COMPOSITE MATERIALS CHARACTERIZATION BY ACOUSTIC EMISSION TECHNIQUE

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ABSTRACT

Standard pencil lead break tests were carried out on CFRP laminates at the aim to characterize the composite materials behaviour from the acoustic emission point of view. Parameters like lay up, thickness and fibre orientation were varied in order to analyse their influence on the wave propagation. The generated waveforms were studied and the flexural mode was distinguished by the extensional one: the attention was put on the latter to correctly determine the sound wave velocity. From two to four sensors were positioned along the same line on the laminate at fixed distances between each other. This allowed the signal attenuation analysis too, performing pencil lead breaks against the panel along the same line of the sensors and comparing the signals, in terms of amplitude, recorded by each of the single sensor. The elastic modulus was predicted by the lamination theory and the related velocity was compared to what measured after experimental tests: a quite good agreement was found. At the final but not simple goal to individuate the exact number of sensors necessary to correctly locate the damage, the determined sound velocities were, then, used as input to verify the efficiency of the location method as a reliable tool to locate the source of an event. A quite good correspondence was found between the point of the pencil lead break against the panel and what shown by the AE system.

1. INTRODUCTION

The difficulty in the prediction of the initiation and propagation of the failure modes in CFRP laminates under mechanical loads, is already well known. It is related to the lack of transparency of the materials that does not allow the inner damage evaluation by simple visual inspections. On the other hand, since the growing interest in the composite materials for applications in fields like automotive and aeronautical ones, the importance and the necessity of a deeper understanding about the behaviour of composite laminates under critical dynamical loads is well known too. A lot of efforts have been done at the aim to investigate about the phenomenon without damaging the structure [1, 2]. X-ray and C-scanning are the non-destructive damage assessment techniques very large adopted today, but they don’t allow to investigate about the defects during loading [3, 4]. In the recent years, acoustic emission is becoming a common tool under investigation as a valid alternative of the above mentioned techniques. The latter, in fact, can provide information about damaging, in real time and on line, without remove the panels from the structures.

Of course, the increasing in the use of composites has lead to an increase on the complexity of shapes and, as a consequence, of the damages. Different kind of failures, such as fibre and matrix cracks, debonding and delamination, are generated in composite laminates under mechanical loads. The problem is that each kind of damage is related to a different acoustic wave form and propagation [5]. It is, so, very difficult the correlation of the different failure modes to the acoustic signals recorded. This is the main reason why the acoustic emission technique is often used to detect just the onset of damage in correspondence of the time of the first emission, or the severity of the damage as the number of the emissions in a fixed period [6, 7, 8]. Moreover, considering that, in general, the waveform produced by a fracture is dispersive and consists of many frequencies and that there are interferences due to reflections from fracture events, different frequencies travel at different velocities introducing errors in the determination of the location [5]. Adding the fact that the sound speed is influenced by the fibre orientation, it is simple to understand how the damage location is very difficult in composite materials.

Numerous studies [9-14] were carried out at the aim to verify the influence of parameters like fibre orientations, panel thickness and lay up, on the acoustic emission response of composite laminates under mechanical loads. Efforts were done in order to characterise the damage, correlating the different kind of failure modes described above, to the acoustic emission parameters, in terms of hits, amplitude and energy in particular. On the other hand, a few was done to characterise the material and its acoustic response, independently of the specific load applied and the damage. This is the aim of the present research where standard pencil lead break tests were carried out on CFRP laminates different in lay up and thickness. The latter were varied to study their influence on the acoustic behaviour of the material.

Pencil lead breaks were performed against the panels in different locations and at different distances from the sensors, in order to record the correspondent way of sound travel across the sensors. Since the final goal is to individuate the exact number of sensors necessary to correctly locate the source of the noise, without signal distortion due to the anisotropy of the material, from two to four sensors, depending on the plate direction and on the scope of the analysis, were positioned on the laminate at a fixed distance between each other. The signal recorded by each of them was analysed in terms of waveform and amplitude. Then, at the aim to verify the influence of the fibre orientation on the sound wave propagation, the sensors were positioned on the laminate along the same line differently oriented respect to the fibre direction, in order to create angles in the range 0° – 45°.

