The 40th International Conference on
Mechanics of Solids, Acoustics and Vibrations &
The 6th International Conference on
"Advanced Composite Materials Engineering"
ICMSAV2016& COMAT2016
Brasov, ROMANIA, 24-25 November 2016

ANALYSIS OF CFRP COMPOSITE WITH DELAMINATIONS USING ENDE METHOD

Adriana Savin[1], Ioan Curtu[2], Mariana Domnica Stanciu[2], Gabriel Dobrescu[1], Nicoleta Iftimie[1]
[1] National Institute of R&D for Technical Physics, Iasi, Romania, asavin@phys-iasi.ro
[2] Transilvania University of Brasov, Romania

Abstract: *Carbon fiber reinforced plastics (CFRP) composite materials that can be considered as multilayered strip gratings structures due to the carbon fifer conductivity. For the manipulation of evanescent waves that appear in the space between carbon fibers an electromagnetic (EM) sensor with metamaterial (MM) lens is used such that exist the possibility to the detect the interruption as well as nonalignment of carbon fibers, lack of resin or voids as well as delamination induced by low energy impacts.*
Keywords: *CFRP, electromagnetic method, sensor with metamaterial lens*

1. INTRODUCTION

Due their specific properties, carbon epoxy composite materials have a wider utilization in different production domains, the aeronautic and sportive good industries being the most consuming of these materials. The usually carbon fiber reinforced plastic (CFRP) has electrical conductivity, normal on the fiber plane about 100S/m [1] and the transversal one is about $2x10^4$ S/m. In the case of impact with low energy, the material is elastically deformed, the electrical conductivity is not locally modified. In the case of impact with high energy, the local deformations lead to delaminations, carbon fibers displacing and/or carbon fibers breaking, leading to major local conductivity modifications. These can be emphasized by electromagnetic nondestructive evaluation methods as eddy current EC [2], [3] and pulsed eddy current thermography (PEC) [4], ultrasound (US) [5], [6] or combined methods [7], [8]. For advanced applications (aerospace for example), full monitoring of structures and their functional integrity is imposed. Indifferent of the control method, the results should be efficient and reliable in order to not introduce ambiguities, implying small speed of the control. In principle, an operation of nondestructive evaluation NDE consists in applying a physical field to the object to be examined and the evaluation of its interaction with the eventually material discontinuities, Figure 1.

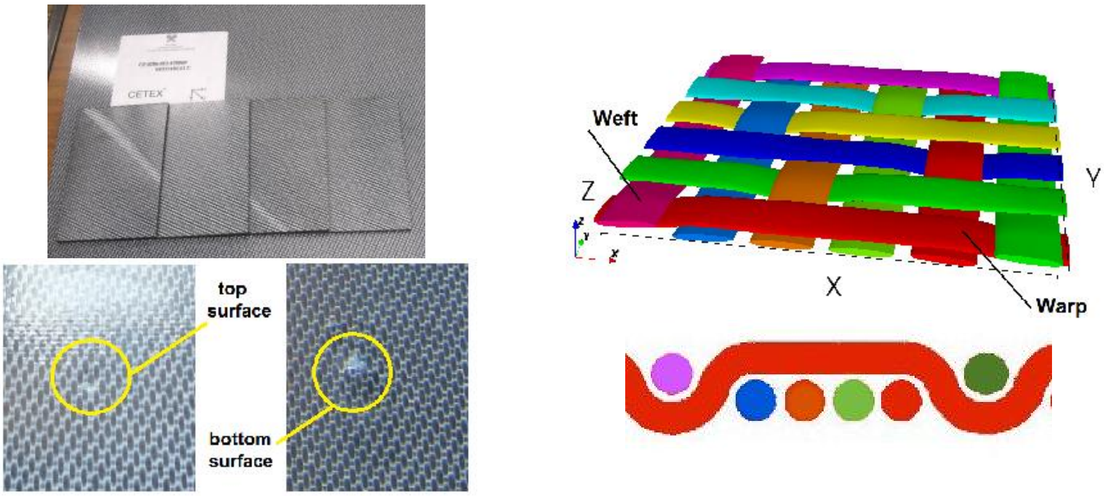
Figure 1: Nondestructive evaluation principle

