PAPER REF: 4668

AMPLITUDE AND TIME SHIFT MEASUREMENTS FOR DAMAGE CHARACTERIZATION IN FIBERGLASS COMPOSITES USING PZT SENSORS

Mário Santos[1(*)], Jaime Santos[1], Ana Amaro[2]
[1]Department of Electrical and Computers Engineering, (CEMUC), University of Coimbra, Coimbra, Portugal.
[2]Department of of Mechanical Engineering and, (CEMUC), University of Coimbra, Coimbra, Portugal
[(*)]*Email:* marioj@deec.uc.pt

ABSTRACT

In this work PZT sensors are proposed to characterize the impact effects in fibre glass composite plates. The analysis of the impact effect has been made by two parameters; amplitude response and time shift. PZT sensors were bonded to the samples in a pitch-and-catch configuration and the Lamb wave symmetrical mode (S_0) signal was used. The results demonstrate that the two evaluated parameters are able to characterise the damages occurring in such composites as well as to evaluate their severity. It was also observed that amplitude predicts well the defect size, whenever fibre breakage occurs.

Keywords: Glass fibres; Defects; PZT; Ultrasounds.

INTRODUCTION

During the service life, a composite structure is subjected to various loading conditions, which can give rise to various defects. Impacts at low velocity that are difficult to detect visually are the principal cause of in-service damage affecting dramatically the performance of composite materials, namely reducing the compressive residual strength (Adams, 1998). Additional defects such as; fiber breakage, matrix cracking and fiber-matrix interfacial debonding can also occur, leading to structural failure. The poor tolerance to accidental low velocity impacts of the composite laminates is yet a limitation to their use in some industries (Collombet, 1996). Recently, damage detection through ultrasound guided waves, such as Lamb waves, has been gained increasing importance due to the possibility of inspecting large composite structures. The generation of Lamb waves by conventional transducers has some limitations because they are relatively large and expensive. An emerging technique based on piezoelectric lead zirconate titanate (PZT) sensors has the potential to improve significantly the structural health monitoring (SHM). These sensors are small, lightweight, inexpensive, and can be produced in different geometries.

Banks was probably the first one that study damage detection with PZT sensors (Banks, 1996). Since then, several authors have studied the applicability of these sensors in different fields, namely in damage detection (Kessler, 2002) defects location using distributed sensors and wavelet signal processing (Su, 2002) delamination evaluation based in the ratio of the power spectrum densities for different propagation modes (Kim, 2007) or detection of transverse crack and delamination in cross-ply laminates (Toyama, 2003).

More recently, localization and monitoring of damages in honeycomb structures using PZT arrays (Chakraborty, 2012), instantaneous delamination detection by comparing time delays of A_0

mode (Yeum, 2012) and diagnosis of damage using in a modified time reversal method (Watkins, 2012), are examples of potential practical applications of the PZT sensors.

This paper is deals with the evaluation of the defects severity caused by impacts in fiber glass composite plates using ultrasound parameters. For that goal, several laminate plates with different stacking sequences and thicknesses were fabricated. In order to give rise to different defect levels multiple impacts were produced on each plate. Using bonded PZTs in a pitch-and-catch configuration, amplitude and time delay signals measurement were performed for the plates.

PZTS FOR GENERATE AND COLLECT LAMB WAVES

Many authors have considered the use of Lamb waves for non-destructive testing. Rose have summarized the potential of these waves in terms of damage detection and characterization, that are mainly: the possibility of inspection of entire cross sectional area of a structure with a single direction displacement, inspection of large insulated or coated structures, no necessity of using complex motion devices, good sensitivity, low energy consumption and low cost (Rose, 2001). However complications that are encountered include the existence of multiple modes, the dispersive character of these modes and also the waves reflected in boundaries, which could mask the signal of interest. Normally the fundamental symmetric (S_0) and anti-symmetric (A_0) are preferred to use in practice due to their better time discrimination, when compared with higher order modes.