The present research starts from the idea that the damage accumulation in the matrix reduces the speed of sound through the matrix for acoustic events and it was related to a reduction in elastic modulus. The latter is directly related to the extensional velocity [5]. The waveform was, so, digitised and analysed and its extensional component, travelling longitudinally, was distinguished from the flexural one. The extensional speed travels faster than the other and reaches the sensor first. It was, so, first determined by dividing the distance between two successive sensors (x) to the difference in arrival time (Δt_x) between them. In order to verify the reproducibility of the results, at least three tests per each conditions were carried out. The results were compared to what obtained by the lamination theory, through the elastic modulus prediction. A quite good agreement between the two methods was found. The determined sound velocities were, then, used as input to verify the efficiency of the location as a tool to locate the source of an event. A quite good correspondence was found between the point of the pencil break and what shown by the AE system, with a maximum error of about 5%. By the evaluation of the amplitude signal, efforts were done at the aim to analyse how the fibres can influence the attenuation of the sound as a function of their orientation. As expected, the growing of the fibre angle respect to the sensors position corresponds to an amplitude signal decreasing.

2. MATERIAL AND EXPERIMENTAL METHODS

Unidirectional carbon fibre were handily overlapped in order to obtain composite square laminates, 300mm in side, different in thickness and lay up. The latter were varied at the aim to study how they can influence the acoustic wave propagation. The fibre, immersed in a thermosetting matrix, SX10, were cured by a stamp forming process between aluminium flat moulds on a hydraulic press at room temperature for 24 hours. The thickness was varied from 0.8 to 2.4mm as a function of the number of the layers organised in the following stacking sequences: $[0, 90]_s$, $[0, 90, 0, 90, 0, 90]_s$, $[0, 0, 0, 90, 90, 90]_s$. The properties of the composite constituents are given in table 1.

Table 1: Material characteristics

E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	ν_{12}	ρ (g/cm^3) resin
64	6	3.5	0.26	1.57

Standard pencil-lead break tests were performed on the obtained CFRP laminates at the aim to correctly determine the sound wave velocity. From two to four 150 kHz resonance ultrasonic emission sensors, type VS150-M, were positioned on the laminate at fixed distances between each other (see figure 1 and 3). The signals were amplified at 34 db by AEP3 preamplifiers and recorded by an AMSY4 digital acoustic emission monitoring system (all the system is from Vallen-System GmbH). For the acquisition, a 90 KHz lower cut filter, an acquisition rate of 5˙000 MHz, a threshold value of 30 db, suggested for composite materials, a pre trigger time of 40 μs, an acquisition time of maximum 100 ms for each acoustic events and a rearm time of 3.2 ms were adopted. It means that the signal has to go over 30 db for 40 μs to be acquired for 100 ms, then the system stops the acquisition for the following 3.2 ms. After that, it goes in stand by waiting for a new signal overcoming the threshold.

First, two sensors were positioned at a distance of 200mm from each other and the pencil leads were broken against the panel externally to the first sensor, at a distance from it of about 10mm (figure 1).

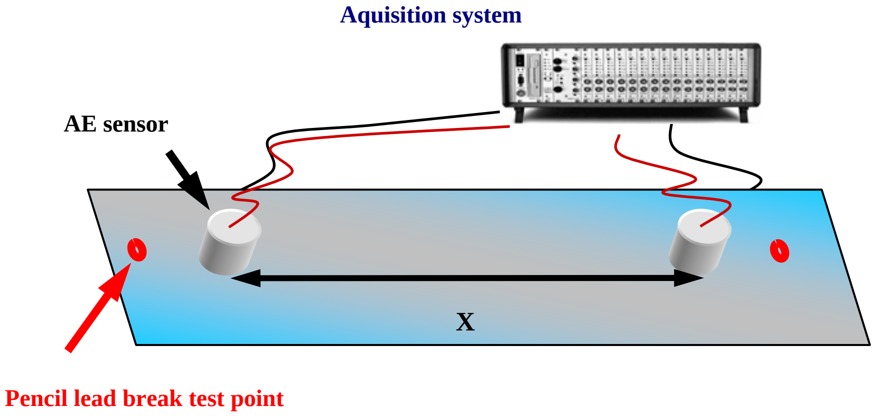


Figure 1: Experimental set up: two sensors at a distance, x, of 200mm.