If the physical field is an electromagnetic field, with frequencies from tens of Hz to tens of GHz or THz, the nondestructive electromagnetic procedure is electromagnetic one (eNDE). When the object to be examined has high electrical conductivity and it has inhomogeneities as voids, inclusions, cracks, etc., with lower conductivity, under the incident electric field, eddy current are induced into the examined object and the inhomogeneity acts as a sum of currents embedded into the tested piece [9]. The induced currents will generate a secondary field in opposition with the incident electromagnetic field. In the case in which the electrical conductivity of tested piece is smaller than of inhomogeneity (case of CFRP with delaminations), the phenomenon which contributes to detection of inhomogeneity is the scattering of electromagnetic field on the conductive regions with different shapes and positions, embedded in dielectric media [10]. As the used frequencies are not high (lower than 1GHz), the incident electromagnetic field is created usually by coils circulated by alternative electrical current or pulsed currents. The detection of electromagnetic field created by the current sources appeared in materials discontinuities or due to scattered field can be carried out by coils. In order to obtain information about regions with conductivities different from the base material, it is necessary that the assembly electromagnetic field generation – detection shall assure the best spatial resolution. It is well known that to obtain the best signal to

noise ratio at detection, leading to the increasing of probability of detection for a high reliability coefficient, it is necessary to use the smallest possible lift-off (the distance between transducer and the object to be controlled) [11], meaning the working in near field [12].
This paper present the possibility to improve spatial resolution of eNDE systems, operating with metamaterials sensors and which focuses the evanescent waves (waves that appear in the spaces between carbon fibers) using the guided structures. The optimal functioning conditions have been established for the sensor with metamaterials, by inversion of data obtained from measuring the network parameters and delamination in CFRP due impacts were emphasized.

2. STUDIED SAMPLES

Samples of CFRP were cropped with dimensions of 150mm×100mm×4.2mm [13]. The CETEX composite, made by Tencate, The Netherlands, is made from PPS matrix reinforced with 12 layers of carbon fibers 5Harness satin fabric type [14]. The carbon fibers are T300JB with 1.75 g/cm^3 density, fabric surface density is 285g/cm^2 and overall fiber volume fraction 50 ± 3% [15]. In figure 2 are presented the studied samples (a), and the layout of 5 Harness satin fabric (b).
The samples were impacted with energies of 2 J, 4 J, 6 J, 8 J, 10 J, and 12 J at room temperature using equipment FRACTOVIS PLUS 9350-CEAST-Instron USA with a hemispherical bumper head having 20 mm diameter and 2.045 kg weight, according to ASTM [13]. The intermediate energy of 8 and 10J has been taken into consideration before the failure of the fibers that have taken place at 12J.



a b

Figure 2: Studied samples: a) composite plates; b) 5 Harness satin fabric layout

The modifications of elastic and mechanics characteristics of delaminated zone is followed, as well their influence over the flexural strength of pieces with slab shape.

3. THE FIELD SCATTERED BY A CONDUCTIVE WIRE ILLUMINATED BY AN ELECTROMAGNETIC PLANE WAVE

Let’s consider a carbon fiber as a conductive wire having diameter 2a and an electromagnetic plane wave illuminates it under an incident angle α, situation presented in Figure 3.
According to boundary condition on the conductive surface

$$E^{inc} + E^{scat} = 0 \tag{1}$$

An expression is required to relate the current induced on a wire by an incident electric field to the scattered field it is produced. For a wire along Z-axis with a radius *a* of length *L*, the relation is [16]

$$\frac{d^2A(z)}{dz^2} + k^2A(z) = j4\omega\varepsilon_0\mu E_z(z) \tag{4}$$

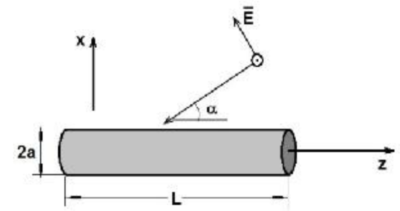


Figure 3: An electromagnetic wave encounters a conductive wire of diameter *2a* and length *L* at angle α

