Examination and monitoring of carbon epoxy composites structures

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Abstract - In the present paper we propose the development of a new method of ultrasound and eddy current data fusion using the theory of evidence given by Dempster and Schafer..

Keywords: ultrasound, eddy current, carbon epoxy composites.

1 Introduction

Given their specific characteristics, the carbon-epoxy composites are used in different applications, from airspace industry to sporting goods. As compared to the metallic materials, carbon-epoxy composites show a series of advantages, among which a high tensile strength, low density and thermal expansion coefficient, absence of phenomena specific to the fatigue state, possibility of a relatively simple manufacturing of large layered structures.

Yet, one of there major disadvantages one should mention the reduced resistance to impact that can induce, depending on their energy, fiber shift or delamination or even fractures. The carbon-epoxy composites exhibit electric properties that depend on the type of carbon fibers and on their volume fraction in the material, having the transverse electric conductivity between 10 and 100S/m, and longitudinal conductivity ranging between $5x10^3$ and $5x10^4$S/m.

In the case of low energy impacts, the composite gets elastically deformed and no local alteration of the electric conductivity occurs. In the same time, desbondings on small zones of reinforcing fibers from the resin epoxy matrix can appear.

The impacts of small energy would be, in principle, detected by ultrasound procedures, such as: acoustic microscopy [1], but cannot be emphasized by electromagnetic methods [2]. For high energy impacts, the local deformation results in delamination, deviation and /or breaking of the carbon fibers. In this case, local modifications of the electric conductivity occur, that can be detected by eddy current methods [3], [4] and by ultrasound methods [5], [6]. Yet, irrespective of the utilized examination methods, they should be effective, secure and should introduce no ambiguities, all these at the higher possible control speed.

A solution for this problem can be constituted by data fusion [7].

In the present paper, we propose the development of a new data fusion method using the theory of evidence given by Dempster [8] and Schafer [9]). The data sets which will fusion come from eddy current examination of impacted zones, the results being presented under the form of eddy current holography [2], [10], and by low frequency ultrasound examination using the transducers with hertzian contact and measuring propagation speed for u.s. beam.

2 Evidence theory's formalism

Let X be the universal set, the set of all states under consideration. The power set, P(X), is the set of all possible sub-sets at X, including empty set, Φ.

The elements of the power set can be taken to represent propositions that are might be interested in, by containing all and only the states in which this proposition is true.

By definition, the mass of the empty set is zero

$$m\left(\Phi\right)=0 \tag{1}$$

The masses of the remaining members of the power set add up to a total of 1

$$1=\sum_{A\in P\left(X\right)} m\left(A\right) \tag{2}$$

The mass m(A) of a given member of the power set, A, expresses the proportion of all relevant and avoidable evidences that supports the claim that the actual state belongs to A but no particular subset of A. The value of m(A) pertains only to the set A and makes no additional claims about any subsets of A, each of which has, by definition, its own mass. The problem is how to combine

two independent sets of mass m_1 and m_2 assignments. The combination is calculated in the following manner [8]:

$$m_{1,2} \quad \phi \quad = 0$$

$$m_{1,2} \quad A \quad = \frac{1}{1-K} \sum_{B \cap C = A \neq \phi} m_1 \quad B \quad m_2 \quad C \tag{3}$$

where

$$K = \sum_{B \cap C = \phi} m_1 \quad B \quad m_2 \quad C \tag{4}$$

K is a measure of the amount of conflict between the two mass sets. The normalization factor, 1-K, has the effect of completely ignoring conflict and attributing any mass associated with conflict to the null set.

The Dempster's rule of combination (3) and (4) is a generalization of Bayes theorem [11] where events are independent.

The problematic we want to solve is the 2D reconstitution of a surface in a carbon-epoxy plate that we inspect with two techniques: low frequency ultrasound by measuring the speed of surface waves and eddy-current holography.

The data fusion should enable us to take advantages of the particularities of both methods. Therefore we are going to calculate the evidence mass associated to each method and then fuse them to obtain the global evidence mass representing the global knowledge we have about the inspected component.