The recorded data were studied in terms of generated acoustic waveform analysis. The same tests were, then, carried out in correspondence of external location respect to the second sensor, at the same distance from it, at the aim to verify the reproducibility of

the results. In this first phase of the work, flexural velocities were distinguished by the extensional ones and the latter were calculated by dividing the fixed distance between the sensors, x, to the difference in arrival time, Δt_x, recorded by the system.
At the aim to locate the source of the damage, the so obtained velocities, together with the sensors distance, were used as input for the AE programm system. In figure 2, a simple scheme about how the AE system locates the sourse of an event is reported.

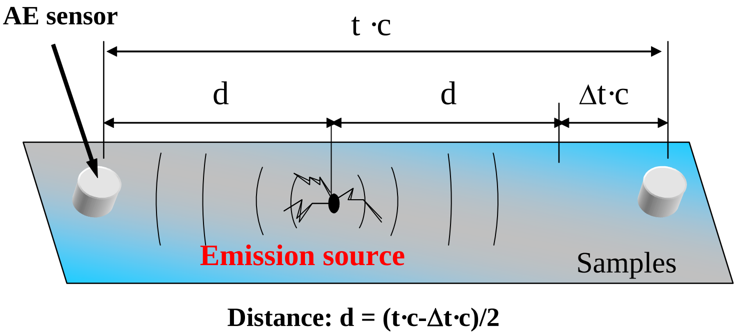


Figure 2: Scheme of AE system location.

In the experimental tests, the pencil lead was broken against the test panel exactly in the middle between the two sensors and the located point was visualised on the display of the AE system.
Four sensors, 80mm far from each other along the same line (see figure 3), were, on the contrary, used to evaluate the signal attenuation. The noise was produced externally to the first and to the last sensor and the detected AE signals, in terms of amplitude values, were analysed and what listen by each single sensor was compared.

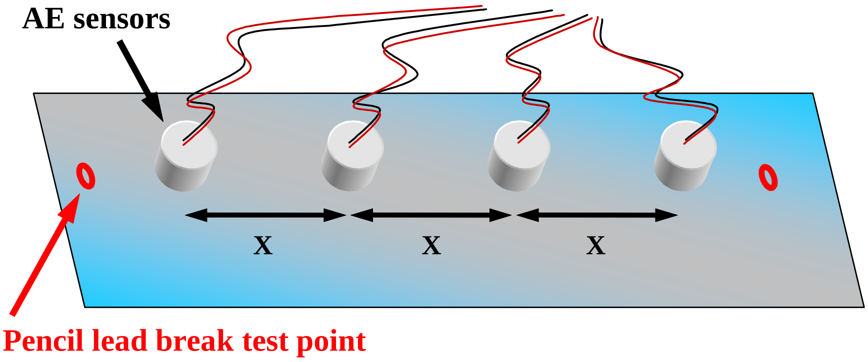


Figure 3: Experimental set up: four sensors.

At the aim to verify the influence of the fibre orientation on the sound wave propagation, the sensors were positioned on the laminate in different directions, always along one line, in order to create angles in the range 0° – 45° with the 0° fibre orientation. A few number of experimental tests were carried out also for 45°-90° of fibre orientation but the results are not sufficiently analysed too so, they won’t be presented hereafter. The distance between the point of pencil lead break and the sensor was varied too, at the aim to obtain different waveforms and so to record the correspondent way of sound travel across the sensors, with different amount of extensional and flexural amount.

