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ASSESSMENT OF CARBON-FIBER-REINFORCED THERMOPLASTICS AFTER IMPACT DAMAGE USING METAMATERIALS SENSOR

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Summary: *This paper presents two methods for electromagnetic nondestructive evaluation (eNDE) of composite materials reinforced with carbon woven fibers using a sensor with orthogonal coils and a sensor with metamaterials lens. 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 eNDE tests.*

1 INTRODUCTION

Fiber Reinforced Polymer Composites (FRPC) materials continue to be used in a large number of applications ranging from aerospace systems to automotive, industrial and consumer products [1]. Due to their increasing use in structural applications, the nondestructive evaluation (NDE) of FRPC continues to receive attention for research and development. The shapes of defects in composites are very often different from those typically formed in metallic materials and the fracture mechanisms are more complex [2] due to the heterogeneous nature of composites. Polyphenylene sulfide (PPS) (Figure 1) used as thermoplastic matrix presents a series of major advantages reported to the matrix from epoxy resin. PPS is an organic polymer consisting of aromatic rings linked with sulfides.

Synthetic fiber and textiles derived from this polymer are known to resist chemical and thermal attack, and the gas released due to ignition of matrix is substantially low [3], the effect of water adsorption is reduced, and the composites carbon fiber woven – PPS have increased strength to impact, the area of delamination surface being smaller.

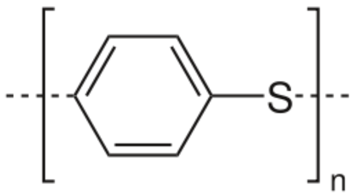


Figure 1. PPS structure

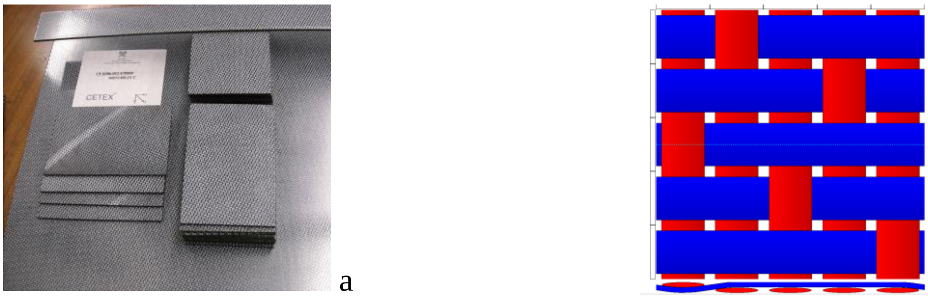
The specific degradations of FPRC are delaminations due to impacts, even at low energies, or overloading of the structure, excessive porosity, and water absorption [4]. Visible damage can be clearly detected and repairing can be done in order to maintain structural integrity. But, a major problem consists is the growth of undetected, hidden damages caused by low velocity impacts. These damages are known in aerospace applications as Barely Visible Impact Damages (BVID) [5].

C-scan or top view ultrasound, Lamb waves using noncontact transducers [6], with Hertzian contact [7] or compression waves generated by normal transducers or phased arrays [8] are usually used for NDE of FRPC. Embedding intelligent sensors, Fiber Bragg gratings type, in composites structures, it is possible to effect monitoring and prediction of delaminations apparition in order to estimate its lifetime [9]. Also, active thermography [10] is used successfully and for desbonding evaluation, bond tests can be used [11]. The matrix of FRPC has low electrical conductivity (<10 S/m) and is paramagnetic, and the carbon fibers of average conductivity are embedded into this matrix and this has suggested that electromagnetic evaluation methods can be also utilized. The starting point for application of electromagnetic nondestructive method is the theoretical modelling based on the idea that one lamina can be considered as an anisotropic electric conductive plan, having different conductivity along the direction of carbon fibers and perpendicularly on them [12]. The composite can be modelled as a succession of thus planes, in thickness, having the direction of anisotropy axis according to the composite layout. But the reality shows that the carbon fibers are not arranged parallel in composite; electrical contact might succeed between fibers that form a lamina and between different laminas.

This situation modifies the electrical conductivity local and completely randomly both in the plane of the fibers and perpendicularly on fibers. Another possibility for eNDE of FPRC consists in using the method described in [13, 14]. This paper proposes the eNDE of FRPC with polyphenylene sulphide matrix reinforced with carbon fibers woven fabric using special electromagnetic sensors for effective visualization of the delamination of FPRC created by impacts with low energies. The electromagnetic behavior of composite was simulated by FDTD software, the samples being CAD designed following textiles features, showing a very good concordance with eNDE tests.

