Damage detection of carbon reinforced composites using nondestructive evaluation with ultrasound and electromagnetic methods

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Abstract. CFRP have applications among most different domains due their low density, high elastic modulus and high ultimate strength along the carbon fibers direction, no fatigue and the expansion coefficient is small. This paper presents the behavior of carbon fiber woven-PPS composites at low velocity impacts. The transversal electrical conductivity is modified due to the plastic deformation following the impacts, and thus electromagnetic procedures can be used for assessment of CFRP using a high resolution sensor with metamaterials lens and comparing the results with those obtained from ultrasound testing with phased array sensor. The area of the delamination is overestimated when the method of phased array ultrasound is used and substantially underestimated by the electromagnetic testing. There were a good agreement between the simulations with finite element method and experimental measurements.

1. Introduction

Carbon fiber reinforced plastics composites are lightweight, strong materials used in the manufacturing of numerous products, from the sports goods to aerospace industry components. CFRP allow the production of goods without scrap parts, becoming a cost effective technology [1]. In general, CFRP composites use thermosetting resins such as epoxy, polyester, or vinyl ester. High performance thermoplastic resins and more particularly Polyphenylene sulfide (PPS) [2] represent a promising alternative to thermosetting resins problems because it offers a number of advantages over epoxy resins (chemical and impact resistance over a wide range of temperatures, high hardness and stiffness and superb long-term creep under load properties, extremely low moisture absorption).

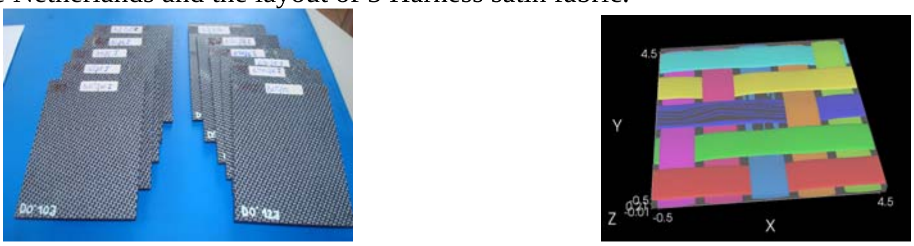
For 2020, it is estimated that the carbon fiber demand will outstrip supply, doubling the production of 2015 (tripling the production of 2010). In order to avoid the incurring of all costs within selection between good and bad parts, NDE is required from the manufacturing stage of composites, from base fiber and production of matrix. Nondestructive evaluation is no longer about “pass/fail” [3]. NDE should provide validation of ply sequences and fiber/woven orientation, the state of the matrix, parameters of the final materials. Low velocity impacts (LVI), that can be defined by quasi-static events of which superior limits can be in the range of tens of m/s [4], depending on material properties as stiffness, can produce delaminations, carbon fiber breaks, cracking of matrix [5] etc.

Usually, CFRP are tested through C-scan or top view ultrasound [6], Lamb waves using noncontact transducers [7], with Hertzian contact [8] or compression waves generated by normal transducers. Also, microwave [9], electrical resistivity measurement [10], shearography [11], acoustic emission [12] can be used in testing CFRP. Carbon fiber have a low electrical conductivity [13], allowing CFRP to be tested using electromagnetic methods. The electromagnetic investigation of CFRP can be done using sensors with orthogonal coils [14], eddy current sensor with 16 individual sensor pairs [15], sensors with metamaterials lens [16], etc.

This paper present the possibility to use a high resolution sensor based on metamaterials lens to assess the delaminations in CFRP with Polyphenylene sulphide matrix reinforced with carbon fibers woven fabric, created by LVI and comparing the results with those obtained from top scan ultrasound using phased array method.

2. Studied samples

The plates taken into study have the dimensions of 150mm×100mm×4.2mm [17]. The composite, named CETEX, is made from PPS matrix reinforced with 12 layers of carbon fibers 5Harness satin fabric type. 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% [18]. In figure 1 are presented the studied samples, made by Tencate, The Netherlands and the layout of 5 Harness satin fabric.



a. b.

Figure 1. Studied samples: a) composite plates; b) 5 Harness satin fabric layout.

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 [17]. The intermediate energy of 10J has been taken into consideration before the failure of the fibers that have taken place at 12J.