At the end, the sound velocity was predicted through the prediction of the elastic modulus by the lamination theory. Laminator programme was adopted for the simulations: it needs the material properties and the lay up as input and gives the elastic modulus of the laminate and the stiffness matrix as output. In order to verify the reproducibility of the results, at least three tests per each conditions were carried out.

3. DISCUSSION

In figure 4, an example of waveform, obtained in one of the examined conditions, is reported at the aim to show the difference between extensional and flexural mode. Of course, it is necessary to put in evidence the not always simple interpretation of the results since it is not always clear the difference between the two different modes, even if the test conditions are the same. It is probably also due to the existence of the multiple modes of wave propagation related to different and dispersive velocities. The different length of the pencil lead and the different hand that produce the break could have an influence too. Disagreement between data obtained in the same conditions were found in literature too [15]. Of course, varying the distance between the pencil break point and the closer sensor results in different lengths of the related propagation modes but, since the arrival times were different too, the measured velocity were found to be the same.

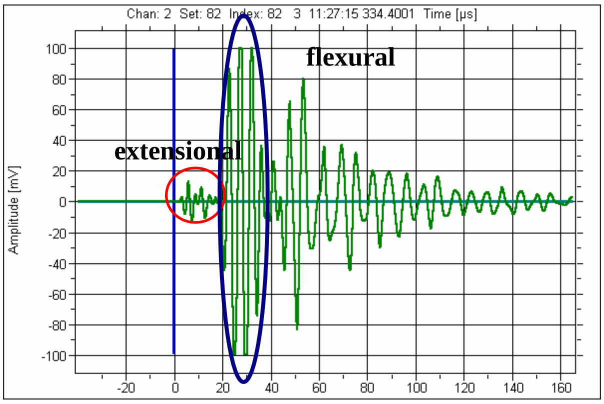


Figure 4: Generic waveform with extensional and flexural components.

The extensional mode, C_e, travels faster than the flexural one and reaches the sensor first. It is characterised by a lower amplitude and a higher frequency and it represents the important component of the waveform to identifying the source of the event. The velocity of the extensional mode can, so, be determined by dividing the preliminarily fixed distance between two successive sensors (x), to the difference in arrival time (Δt_x) of the signal between the closest and the most far sensor, respectively:

$$C_e = \frac{x}{\Delta t_x} \tag{1}$$

Since the higher velocity, the extensional mode presents itself without any dispersion and superimposition up to the reaching of the sensor, so it represents the real way of the wave to travel across the material. After reaching of the sensor, it is superimposed on the larger amplitude flexural mode and it is not possible to distinguish it anymore. So, as already said, two sensors were positioned on the laminate at a fixed distance of 200mm and the pencil lead was broken externally to the sensors along the same line. The flexural velocity was, first, calculated by equation 1. The results were plotted in figure 5 as a function of fibre orientation for the different laminates studied. Since the fibre represent a discontinuity of the matrix, it was expected that the signal decreases with the increasing of the fibre orientation respect to the sensor position. The sensors, in fact, listen and record the wave sound propagation along the fibre direction when they are positioned along the same direction. In correspondence of different angles, they record the wave component propagation that meet the fibre differently oriented. The signal decreases since in that way the fibre represent an obstacle for the wave propagation. Of course, what asserted is true for unidirectional laminates. For different stacking sequences, it could be the first lamina, the sequence of the different orientations or the thickness of the layers differently oriented [11] to be the more influent for the wave propagation. From figure 5, it is possible to note that the influence of the stacking sequence is negligible up to 15° of fibre orientation and it seems to become more significant from 30° of fibre orientation. Increasing the fibre orientation, the velocity of the $[0, 0, 0, 90, 90, 90]_s$ laminate become lower, followed by the $[0, 90]_s$. It could confirm what found by Prosser et al. [11] about the influence of the sequence of the 90° oriented lamina: the thicker is the 90 degree layer, the higher is the influence on the acoustic waveform but, on the contrary to what happens in [11], it is possible to anticipate that the thicker is the 90 degree layer, the lower is the amplitude signal. The latter result will be confirmed by the experimental data plotted in figure 8.