On each pixel of the reconstruction surface we consider three hypotheses:

- hypothesis of delamination presence, associated to an evidence mass that we call positive evidence;
- hypothesis of delamination absence, associated to an evidence mass that we call negative evidence;
- hypothesis of delamination presence or absence, associated to evidence mass that we call doubt.

The method used for the calculation of the evidence masses is based on a comparison between the local and global amplitude distribution around the considered pixel. Here, the concept of local corresponds is defined as the neighborhood of the pixel. The global concept includes all the pixels.

The calculation stages are the following:

- we calculate the amplitude average and the standard deviation on the neighborhood;
- we calculate two indicators: low limits corresponding to the amplitude average minus standard deviation; high limit corresponding to the amplitude average plus standard deviation.
- we suppose that the global amplitude distribution is described by a normal distribution.

The area under this curve up to the low limit corresponds to the positive evidence.

The area under the curve from the high limits corresponds to the negative evidence and the area under the curve between low and high limits corresponds to the doubt (Figure 1).
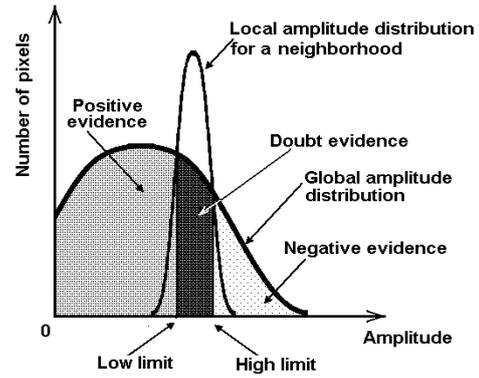

Figure 1. Definition of evidence masses

3 Studied samples

Carbon epoxy composite plates, having 48 layers id carbon fibres with $200 \times 200 \times 5$mm dimensions and the layout $45_2, 0_2, -45_2, 90_2 \quad _S$ were taken in study.

For all the plates, the fiber's specific volume was 0.56 and density 1.58×10^3kg/m^3. The plates were impacted with 0.5J, 2.5J, 3J and 4J energies.

Ultrasound examination of plates from carbon epoxy composites

The experimental set-up is presented in Figure 2a and the transducers in Figure 2b. The frequency of the US beam is 60 kHz.

The transducers were coupled with the examined material through hertzian contact [12] using buffer rods made from 7075-T6 aluminum-magnesium alloy, with the density 2.7×10^3 kg/m^3, the Young modulus 7×10^{10}N/m^2, the Poisson coefficient 0.34 and a point curvature radius of 3mm.

The emission transducer is pressed on the plate surface with 10N force. The propagation speed of the US beam is measured through the measurement of the time of propagation, the distance between the emission and reception transducers being maintained constant, with an UK 14-PM US equipment that allows the measurement of the propagation speed with a precision of $\pm 0.1\mu$s. The plates of composites were placed on a Newmark X-Y displacement system that assures the displacement in plan with $\pm 10\mu$m precision and a rotation with ± 2".

In Figure 3 we present the angular dependency of US propagation speed on a zone without delamination. In figure is shown the average propagation speed as well as the average value *±3x dispersion a.*

In the moment in which a delaminated zone exists between the emission transducer and the reception one, a decrease of propagation speed is observed, exceeding the threshold value.

$$V_{thr} = \overline{V} - 3\sigma \tag{5}$$

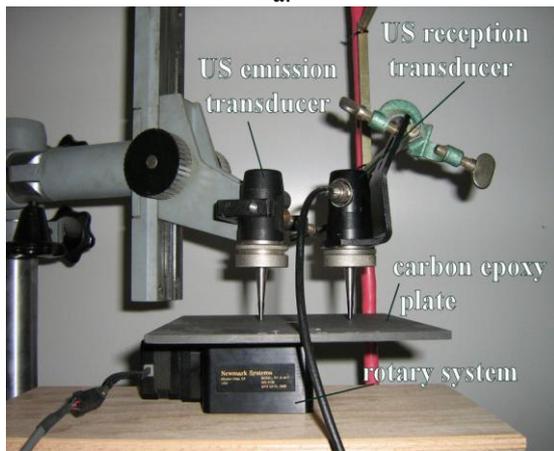where $\overline{V}$ is the medium speed and σ is the dispersion.