3. Experimental setup

3.1. Mechanical tests

The conditions of impacts were established by simulating the Drop Weight impact method [19] using Finite Element Method (FEM). Drop weight testing is the preferred method when using low velocity impact testing and the results may also be enhanced with post impact testing. The energy of impact can be calculated knowing the mass of the impactor *m* and the height of dropping *h* as $E = m \cdot g \cdot h$, where *g* is the gravitational acceleration. The geometry of the impact is presented in figure 2, where the displacement of the impactor δ is the sum of the displacement of the impacted plate median plane ω and the plastic deformation of the plate after impact α, as $\delta = \omega + \alpha$. The displacement of the composite plate during the impact is

$$\delta = \iint_i \frac{F(t) - gM_{total}}{M_{total}} dtdt \tag{1}$$

with δ the displacement of the plate in point *i*; *F(t)* is recorded by the data acquisition system, M_{total} is total mass of the impactor. The absorbed energy until the *i* point is calculated as the area described by the curve in the Force-Displacement diagram

$$E_i = \int_i F(\delta) d\delta \tag{2}$$

The speed till point *i* is calculated by simple integration of Force-Time diagram

$$v_i = \int_i \frac{F(t) - gM_{total}}{M_{total}} dt \tag{3}$$

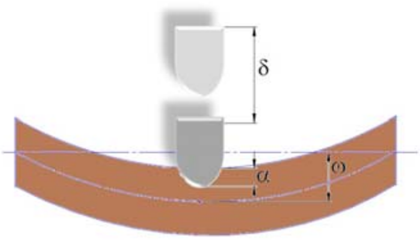


Figure 2. Geometry of the impact of plate.

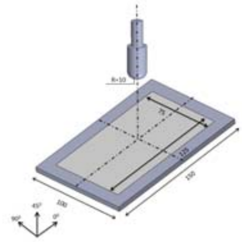


Figure 3. Dimensions of sample for the impact tests [17].

3.2. Electromagnetic testing

The plates were examined using the sensor with metamaterial lens for detection. The sensor has the emission part made from a 20mm diameter coil, 2 turns of Cu wire (1.2mm diameter). The reception coil has a 1mm diameter, 2 turns of Cu wire (0.1mm diameter). In front of the reception coil is placed a conductive screen made from a flexible foil LONGLITE^{TM}200 produced by ROGERS CORPORATION USA, having a circular aperture, with 0.1mm diameter, coaxially placed at 0.05mm distance from the reception coil. The screen was grounded. The circular aperture serves for the diffraction of the evanescent waves, appeared in the slits. A conical Swiss roll [20] is placed above the reception coil and acts as metamaterials allowing the transmission of the evanescent waves [20] from the region between carbon fibers towards the reception coil (Figure 4). The transducer was fixed, being connected to the Network/Spectrum/Impedance Analyzer 4395A Agilent USA. The plate is displaced by a motorized XY stage Newmark USA, commanded by PC through RS232 interface. The command and the data acquisition were made through a GPIB IEEE 488 interface, using programs elaborated in Matlab 2014a. The surface was raster scanned using 1mm steps in both directions.

3.3. Ultrasound testing

The testing using ultrasound phased array sensors has been effectuated using Phasor XS - GE USA. The sensor contains a linear array of 32 sensors having the pitch of 0.5mm and the central frequency 5MHz. The sensor is placed on an edge of 36° and the displacement has been assured by an axial scanned ENCSTD with linear encoder (Figure 5). The coupling is a gel with average viscosity.

Figure 4. Electromagnetic testing.

Figure 5. Ultrasound testing.

4. Experimental results and discussions

The composite specimen prepared for mechanical tests, is cropped from the central region of a sample impacted with 10J. This impact only produce a dent. The tensile tests were done using Instron E8801 with a displacement speed of 0.2mm/min, using the pressure of 70barr [21]. In figure 6 is presented the residual stress at tensile test after impacts. Approximating the plot as a parabola, it can be shown that the residual stress of the sample impacted with 12 J energy is 50% from the non-impacted samples.