PZT ceramics deliver excellent performance in Lamb wave generation and acquisition. They are also called active sensors due to its dual sensing and excitation characteristics. Typically when working in kHz range is possible to obtain around an hundred of mV or more in sensing, using as excitation signal a tone burst with 10 V of amplitude.

The strain $\varepsilon(x)$ induced by a plate-mounted PZT perfectly bonded to the structural surface has response amplitude given by (Giurgiutiu, 2008)

$$\varepsilon(x) = i\varepsilon_a(\sin(kL/2))e^{i(kx-\omega t)} \tag{1}$$

where ε_a is the induced strain over the PZT length L and k is the wavenumber of the propagation mode in the plate. The response amplitude follows a sinusoidal variation with respect to the parameter $kL/2$ and the response peaks are observed at odd multiples of $\pi/2$.

The optimal excitation frequencies can be obtained by

$$f = \frac{v}{L}\left(n + \frac{1}{2}\right) \quad (n = 0,1,2,...) \tag{2}$$

where v is the Lamb wave velocity of the propagating mode in the material. The thickness selection have to take in account the maximum voltage allowed by the PZT without depolarising, that is typically around 250-300 V/mm (Su, 2006).

Velocity measurements and consequently identification of ultrasonic bulk waves are usually possible using time of flight method. Considering the time difference between nth peak of the signal for two different locations, easily conducts us to the propagation velocity, if the shape of the signal remains the same. In the presence of dispersive waves like Lamb waves, frequency domain techniques are demanded for correct velocity evaluation and consequently mode identification. Using one of these techniques called phase spectrum method (Sachse, 1978) the phase velocity v_p can be obtained by

$$v_p = \frac{2\pi\, f\, D}{\Delta\varphi} \tag{3}$$

where $\Delta\varphi$ is the difference in the phase spectrum of two signals that were collected with a different distance between them of D and f is the frequency.

PROCESSING TECHNIQUES

When using guided waves generated by PZT ceramics, the most important signal processing and damage identification techniques can be divided in time, frequency and integrated time-frequency analysis.

Time domain analysis usually uses time of flight or amplitude variations measurements associated to triangulation techniques and artificial neural networks. Normally this analysis, except for few successful applications, needs a benchmark signal for comparison (Su, 2006), (Kessler, 2002).

In frequency domain is possible to get additional information about the signals behaviour than in time analysis. Fast Fourier transform (FFT) and its two-dimensional variant (2D-FFT) (Kim, 2007), (Toyama, 2003) are widely used when spectrum information is demanded. With 2D-FFT is possible to isolate different propagation modes, which could exist in the original signal, and present them in frequency-wavenumber domain. The main drawback of this method is the need of a great number of collected signals, which, in some cases, makes it difficult to put into practice.

Finally the integrated time-frequency analysis combines the two previous techniques, giving rise to 2D representations. Practical implementation of one of this techniques is the Short-time Fourier transform (STFT), that is obtained by applying a FFT to a small piece of the time signal (time window). After, a continuous movement of this time window along the time axis give rise to a time-frequency representation. A variant of the STFT is the Winger-Ville distribution (WVD) that uses a flexible transform window size. Another recent tools used in PZT guided waves signal processing is the Wavelet transform (WT). This transform uses a special signal called wavelet, which has a limited time duration and average amplitude equal to zero. Continuous Wavelet transform (CWT) and discrete Wavelet transform (DWT) are the typical forms of WT. CWT is used for 2D frequency-time analysis. Applied to an analog signal is possible to obtain directly in a scale-time domain and the scale variable can be connected with frequency in an easier way. The difference from STFT in that the resolution depends on the scale. The CWT modifies the length of the wavelet at different scales (frequency) to analyze adaptively signals with localized information. DWT is widely useful in signal de-noising, filtering and compression. For more details about WT, see for instance reference (Su, 2006).