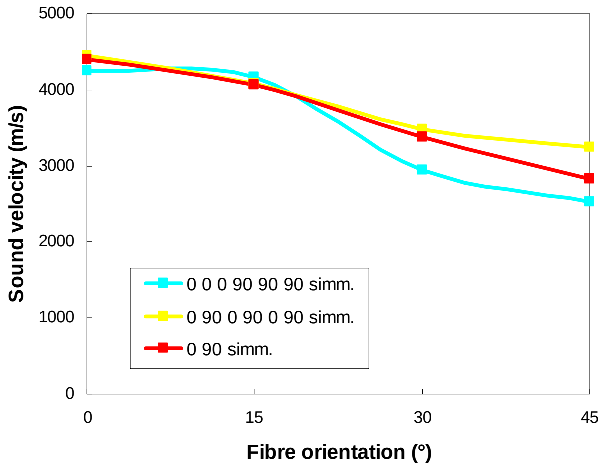
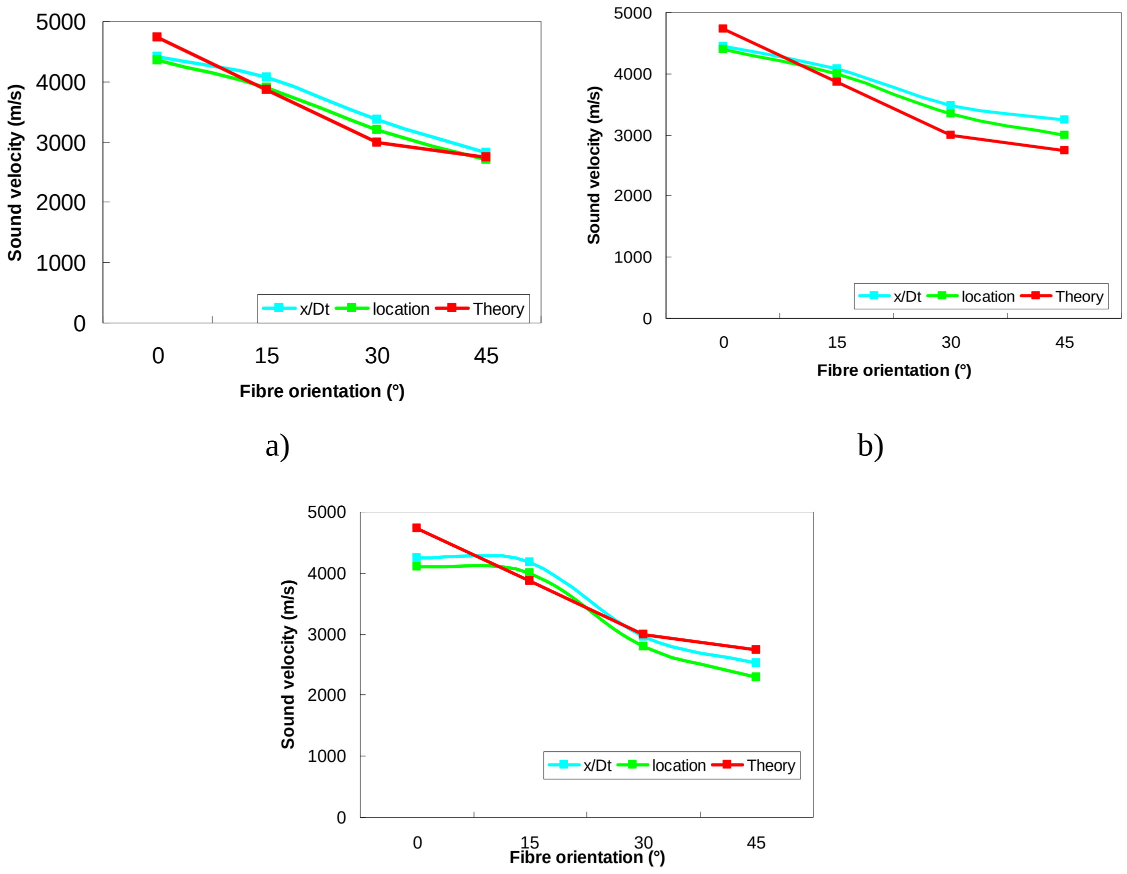


Figure 5: Effect of fibre orientation and stacking sequence on the extensional velocity obtained by equation 1.