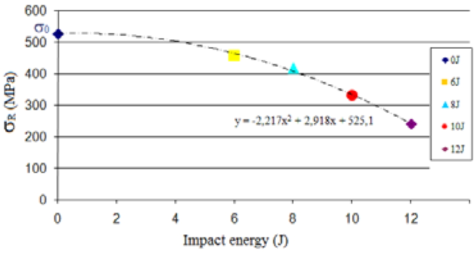


Figure 6. Residual stress vs impact energy.

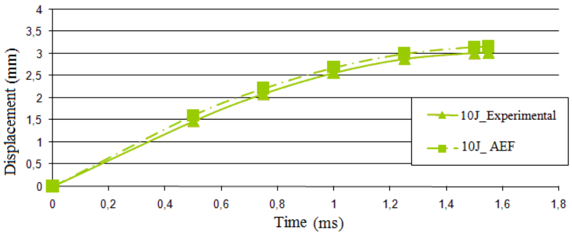


Figure 7. Displacement of the center of the plate during the impact vs time at 10J energy impact.

Taking into account the values of displacement at impact simulated by FEM in the conditions specified above, there were found a good concordance with the values experimentally determined during the impact tests (Figure 7). The tests were determined on the sample impacted with 10J, energy below the energy where breaking of the fiber appears [22].

Microscopic analysis using Olympus Microscope BX51 of the composite specimens impacted with 10J has been effectuated for evaluation of the the damage initiation and propagation of delamination. The specimen has been cut on the middle of the impacted zone and prepared for optical inspection. The damage developed in the 5-HS fabric under impact takes the form of weft yarn cracking, which is perpendicular to the loading direction. The damage is developed at the yarn crossover positions, and then propagates into the matrix (Figure 8).

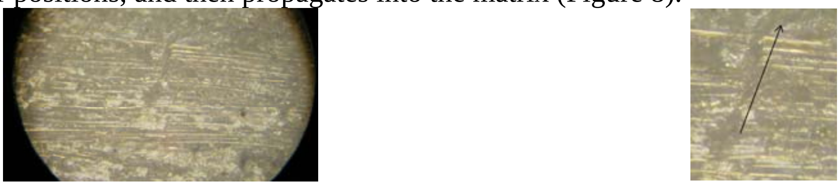
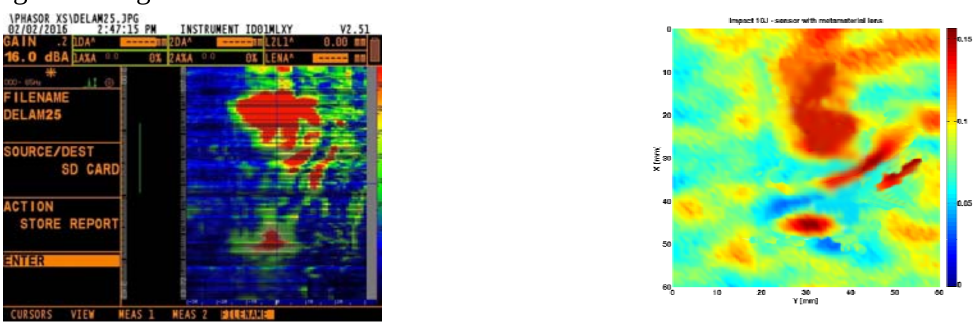


Figure 8. Microscopic analysis of the edge of specimen cut on the middle axis of the impacted zone.

From the point of view of nondestructive evaluation, the two complementary methods presented above were involved in determination of the area of delamination due to impact with energy of 10J, the energy below the value where the breaking of fibers occurs. Both types of measurements were effectuated on the impacted face of the plate. In figure 9a is presented the ultrasound image of top scan obtained at the scanning of the plate impacted with 10 J energy meanwhile in figure 9 b is obtained the electromagnetic image.



a. b.

Figure 9. Scanning of the plate impacted with 10J energy: a) ultrasound; b) electromagnetic image.

The obtained experimental results show that the area of delamination is overestimated by the proposed ultrasound method and it is underestimated by the electromagnetic. The impact damage exists at different levels through thickness. The delamination near the back wall is larger than the ones near the front wall (where the impact took place), there is rapid local bending at the impact point and at the face of the delamination, almost all the energy will be reflected back to the sensor as an echo. It is not possible to penetrate past the first incident delamination to those in its shadow; all the energy is then confined between the first incident delamination and the front wall to create repeat echoes. Multiple level delaminations are detected by virtue of the conical damage feature (those near the back wall being larger in area).The underestimation using electromagnetic method is given by modification of transversal electrical conductivity of the composite material due to the impact, that took place in the central region of the impact, where the material suffers a plastic deformation. The electromagnetic sensor "senses" only the subsurface delamination.