$$A(z) = \int_{-L/2}^{L/2} I_z(z')G(z,z')dz' \tag{5}$$

$$G(z,z') = \int_0^{2\circledR} \frac{\exp(-jkR)}{R} d\text{¤}\,, \tag{6}$$

$$R = \sqrt{(z-z')^2 + \left(2a\sin\frac{\text{¤}'}{2}\right)^2} \tag{7}$$

where A is the vector potential, £_0 is dielectric permittivity of vacuum, I_z is the amplitude of current induced in wire, G is the Green's function of free space, k is the wave number.
The incident electric field along the conductor from a plane wave at angle α is

$$E_z = \exp(jk\cos\sim)\cdot\sin\sim \tag{8}$$

This plane wave will drive the current in a symmetrical manner

$$I(z) = I(-z);\ A(z) = A(-z)$$

The final form of the integral equation of the wire current is

$$\int_{-L/2}^{L/2} I_z(z')G(z,z')dz' = C_1\cos kz + j\frac{4\circledR\mu\text{£}_0}{k^2\sin\sim}\exp(jkz\cos\sim) \tag{9}$$

The eq.(9) is a Fredholm integral equation of the first kind and C_1 is an unknown coefficient that must be determined using, for example, block-pulse functions methods **Error! Bookmark not defined.**. The radiation pattern of this wire is obtained as

$$f(\sim) = \int_{-L/2}^{L/2} I_z(z')\exp(jkz'\cos\sim)dz' \tag{10}$$

and

$$F = 20\log_{10}(f) \quad [dB] \tag{11}$$

We consider an electromagnetic wave with the wavelength in vacuum 1m and the conductive wire having 0.8mm diameter, the same order of magnitude as of the carbon fibers and 1m length. The radiation pattern, F, is presented in Figure 4.

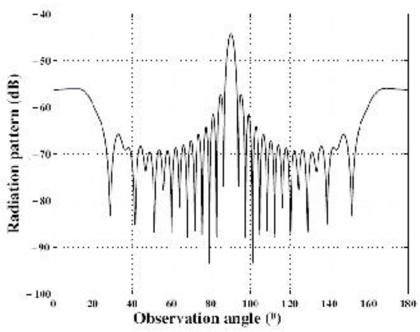


Figure 4: Radiation pattern for a conductive wire with 2a=0.8mm, L=1, λ=1m

The radiation pattern shown in Figure 4 indicates the presence of a lobe for $\alpha=90^0$ as well as a multitude of secondary lobes, with smaller amplitudes. A simple measurement of the scattered field might delivers less information to make an evaluation over some lattice of conductive fibers different oriented, as in the case of CRFP with reinforcement of carbon fibers woven. A possibility to enrich the quantity of information delivered by the electromagnetic examination of CFRP shall consist in the using of the evanescent waves diffraction, the waves that attenuate rapidly and can exist only in the immediate proximity of the material to be examined. The theoretical results presented in Figure 4 show that the optimal value for the angle α is $\pi/2$.

4. METAMATERIAL SENSOR FOR ENDE, THEORETICAL PRINCIPLE OF THE METHOD

MM [17] can provide an engineered response to EM radiation that is not available from the range of naturally occurring materials. The MM is an arrangement of artificial structural elements designed to achieve advantageous and unusual properties. Nowadays, a multitude of MM structural elements types are known, conferring special EM properties [18]. They consist of individual or arrays of elements for which all the geometrical dimensions are small compared to the wavelength operation. MM named Conical Swiss Roll (CSR) consists of a number of spiral wound layers of an insulated conductor on a conical mandrel. Because the wavelength of the EM radiation is large (at 300MHz, the wavelength in air, λ_0=1m), the condition that the element should be much smaller than wavelength is accomplished.