In Figure 4 we present the three position of the emplacement of emission transducer and the angles where the measured propagation speed is smaller than

the propagation speed given in (5). In this way, by triangulation, the delamination location is determined.

a.

b.

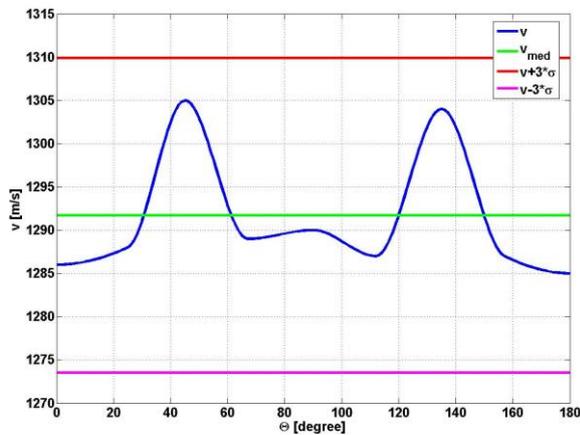Figure 2 Experimental set-up:a) Equipment; b) US transducers

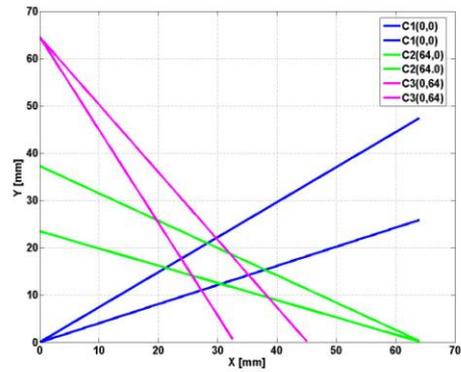Figure 3. The angular dependency of US propagation speed on a zone without delamination
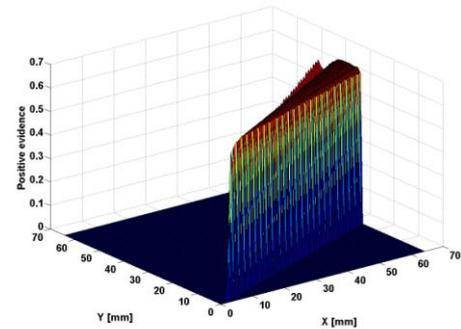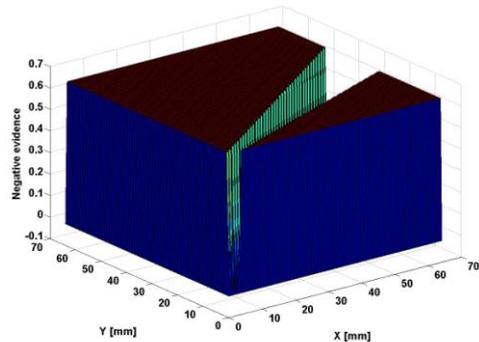

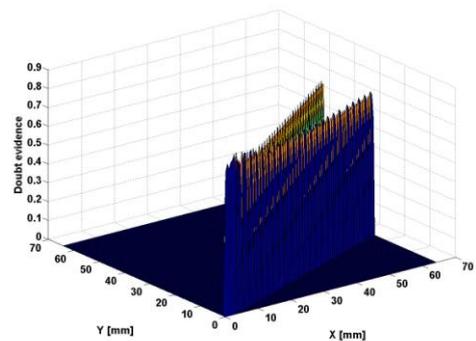Figure 4. The angular positioning of emission transducers

For each of the three positions of the emission transducer (meaning for each angular US beam) the evidence masses were calculated, considering a neighborhood of 8 pixels around the considered pixel (a neighbor for each direction).

a.

b.

c.

Figure 5. The evidence for ultrasound beam with centre in C_1.:a) positive evidence; b) negative evidence: c) doubt evidence

In figures 5 a, b, c we present for exemplification the positive evidence, negative evidence and doubt for ultrasound beam with centre in C_1.

