at impact [20].

The optical block diagram of measuring method is show in figure 3.

It consist of a broadband light source (LED) that illuminates the optical input line and a reference cell after passing a 2 by 2 coupler. The reflectance cell consists of a double FBGs housed in an athermal package and reflects two wavelength peaks (around 1529 nm and 1571 nm). Together with the reflected signals coming from the optical input, the reflected spectrum will be analyzed after the 2 by 2 coupler using an optical spectrum analyzer.

2.3. Electromagnetic sensors

Sensor with orthogonal coils. First of eNDE method of the studied samples, a focused eddy current sensor with orthogonal coils [21] has been used. The sensor is absolute send receiver type. The emission part is wounded inside a high frequency ferrite cup core with 2.5 mm inner diameter, 3.5 mm outer diameter and 2.8 mm height. The reception coil is orthogonal on the emission one (figure 4a). The surface is XY raster scanned with 1mm step in both directions and give information about the amplitude and the phase of the signal. The wave front of the field created by the emission coil in material can be considered quasispherical.

Sensor with metamaterials lens. Second electromagnetic sensor involved in characterization of studied samples is a sensor that contains a metamaterial lens for detection (figure 4b). The lens is constructed from two conical Swiss rolls (CSR) with the characteristics and functioning mode given in [18], with large basis face to face. The rectangular frame used for the generation of TMz polarized electromagnetic field has 20 mm x 60 mm dimensions from 1.2 mm diameter Cu wire.
The electromagnetic sensor (either the one with orthogonal coils as well as the one with metamaterials lens) is coupled to a Network/Spectrum/Impedance Analyzer, 4395A type – Agilent USA. The sample is fixed on a XY motorized stage type Newmark USA. The command, the displacing and the acquisition of the amplitude and the phase of the signal received by the sensor are made by PC. The equipment Agilent 4395A is coupled with PC through a parallel interface type IEEE 488.2 and the XY motorized stage through serial interface type RS232 (figure 5). The commands and the data acquisition are carried out through a code developed in Matlab 2011b.

Figure 4. Electromagnetic sensors: a) with orthogonal coils b) with metamaterial lens.

Figure 5. The experimental set-up for electromagnetic methods - block diagram.

3. Experimental results
A region of 60x60 mm from the sample has been scanned in both directions with 1 mm step, using the electromagnetic sensors described above. For the sensor with orthogonal coils, the working frequency was 2.2 MHz and the lift-off 1 mm. For the sensor with metamaterials lens, the frequency was 478 MHz and lift-off 0.5 mm. The obtained electromagnetic images are presented in figure 6a and b, for the sample impacted with 8 J energy. This energy is the threshold from which delaminations start to appear in this type of composite.
It can be shown that the metamaterials lens allow the increasing of spatial resolution, the layout of the woven being emphasized. This is possible due to the appearance of the evanescent modes between the carbon fibers at the excitation with TMz polarized wave \[18\].

One cell of carbon fiber woven has been designed in TexGen -Textile Geometric modeler software (figure 7a) and exported as CAD format in order to be used in Finite Difference Time Domain software XFDTD Remcom USA. The result of the simulation is presented in figure 7b.

It is shown the apparition of evanescent modes on the edge of the carbon fibers tow, allowing their manipulation using the sensor with metamaterials lens \[18\].

In figure 8 is presented the image obtained at the scanning of the sample with ultrasound phased array sensor. The equipment operate in TOP VIEW mode, the scanning being made with the help of an encoder, in order to have accurate measurement of the distance.

It can be observed that US scan overestimate the area of delaminated surface. The under estimation of delaminated area using electromagnetic methods is due, to the modification of transverse electrical conductivity in the region of the impact, where the material suffers a plastic deformation \[14\].

In one of the sample taken into study, single tower grating having core diameter 6 μm and fiber diameter (with cladding made of ORMOCER) of 125 μm has been embedded. Centre wavelength has been 1535 nm with strain sensitivity 7.8x10^7 με^{-1} and temperature sensitivity 6.5x10^6 K^{-1}. During the experiments, the temperature has been maintained constant at 19±1°C. The sample was subjected to a series of static flexural load with increment of 0.5 N under INSTRON 8801 testing machine. The FBG was connected at a stand–alone system for monitoring one optical line type Spectral Eye 600 coupled...
with a notebook via RS232-USB2 connector. The data processing has been made in Matlab 2011b, the temperature correction being made, the equipment indicating the temperature of fiber grating, too. The measurements were effectuated on sample loaded with 528.2 N force and respectively unloaded, the experimental results representing the average of 10 measurements. Two parameters were recorded simultaneously, the deformation of the sample and the reading from optical sensor. The results are presented in figure 9. The modifications in the position of diffraction peak are very small so that the image has been zoomed in. The shifts of the reflected wavelength showed a steady and consistent deformation from 0 N to 528.2 N.

**Figure 8.** Ultrasound image using phased array sensor and TOP VIEW mode.

**Figure 9.** The response of FBGs embedded in sample delaminated under 8 J impact, for loading-unloading, four points bend flexural type.

### 4. Conclusions

CFRTP were impacted with low energies in order to obtain delaminations. They were tested with complementary methods to estimate the influence of delamination over the composite behavior. Due to impact, local modification of the conductivity appear. Only delaminations were emphasized, not breaking of fibers. It has been found that at the scanning with electromagnetic sensors, an improving of the spatial resolution can be obtained if metamaterials lens is used, due to manipulation of evanescent waves that appear between carbon fibers, fact emphasized also by numerical simulation using FDTD software. The evaluation with ultrasound phased array sensor shown an over estimation of delaminated area. Replacing a carbon fiber with a FBG grating has allowed determination of the sensitivity at plastic deformation of material due to the apparition of delamination. These methods are suitable for SHM of final parts made from these composites.

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