MATERIALS AND EXPERIMENTAL PROCEDURES

The composite materials used in this study are manufactured from unidirectional E-glass fibers and epoxy resin. The volume fraction of E-glass fiber is 44.5 %. The laminate is processed in agreement with the manufacturer recommendations using the autoclave/vacuum-bag molding process. The processing setup consisted of several steps: make the hermetic bag and apply 0.05 MPa vacuum; heat up to 125º C at a 3–5º C/min rate; apply a pressure of 0.5 MPa when a temperature of 120–125º C is reached; maintaining pressure and temperature for 60 min; cool down to room temperature maintaining pressure and finally get the part out from the mould. Several laminates with different stacking sequences were considered to manufacture plates with three different thicknesses, relatively to the number of plies, 8, 16 and 32 respectively. The plates were manufactured in a useful size of 300 x 300 x t [mm]. Complete description of the composite laminates is presented in Table 1. The mechanical properties of the glass/epoxy unidirectional composite laminate are obtained according to standard procedures and are presented in Table 2.

Table 1 Composite laminated samples

Sample	Stacking sequence	Thickness (mm)
A	$[0_2,90_2]_s$	1
B	$[0_2,90_2]_{2s}$	2.1
C	$[0,90,0,90]_{2s}$	2.1
D	$[45_2,90_2,-45_2,0_2]_{2s}$	4.2

Table 2 Mechanical properties from unidirectional glass/epoxy laminate.

E_1 (Gpa)	E_2=E_3 (Gpa)	G_{12} = G_{13} (Gpa)	G_{23} (GPa)	ν_{12}
35.00	12.42	2.31	2.31	0.26

For detection and identification of Lamb waves in the laminates a contact setup presented in Fig.1 was used. Additionally a Panamatrics pulser/receiver is used as a main power system and a digital oscilloscope to average and collected the signals after propagation on the plate. Finally the signals are transfer via USB port to further processing. Two Panametrics transducers with central frequency of 500 kHz are coupled to the laminate plates by acrylic blocks with variable inclination. The transducers are glued to the blocks and coupling gel is utilized between blocks and the laminate plates.From both fundamental modes, symmetrical S_0 mode was selected. A typical collected signal is presented in Fig. 2.

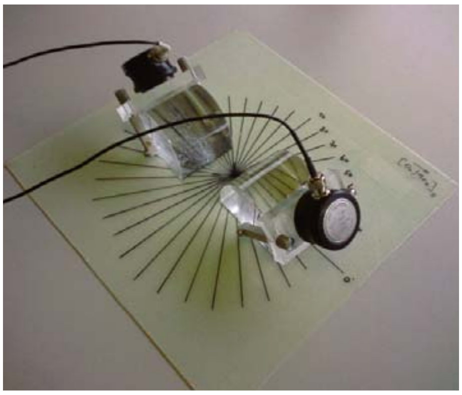


Fig. 1. Experimental setup for Lamb wave detection and identification.

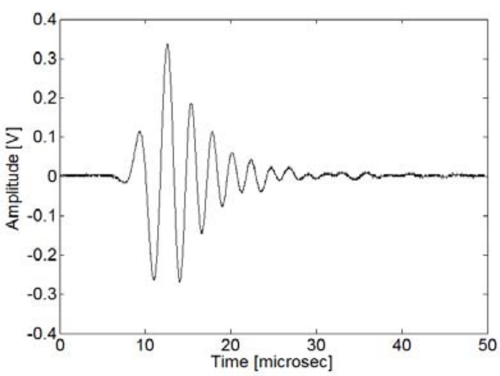


Fig. 2. Typical collected signal for the laminate composite plate

The correct inclination for the blocks was obtained maximizing the amplitude of the collected signals. For sample A the inclination is around 40º, which is according the co-incident principle (Santos, 2004). The phase velocity, presented in Fig.3, was obtained using the phase spectrum method for two signals collected 5 cm apart. The considered spectrum is from 200 kHz to 500 kHz because there was a spectral shift from original transducers central frequency to 350 kHz, probably due to some filtering effects of the laminate composites. The small decreasing of the phase velocity is according to the theoretical behavior in low frequency regime.