2 STUDIED SAMPLES

Plates of FRPC made by Tencate, the Netherlands [3] 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 types 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 2 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. Under impact, the FRPC 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 electromagnetic nondestructive methods can be applied.



a b

Figure 2. Carbon fibers layout in FPRC: a) composite plates; b) 5 H satin layout

3 ELECTROMAGNETIC SENSORS

3.1. Sensor with orthogonal coils

First of eNDE method of the studied samples, a focused eddy current absolute send receiver sensor with orthogonal coils [14] has been used (Figure 3a). The emission part is winded inside a high frequency ferrite cup core with 2 mm inner diameter, 3.5 mm outer diameter and 2.8 mm height. The reception coil is orthogonal on the emission one. 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.

3.2. Sensor with metamaterials lens

Second electromagnetic sensor involved in characterization of studied samples is a sensor that contains a metamaterial lens for detection (in inset of Figure 3a). The lens is constructed from two conical Swiss rolls (CSR) with the characteristics and functioning mode given in [17], with large basis face to face. The rectangular frame used for the generation of TM_z polarized electromagnetic field has 20 mm × 60 mm dimensions from 1.2 mm diameter Cu wire. The small side of the frame is perpendicularly on the direction of the sensors displacement over the tested sample in order to assure TM_z polarized electromagnetic field.

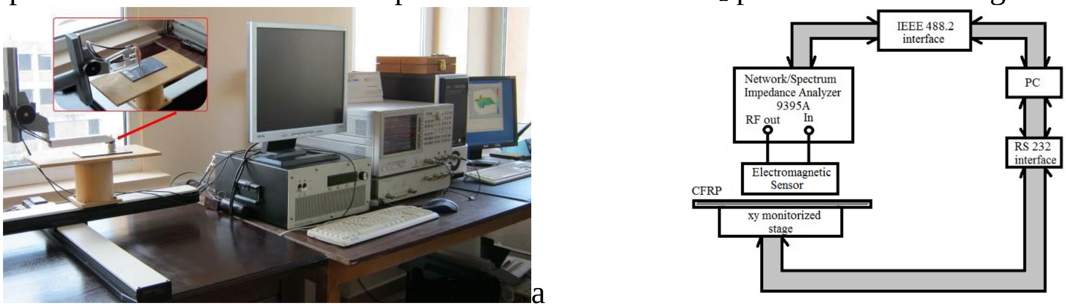


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Figure 3. Experimental set-up using electromagnetic sensors: a) in inset, the sensor with metamaterial lens replaces the sensor with orthogonal coils; b) block diagram

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 3b). The commands and the data acquisition are carried out with a code developed in Matlab 2011b.

4 EXPERIMENTAL RESULTS

During the impact, the following parameters were determined: the impact force, the impact energy, the deformation of the composite plate in the region of contact and the speed of the impactor. In Figure 4 is presented the time dependency of the impact force for all the impact energies taken into consideration. Analyzing Force -Time diagram, it can be observed that the curves for 2 J, 4 J and 6 J doesn't present fluctuations that indicates the producing of damages in material. Starting with 8 J, the amplitude of fluctuations increases with the increases of the impact energy, showing the apparition of damage phenomenon due to impact.

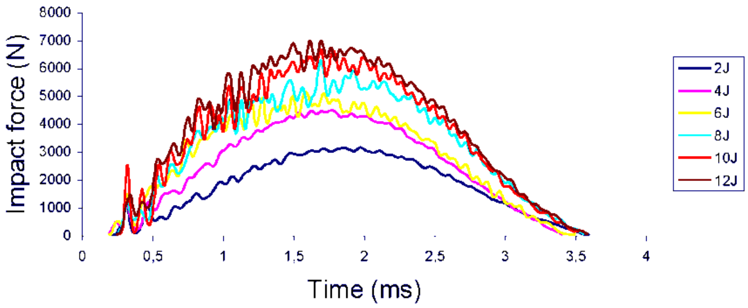
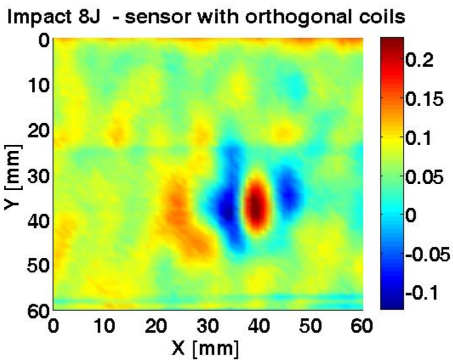


Figure 4. Time dependency of the impact force

The energy absorbed by the composite serves at the plastic deformation of the composite in the contact zone, being dissipated through internal friction between the matrix's molecules, carbon fibers, matric -carbon fibers as well as at the creation of delaminations.