5. Conclusions

CFRP plates made from 12 layers of carbon fibers 5Harness satin fabric embedded into PPS matrix have been impacted with different energies in order to study their damage using nondestructive evaluation methods by means of ultrasound phased array and electromagnetic sensors. The residual stress of the sample impacted with 12 J energy is 50% from the non-impacted samples. The area of delamination is overestimated by phased array ultrasound method because the delamination on the back face is larger than the ones on the impacted face and due to repeated back end echoes and respectively is underestimated by the electromagnetic method due to plastic deformation that modify local conductivity. In order to obtain more eloquent results, a fusion of data obtained by both nondestructive evaluation methods using Dempster Shafer theory of evidence is required and will be further studied.

Acknowledgments

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References

[1] Morgan P 2005 Carbon fibers and their composites *CRC press*
[2] Vielle B and Taleb L 2011 About the influence of temperature and matrix ductility on the behavior of carbon woven-ply PPS or epoxy laminates: Notched and unnotched laminates *Composite Science Technology* **71** pp 998-1007
[3] Brosius D 2016 Advanced composites – An idealized future *Composites World*
[4] Richardson M O W and Wisheart M J 1996 Review of low-velocity impact properties of composite materials *Composites Part A: Applied Science and Manufacturing* **27(12)** pp 1123-1131
[5] Abrate S 1991 Impact on Laminated Composite Materials *Appl Mech Rev* **44(4)** pp 155-190
[6] Hosten B and Castaings M 2008 Comments on the ultrasonic estimation of the viscoelastic properties of anisotropic materials *Composites Part A: Applied Science and Manufacturing*. **39(6)** pp1054-1058
[7] Su Z, Ye L and Lu Y 2006 Guided Lamb waves for identification of damage in composite structures: A review *Journal of sound and vibration* **295(3)** pp 753-780
[8] Grimberg R, Savin A, Steigmann R, Bruma A and Barsanescu P 2009 Ultrasond and eddy current data fusion for evalution of carbon-epoxy composite delaminations *Insight-Non-Destructive Testing and Condition Monitoring* **51(1)** pp 25-31
[9] Sediq A S B and Qaddoumi N 2005 Near-field microwave image formation of defective composites utilizing open-ended waveguides with arbitrary cross sections *Composite Structures* **71(3)** pp 343-348
[10] Park J M, Lee S I and DeVries K L, 2006 *Composites Part B: Engineering* **37(7)** pp 612-626
[11] Hung Y Y 1999 Applications of digital shearography for testing of composite structures *Composites Part B: Engineering* **30(7)** pp 765-773

[12] Park J M, Kim P G, Jang J H, Wang Z, Kim J W, Lee W I, Park J G and DeVries K L 2008 Self-sensing and dispersive evaluation of single carbon fiber/carbon nanotube (CNT)-epoxy composites using electro-micromechanical technique and nondestructive acoustic emission *Composites Part B: Engineering* **39(7)** pp 1170-1182

[13] Mook G, Lange R and Koeser O 2001 Non-destructive characterisation of carbon-fibre-reinforced plastics by means of eddy-currents *Composites science and technology* **61(6)** pp 865-873

[14] 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

[15] Schulze M H, Heuer H, Küttner M and Meyendorf N 2010 High-resolution eddy current sensor system for quality assessment of carbon fiber materials *Microsystem technologies* **16(5)** pp 791-797

[16] Grimberg R and Savin A 2011 Electromagnetic transducer for evaluation of the structure and integrity of composite materials with polymer matrix reinforced with carbon fibers *(Patent no. RO126245-A0)*

[17] 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

[18] ***www.tencate.com

[19] ASTM D 3763, High Speed Puncture Properties of Plastics Using Load and Displacement Sensors 1997

[20] Grimberg R, Savin A and Steigmann R 2012 Electromagnetic imaging using evanescent waves *NDT & E International* **46** pp 70-76

[21] ***www.vishaypg.com/docs/11331/125tm.pdf

[22] 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)** pp15903-15920