For Lamb waves generation the used PZT sensors were cut from bar type PZ29 (50x20x0.4 mm) in square pieces of 7x7 mm. For excitation an arbitrary waveform generator Tektronix AFG3022 was used to produce a 3-cycle toneburst with a Hanning window, that was previous synthesized in Matlab. This windowing technique is used to narrow the signal bandwidth and to focus the maximum amount of energy into the desired frequency with a minimum spreading to neighbor frequencies. The signal has 10 V of amplitude. The PZT sensors are mounted in a pitch and catch configuration. The received signal after amplification was collected by a digital oscilloscope and transferred by USB to further processing. The complete setup using an aluminium plate is presented in Fig. 4.

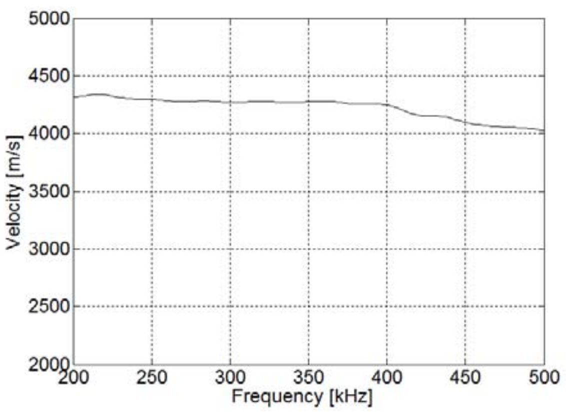


Fig.3. Experimental S_0 phase velocity for sample A in 0º direction.

Fig. 4. Experimental setup using an aluminium plate.

For composite plates the PZTs were mounted 100 mm apart on the surface using conductive glue. A frequency swept was done, allowing to verify that the maximum signal in the receiver was obtained for 320 kHz. Using time of flight it has easily been proved that the signal obtained corresponds to the fundamental symmetrical mode S_0. A typical signal propagating in a composite plate is presented in Fig. 5 where is possible to see the direct signal and the reflection from the end of the plate.

RESULTS

Low velocity impact tests were made using a drop-weight testing machine Instron-Ceast 9340. A hemispherical impactor of 10 mm in diameter and a mass of 3.4 kg were used. The specimens were centrally supported. Fig. 6 represents typical energy versus time curves for sample A. The beginning of the curve plateau energy coincides with the loss of contact between the striker and the specimen, and this energy level corresponds to the absorbed one by the specimen (Rio, 2005). In this context, the dissipated energy is calculated as the difference between the absorbed energy and the energy at the peak load.

As the glass laminate plates are translucent, an image of the damage is possible by photography. The plates were photographed on the opposite side of the impact (back face) and are shown in Fig. 7.