We note: PE_1, NE_1 and DE_1 respective PE_2, NE_2 and DE_2, positive evidence, negative evidence and doubt for beam with centre in C_1 respective in C_2. We perform the data fusion between the indications from the two beams using the relations:

$$PE_{1-2} = PE_1 \times PE_2 + PE_1 \times DE_2 + DE_1 \times PE_2 \ / \ 1 - K_{1-2}$$

$$NE_{1-2} = NE_1 \times NE_2 + NE_1 \times DE_2 + DE_2 \times NE_2 \ / \ 1 - K_{1-2}$$

$$DE_{1-2} = DE_1 \times DE_2 \ / \ 1 - K_{1-2}$$

(6)

where $K_{1-2} = PE_1 \times NE_2 + NE_1 \times PE_2$

In same manner we proceed for data fusion with the ultrasound beam with centre in C_3, too.

$$PE_{1-2-3} = PE_{1-2} \times PE_3 + PE_{1-2} \times DE_3 + DE_{1-2} \times PE_3 \ / \ 1 - K_{1-2-3}$$

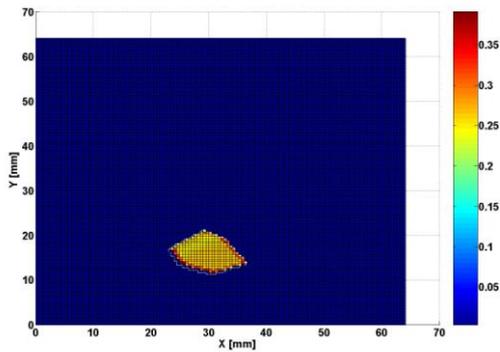$$NE_{1-2-3} = NE_{1-2} \times NE_3 + NE_{1-2} \times DE_3 + DE_{1-2} \times NE_3 \ / \ 1 - K_{1-2-3}$$

$$DE_{1-2-3} = DE_{1-2} \times DE_3 \ / \ 1 - K_{1-2-3}$$
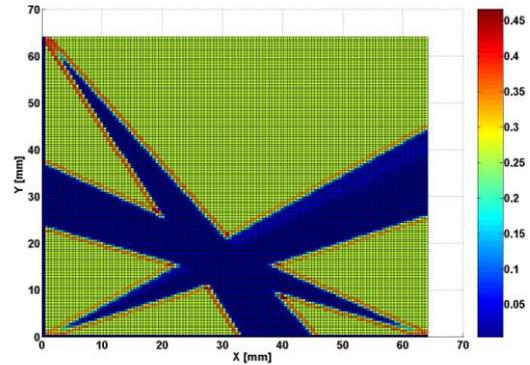
(7)

where $K_{1-2-3} = PE_{1-2} \times NE_3 + NE_{1-2} \times PE_3$

The result of the data fusion between three ultrasound examinations sets are shown in Figure 6.
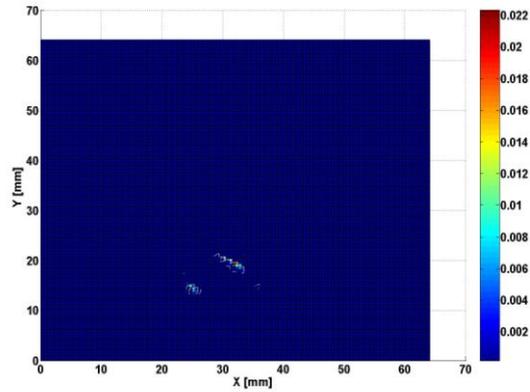
Comparing data from Figure 6a with data from figure 4 it is observed that the image of delaminated zone decrease due to the data fusion.

a.

b.

c.

Figure 6. The evidence for US data fusion: a) positive evidence; b) negative evidence: c) doubt evidence

4 Eddy current holography

The composites plates were fixed on a displacement system X-Y, assuring the scanning of 64×64mm with 1 mm step on both directions.

Eddy current inspection was made with a transducer with orthogonal coil [3], the frequency of control being of 2,2MHz and the lift-off 1mm. The signals are generated and processed by 4395A HP Agilent Impedance/Spectrum/Network Analyzer coupled through IEEE 488 interfaces with a PC which command the displacement system, too.