The experimental set-up employed one type of absolute emission-reception sensor with MM lens [12] that have the characteristics, as shown in [19], that assure focusing the EM field and also the evanescent waves. The electric evanescent modes can be manipulated with this sensor [20], functioning in a range of frequency that assures the maximum μ_{eff}. The spatial resolution of the system (the distance between two distinctively visible points) was verified according to [3] and the analysis of data obtained shows that the realization of MM lens in the RF range is possible using the CSR, whose distortions are minimal and whose calculation is made based on Fourier optic principles [21]. Using the Fourier optics method, an object O(x,y) that can represent the eigenmode e_υ or h_υ in function of the polarization of incident EM field, has, while passing through the circular aperture and the lens, an imaging I(x',y') given by

$$I\left(x^{'},y^{'}\right)=\frac{1}{\lambda d_1 d_2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\exp\left[j\frac{k\left(\left(x^{'}-x_1\right)^2+\left(y^{'}-y_1\right)^2\right)}{2d_2}\right]P\left(x,y\right)\exp\left[j\frac{k\left(x_1^2+y_1^2\right)}{2f}\right]\times$$
$$\times\left(\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}O\left(x,y\right)\exp\left[j\frac{k\left(\left(x_1-x\right)^2+\left(y_1-y\right)^2\right)}{2d_1}\right]dxdy\right)dx_1dy_1 \tag{12}$$

where *P(x,y)* is pupil function defined as

$$P\left(x,y\right)=\begin{cases}1, & x^2+y^2\le d^2\\ 0, & otherwise\end{cases}$$

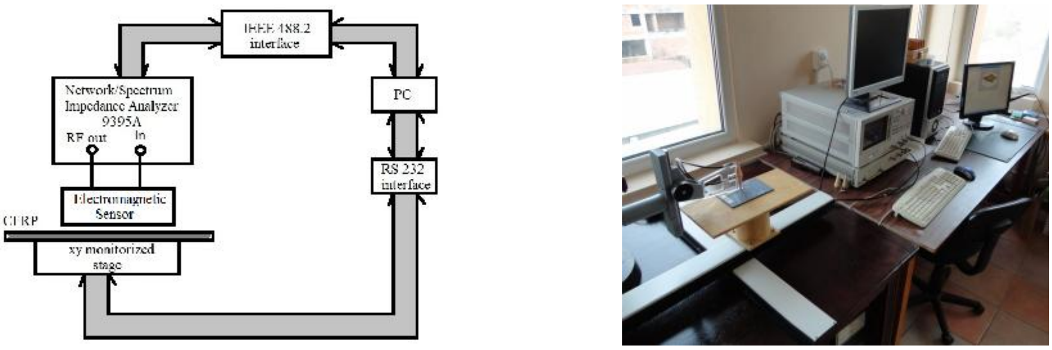
O(x,y) is the object defined as

$$O\left(x,y\right)=\begin{cases}e_\upsilon\left(x,y\right) & for\quad TE_z\quad polarized\quad incident\quad waves\\ h_\upsilon\left(x,y\right) & for\quad TM_z\quad polarized\quad incident\quad waves\end{cases}$$

$d_1 = R + l$ is the distance from the object to the center of the lens, $d_2 = l$ is the distance from the center of the lens to detecting coil and K=2π/λ is the wave number. The detection principle is similar with the one of near-field electromagnetic scanning microscopy (NFESM). NFSEM imaging is a sampling technique, *i.e.*, the specimen (in our case plate CFRP) is probed point by point by raster scanning with the sensor over the specimen surface and recording for energy image pixel a corresponding electromagnetic signature. The reception coil functions as a detection antenna, converting localized energy into an electromotive force.

5. EXPERIMENTAL SET-UP

The principle of the experimental set-up is presented in figure 5.



a b

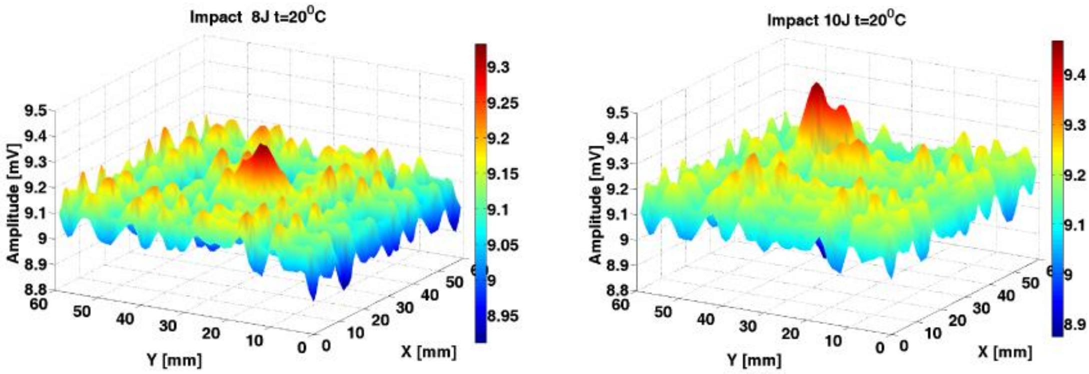
Figure 5: Experimental set-up. a) basic diagram; b) equipment