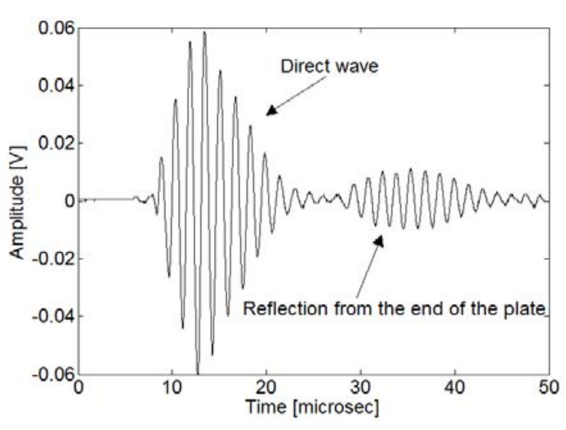


Fig. 5. Fundamental symmetrical S_0 mode in the composite plate

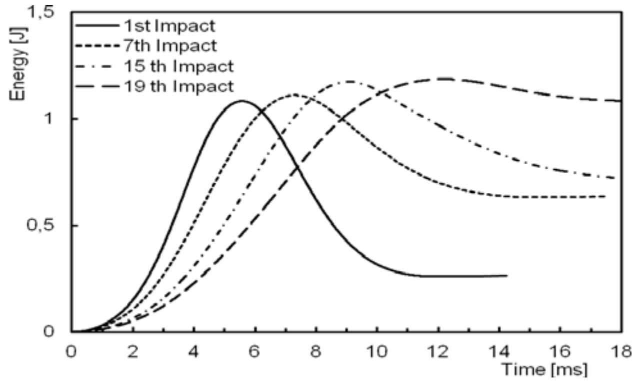
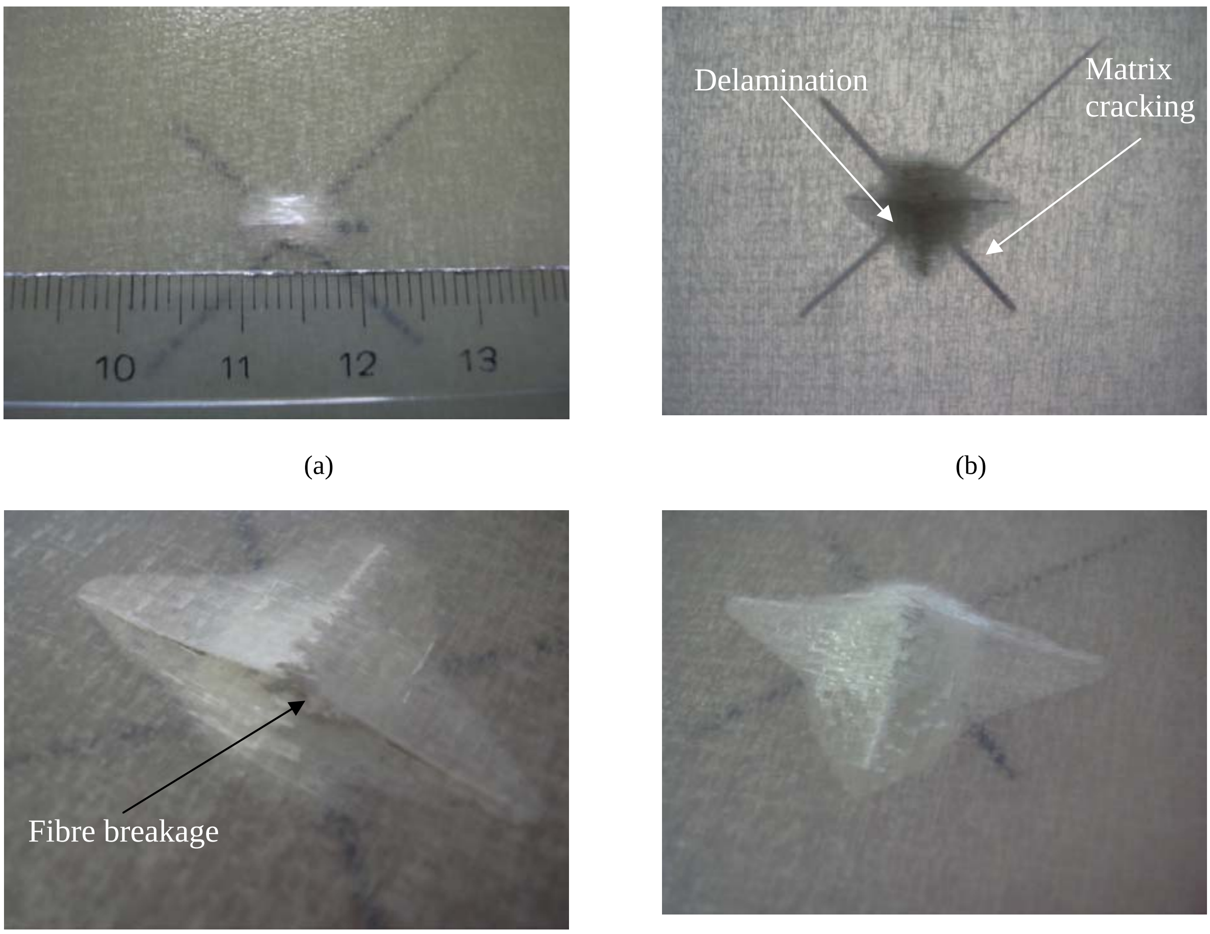


Fig. 6. Typical energy versus time curves for sample A.