In figure 7 a and b is presented the information about amplitude and respective phase for signal induced in reception coil of transducer at the scanning of a zone of carbon-epoxy composite which presents a delamination due to an impact with 2.5J energy. The periodical structure which is observed in the data from figure 7, is due to the carbon fibers of the plate and their influence was diminished through wavelets filter with Daubechy 2 wavelets.
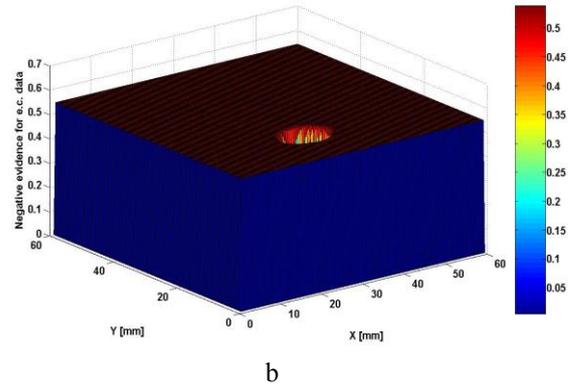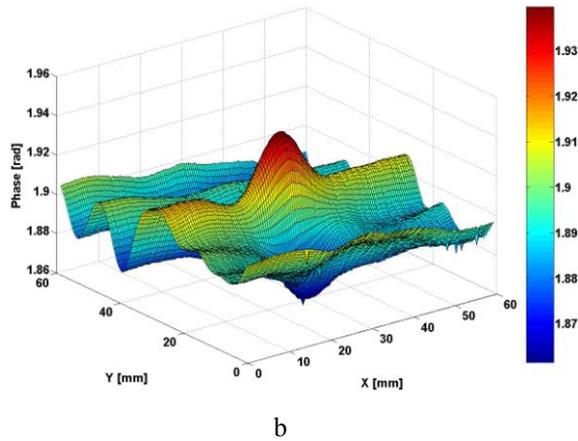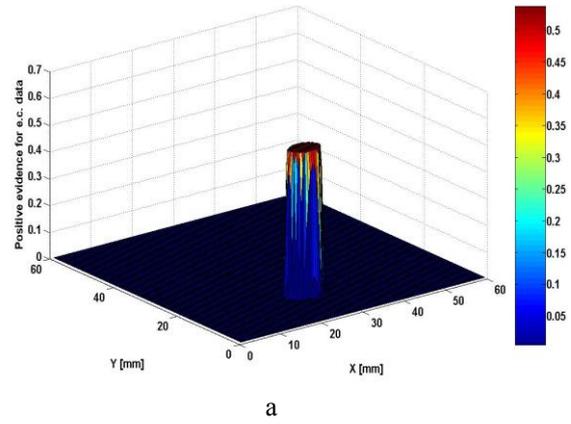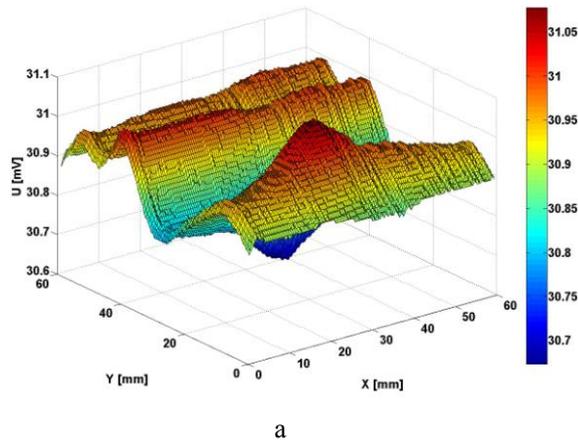
a

b

Figure 7. Eddy current signal at the scanning over a delamination: a) amplitude; b) phase