The discussed results were, then, compared to the prediction of the lamination theory. As already said, the output of the adopted Laminator programme was the elastic modulus. The extensional velocity was, then, calculated considering the following relation between the extensional velocity and the elastic modulus, E:

$$C_e = [\frac{E}{\rho(1-\nu^2)}]^{1/2} \tag{2}$$

where ρ is the density and ν the Poisson's ratio. As it is possible to observe in the graphs reported in figures 6, a), b) and c), a quite good agreement between the two different methods was found (blue and red lines), irrespective of fibre orientation and laminate.



a)

b)

c)

Figure 6: Sound velocity *vs* fibre orientation. Comparison between different methods: a) $[0, 90]_s$; b) $[0, 90, 0, 90, 0, 90]_s$; c) $[0, 0, 0, 90, 90, 90]_s$.

The determined sound velocities, together with the fixed distance between the sensors, were used as input for the location analysis. At the aim to individuate with a good precision the source of the event, very little adjustments of the velocities were necessary but, adopting the predicted or calculated sound velocities, a quite good correspondence was found between the point of the pencil lead break and what shown by the graph of the AE system, with a maximum error of about 5%. The results were add to the previously showed data in figures 6 (green line): the agreement confirms the goodness of the obtained data.

Comparing the data showed in the previous graphs, it is possible to verify the effect of the thickness too: in the range of the parameters here analysed, it seems do not have a significant influence. Of course, more experimental data are necessary to confirm what asserted.

By the amplitude analysis, it was possible to verify how the fibres can influence the attenuation of the signal. In figure 7, the recorded amplitude values are plotted against the sensors position for all the varied fibre orientations. The showed results are about $[0, 90, 0, 90, 0, 90]_s$ stacking sequence but the same trend was observed in the other analysed cases.

Of course, the signal become lower at the increasing of the distance between the source of the noise and the sensor but, on the contrary to what expected and what recorded about the velocities, the fibre orientation seems do not have any significant or regular effect. The signal, in fact, seems to become lower at the increasing of the fibre angle but the 15° represents an exception like what recorded by the third sensors. It is an important point that needs to be deeper studied by a larger experimental campaign. For space problems, in correspondence of 0° and 15° it was possible to locate just three sensors. This is the reason for that for these conditions just three points are plotted.

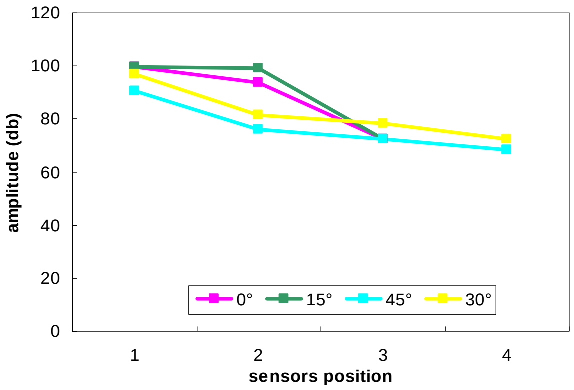
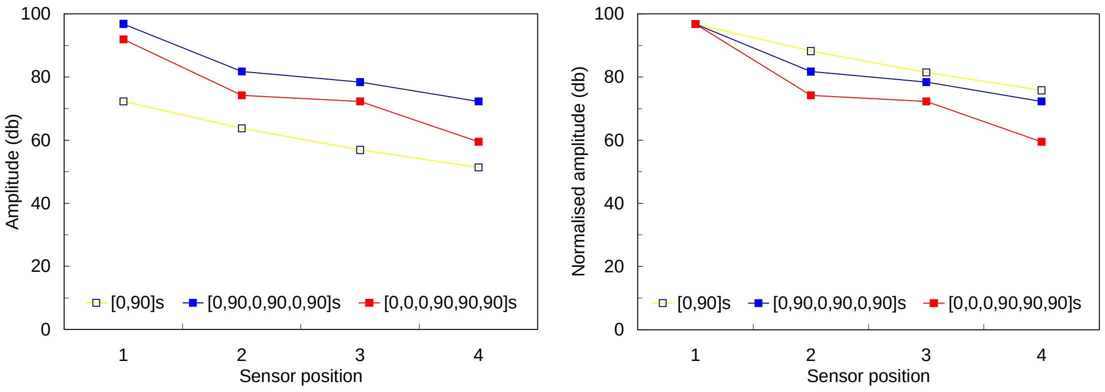