The EM sensor with MM lens [11] is connected to a Network/Spectrum/Impedance Analyzer type 4395A Agilent USA. During the measurements, the sensor was fixed and the samples is mounted on a XY displacement system, type Newmark USA that assures the displacement in both horizontal direction with ±10 μm precision. A PC allows the command of displacing system and measurement instruments, the data being acquired and stored automatically by a code developed in Matlab 2014. The electromotive force induced in the reception coil of measurement system in the average of 10 measurements in the same point in order to reduce the effect of the white noise, the bandwidth of the analyzer being set-up to 10 Hz, also diminish the noise level. The frequency dependency of lens effective magnetic permeability has been determined measuring the S parameters (S_{11} and S_{12}) and applying the effective medium method [19], [22], using also Agilent 4395A Analyzer coupled with Agilent S Parameters Test kit 87511A. The real component of the effective magnetic permeability reaches the maximum value at 473.8 MHz and the value of -1 at 476 MHz. The distance between screen aperture of sensor and surface to be examined has been maintained at 20μm±1 μm. The rectangular frame used for generation of polarized EM field have one turn with size of 20x60mm, 1mm diameter of Cu wire.

6. RESULTS AND DISCUSSIONS

The plates have been examined by electromagnetic method with the sensor with MM lens [3]. According the measurement conditions presented above, the examined plate is placed in the aperture plan, the detection coil being placed in the focal plan of the lens. The control frequency was 476 MHz.

In figure 6a is presented the amplitude of the signal delivered by the sensor at the scanning of a region containing a delamination induced by impact with 8J and in Figure 6b, that for impact with 10J. It can be observed on the edge of images that the structure of carbon fiber woven is emphasized. The delaminated region has been confirmed by measurements using ultrasound method with phased array sensor (Figure 7).



a b

Figure 6: Signal delivered by EM sensor s at the scanning of delaminated area due to impact with: a) 8J; b) 10 J

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. 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 [23].

Figure 7: Phased array sensor

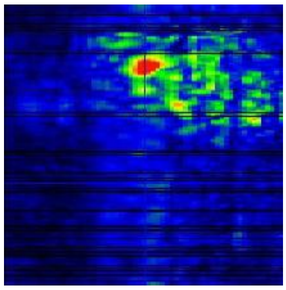


Figure 8: Ultrasound image using phased array sensor and TOP VIEW mode for sample impacted with 8J.

7. CONCLUSIONS

The EM method permits to render evident local modifications of the transverse electric conductivity in composite materials, as results of impacts. Using a type of EM sensor with MM lens CSR type, a series of applications such as eNDE procedures can be designed. The use of evanescent waves and the lens with MM in construction of EM sensor allow the increasing the spatial resolution. For a CFRP composite plate with 5H satin woven carbon fibers in order to significantly improve the spatial resolution of EM method, the use of evanescent waves that can appear in the space between the carbon fibers in CFRP and on the edge of open micro cracks is proposed.

ACKNOWLEDGEMENTS
This paper is supported by Romanian Ministry of National Education under project UEFISCDI PN-II-ID-PCE-2012-4-0437 and Nucleus Program, Contract PN 16 37-01-01.