Figure 8. Eddy current holography

a

b

c

Figure 9. The evidence for eddy current examination: a) positive evidence; b) negative evidence: c) doubt evidence
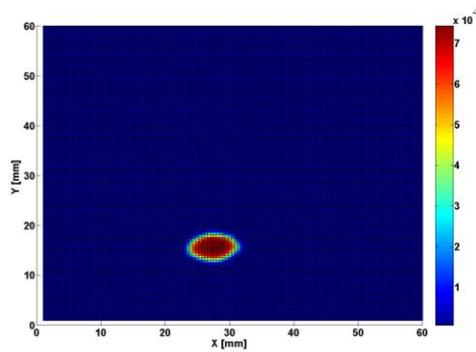
The procedure to obtain the eddy current holography was described in [3], [13]. The method presents the advantage that gives in one representation both the information about amplitude and phase obtained from eddy current transducer. In figure 8 we show the holography image of a delamination due to an impact with energy of 2.5J.

Figure 9 a, b, c presents the positive evidence, the negative evidence and the doubt for case delamination presented above, the sizes are calculated in a similar manner with the one used in ultrasound examinations.
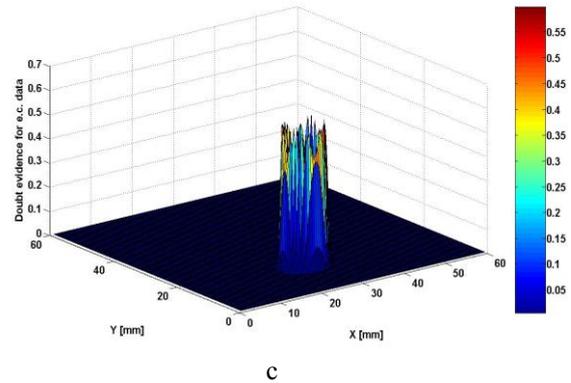
5   Data fusion US eddy current

The data fusion proceeded from ultrasound examination (figure 6) and the one proceeded from eddy current examination (figure 9) was achieved in the manner presented previously.

In Figure 10 we present the data fusion results, positive evidence for a carbon-epoxy plate impacted with 2.5J energy. The same method of data fusion was applied for all the plates take in study.
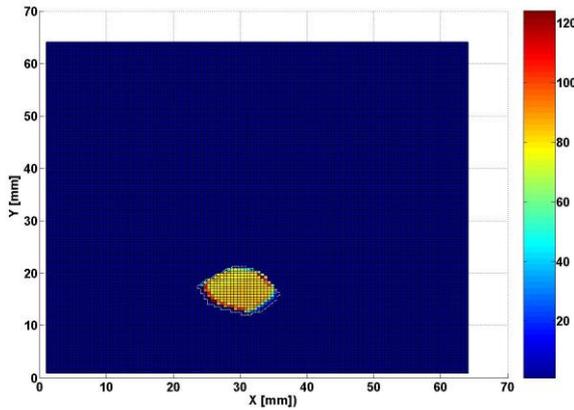
Figure 10. The result of data fusion

Table 1 presents comparatively the areas of the delaminated surface emphasized by the proposed ultrasound method, eddy current holography, data fusion and ultrasound C-scan with 20MHz focused transducer, standard method for delamination evaluation. It should specify that only the C-scan ultrasound microscopy can emphasize the zones impacted with 0.5J energy.

Table 1 Comparison between area of delaminated surfaces determined through different methods

Energy [J]	Delaminated areas $[mm^2]$ detected by			
	Propagation speed measured	Eddy current holography	Data fusion	C-scan
0.5	-	-	-	43
2.5	175	52	85	96
3.0	200	69	128	132
4.0	290	50	141	157

The analysis of data from Table 1 shows that the using data fusion indicate a value for delamination area in very good concordance with US C-scan ultrasound, considered classical method of evaluation. The proposed methods can be applied for structures of composites too, while C-scan can be used only on immersed plates. Also, the proposed methods have increased the inspection speed.

6 Conclusion

For nondestructive evaluation of carbon epoxy composites materials, two methods for relative rapidly inspection were developed: ultrasound using transducers with hertzian contact and determination of US beam propagation speed, and eddy current holography using transducers with orthogonal coils. By data fusion given by both of the proposed methods, using Dempster-Schafer theory of evidence, we obtain a good concordance between delamination areas emphasized by ultrasound, C-scan and information obtained by data fusion.

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