A region of 60 x 60 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, the emission current amplitude 50 mA and the lift-off 0.1 mm [15]. For the sensor with metamaterials lens, the frequency was 476 MHz. Thus, we present the results obtained at testing of the FRPC samples impacted with 8 J and 10 J. In Figs. 5a and b are presented the answer in amplitude of sensor with orthogonal coils, meanwhile, in Figs. 6 a and b, are presented, comparatively, the answer of sensor with metamaterials lens. The conductivity locally increases because of in-plane shear plastic deformation during the impact [16]. According to [15], it can be seen that the area of delamination increase linear with the increasing of impact energy.

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 tows at the excitation with TM_z polarized wave [17].



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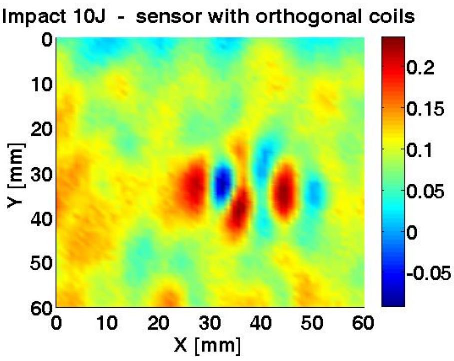

b

Figure 5. The answer of the sensor with orthogonal coils: a) for 8 J; b) for 10 J

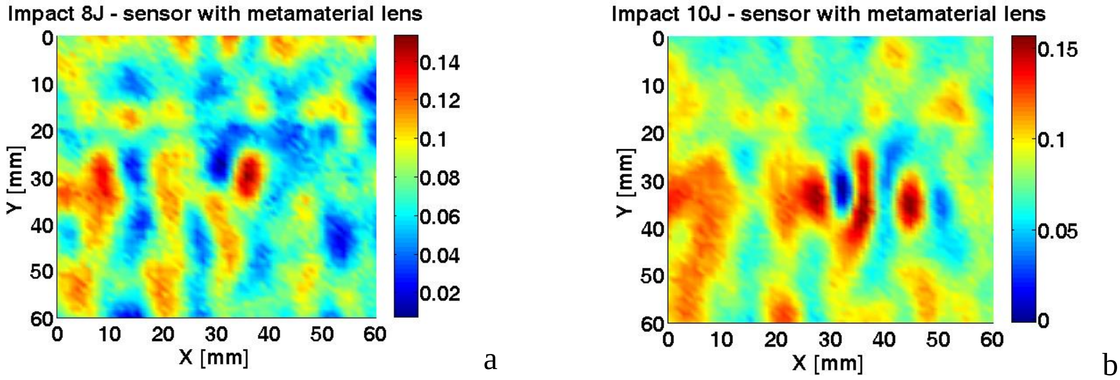

Figure 6. The answer of the sensor with metamaterials lens: a) for 8 J; b) for 10 J

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 FDTD software - XFDTD Remcom USA. The result of the simulation is presented in Figure 7b. The apparition of evanescent modes on the edge of the carbon fibers tow is emphasized, their manipulation being made using the sensor with metamaterials lens [17].

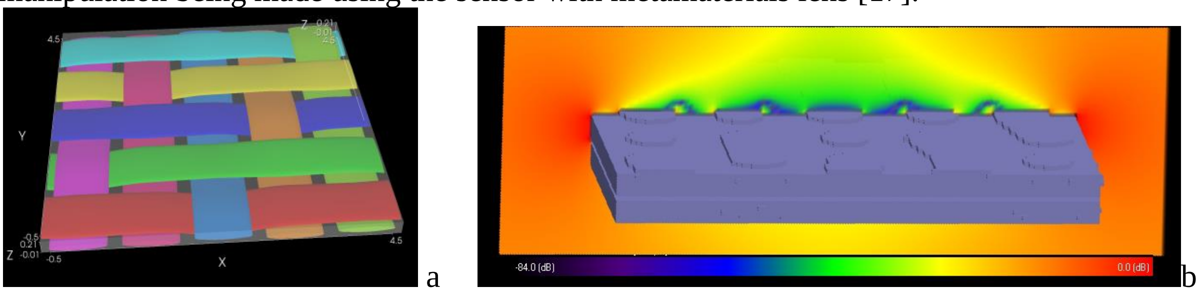

Figure 7. One cell carbon woven simulation: a) TexGen; b) XFDTD

CONCLUSIONS

FRPC were impacted with low energies in order to obtain delaminations. Due to impact, local modifications of the conductivity appear. They were tested with electromagnetic methods using two sensors developed in this purpose (with orthogonal coils and with metamaterials lens), in order to estimate the influence of delamination over the composite behavior. It has been found that 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 tows, fact emphasized also by numerical simulation using FDTD software. These methods are suitable for SHM of final parts made from these composites. Further works will implies the investigation of structures made from FRPC, as wind turbine blades, and development of sensors and methods for complete characterization of damages in SHM procedures.

Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript. All authors contributed equally.

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