Figure 7: Signal attenuation. Influence of fibre orientation for stacking sequence [0, 90, 0, 90, 0, 90]

What observed in the discussed case was verified in all the other laminates, confirming very little differences between 0 and 15° and a bigger influence of the fibres with the increasing of the angle between fibre orientation and sensors direction.

Looking at figure 8 a), where the amplitude signal is plotted against the sensors positions for all the laminates studied, it is possible to note, as anticipated, the larger influence of the thicker 90° layer. For the same thickness, the higher amplitude concerns the [0, 90, 0, 90, 0, 90]$_s$ stacking sequence, contrarily to what found by Prosser et al. [11], even if in the latter case the recorded noises were generated by matrix cracks occurred in the 90° layers. Guilde et al. and Mielke et al. [16, 17], in fact, have found an influence of the kind of source on the amplitude signal. Moreover, the thinner laminate generated lower amplitude signals.



a) b)

Figure 8: Signal attenuation. Influence of stacking sequences. θ = 30°.

In figure 8 b), the same data were normalised respect to the thinner laminate amplitude. It seems to be clear, comparing the slopes of the line, the stronger attenuation of the thicker 90° layer from the data recorded by the closer and the most far sensor from the break point. The discussed results concern the 30° of fibre direction, but the same was obtained for the other analysed orientations.

4. CONCLUSIONS

Pencil lead break tests carried out on CFRP laminates different in lay-up, thickness and fibre orientation, at the aim to characterise the acoustic behaviour of this kind of material, lead to the following results:

- two different methods, experimental and theoretical ones, were adopted to obtain the extensional velocity and a quite good agreement between them was found, irrespective of fibre orientation and laminate. The obtained results were used as input to verify the sensitivity of the location analysis: good agreements were obtained in this case too;
- the influence of the stacking sequence on the sound velocity was found to be almost negligible up to 15° of fibre orientation and more significant from 30°;
- as expected, a decrease of extensional velocity at the increasing of fibre orientation was observed;
- at the increasing of the fibre orientation, the velocity of the $[0, 0, 0, 90, 90, 90]_s$ laminate become lower than the other orientations. It could means, as found in literature, that the thickness of the 90° layers has a bigger influence on the acoustic wave propagation;
- in the range of the analysed parameters, the thickness seems do not have a significant influence on the studied parameters;
- about the amplitude data, it was found that the signal become lower at the increasing of the distance between the source of the noise and the sensor, verifying in this way the signal attenuation;
- a bigger influence of the fibre orientation was noted with the increasing of the angle between fibre orientation and sensors direction except for 15°;
- the thicker 90° layer was found to largely influence the amplitude signal too, showing a stronger attenuation. Moreover, the thinner laminate generated lower amplitude signals.

All the experimental tests up to now, were performed with all the sensors adopted positioned along the same line, since the beliefs that it is necessary to begin the researches starting always from the simplest conditions. Different sensors location will be the future step of the present work and the results presented in this paper will be useful to correctly locate the source of an event without any distortion due to the influence of the different composite parameters analysed.

At the end, it is important to underline the general real difficult, widely found in literature too, in analysing the acoustic emission data since the large number of parameters that can influence the acoustic response of the materials. This difficult is worse for composite materials that are non homogeneous and anisotropic. Very deep studies were necessary to understand and correctly explain the phenomena and the different results found also in the same tests conditions.

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