REFERENCES

[1] Grimberg, R., Savin, A. and Rotundu, C.R., 2001. Eddy current microscopy applied to graphite-epoxy composite. Sensors and Actuators A: Physical, 91(1), pp.73-75.
[2] Grimberg, R., Premel, D., Savin, A., Le Bihan, Y. and Placko, D., 2001. Eddy current holography evaluation of delamination in carbon-epoxy composites. INSIGHT, 43(4), pp.260-264.
[3] Savin, A., Steigmann, R., Bruma, A. and Šturm, R., 2015. An electromagnetic sensor with a metamaterial lens for nondestructive evaluation of composite materials. Sensors, 15(7), pp.15903-15920.
[4] He, Y., Tian, G., Pan, M. and Chen, D., 2014. Impact evaluation in carbon fiber reinforced plastic (CFRP) laminates using eddy current pulsed thermography. Composite Structures, 109, pp.1-7.
[5] Shen, Q., Omar, M. and Dongri, S., 2012. Ultrasonic NDE techniques for impact damage inspection on CFRP laminates. Journal of materials science research, 1(1), p.2.
[6] Mook G, Pohl J, Michel F., 2003.Non-destructive characterization of smart CFRP structures. Smart Materials and Structures 12 997–1004 - PII: S0964-1726(03)70305-X
[7] Gros, X.E., Ogi, K. and Takahashi, K., 1998. Eddy current, ultrasonic C-scan and scanning acoustic microscopy testing of delaminated quasi-isotropic CFRP materials: a case study. Journal of reinforced plastics and composites, 17(5), pp.389-405.
[8] Zhang, J., Li, W., Cui, H.L., Shi, C., Han, X., Ma, Y., Chen, J., Chang, T., Wei, D., Zhang, Y. and Zhou, Y., 2016. Nondestructive Evaluation of Carbon Fiber Reinforced Polymer Composites Using Reflective Terahertz Imaging. Sensors, 16(6), p.875.
[9] Van Bladel, J.G., 2007. Electromagnetic fields(Vol. 19). John Wiley & Sons.
[10] Balanis, C.A., 2012. Advanced engineering electromagnetics. John Wiley & Sons.
[11] Savin, A., Bruma, A., Steigmann, R., Iftimie, N. and Faktorova, D., 2015. Enhancement of Spatial Resolution Using a Metamaterial Sensor in Nondestructive Evaluation. Applied Sciences, 5(4), pp.1412-1430.
[12] Savin, A., Steigmann, R. and Bruma, A., 2014. Metallic Strip Gratings in the Sub-Subwavelength Regime. Sensors, 14(7), pp.11786-11804.
[13] ASTM D7136 / D7136M - 15 Standard Test Method for Measuring the Damage Resistance of a Fiber-Reinforced Polymer Matrix Composite to a Drop-Weight Impact Event
[14] Akkerman, R., 2006. Laminate mechanics for balanced woven fabrics. Composites Part B: Engineering, 37(2), pp.108-116.
[15] www.tencate.com
[16] Bancroft, R., 1996. Understanding Electromagnetic Scattering using the Moment Method: A Practical Approach Artech House.
[17] Veselago, V.G., 1968. The electrodynamics of substances with simultaneously negative values of ε and μ. Soviet physics uspekhi, 10(4), p.509.
[18] Smith, D.R., Pendry, J.B. and Wiltshire, M.C., 2004. Metamaterials and negative refractive index. Science, 305(5685), pp.788-792.
[19] Grimberg, R., 2013. Electromagnetic metamaterials. Materials Science and Engineering: B, 178(19), pp.1285-1295.
[20] Grimberg, R., Savin, A., Steigmann, R., Serghiac, B. and Bruma, A., 2011. Electromagnetic non-destructive evaluation using metamaterials. Insight-Non-Destructive Testing and Condition Monitoring, 53(3), pp.132-137.
[21] Born, M. and Wolf, E., 1980. Principles of optics. Pergamon, New York, 19891, pp.747-754.

[22] Chen, X., Grzegorczyk, T.M., Wu, B.I., Pacheco Jr, J. and Kong, J.A., 2004. Robust method to retrieve the constitutive effective parameters of metamaterials. Physical Review E, 70(1), p.016608.
[23] Grimberg, R., Savin, A., Steigmann, R., Bruma, A. and Barsanescu, P., 2009. Ultrasound and eddy current data fusion for evaluation of carbon-epoxy composite delaminations. Insight-Non-Destructive Testing and Condition Monitoring, 51(1), pp.25-31.