(a) (b) (c) (d)

Fig. 7. Typical damages occurred after impact for sample A: (a) 1st Impact; (b) 7th Impact; (c) 15th Impact; (d) 19th Impact.

For the remaining samples B, C and D similar impact tests with different energy levels were performed.
In Fig. 8 is presented the relation between the damage area and the number of impacts for all tested samples. Only for the sample A is was observed a constant increase in the damage area with the increasing of number of impacts, for the same value of the impact energy. To the others three layup just when the impact energy is greatly increased a jump in the damage area is observed.
Due to different energy levels and plate thicknesses used, fibre breakage exists from the beginning of the impact test sequence in samples A and C (1st impact for sample A and 3rd for sample C), while for the other samples the fibre breakage appears only for high order impacts (23rd impact for sample B and 14th impact for sample D).

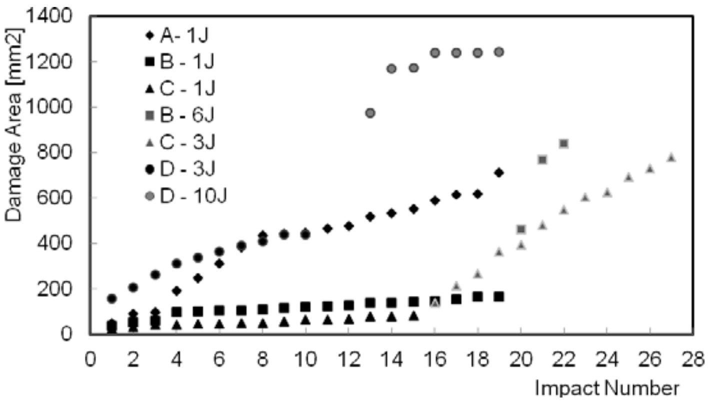


Fig. 8. Damage area versus number of impacts for all studied layups.

For evaluation of the impact effects in the fibre composite plates, the previous presented pitch and catch method was used. A pair of PZT sensors was bonded on each plate and after each impact the signals were acquire and processed. The damage area was correlated with ultrasound parameters. The amplitude and time shift approaches were used as they provided the best results. The normalized peak to peak amplitude versus damage area for sample A is illustrated in Fig. 9.

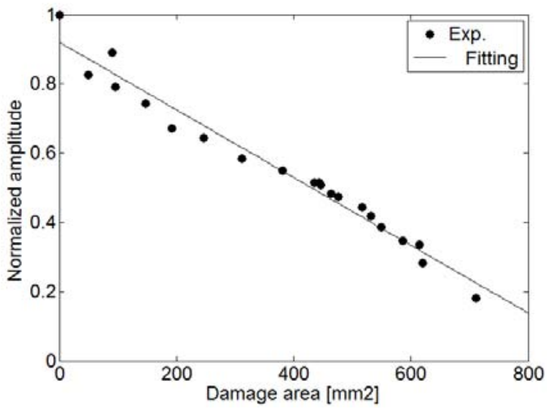


Fig. 9. Signal amplitude versus damage area for sample A.

A high linear correlation between these two parameters (R^2=0.968) is observed. As expected, the amplitude decreases as the defect severity increases, which is mainly due to the broken fibres that are visible after the first impact (Fig.7 a)).
The time shift parameter was measured correlating the received signal with a benchmark signal (obtained from a reference plate without damage). For this purpose, a cross-correlation

technique was used in order to improve the time resolution and also due to the slightly dispersive behaviour of the S_0 Lamb wave mode. This technique widely used in signal processing (Foster, 1990), (Hein, 1990), measures the similarity between two waveforms as a function of the time-lag applied to one of them. The discrete cross-correlation function between two signals $y_1(i)$ and $y_2(i)$ is given by

$$R(s) = \frac{\sum_{i=1}^{N} y_1(i) y_2(i+s)}{\sqrt{\sum_{i=1}^{N} y_1(i)^2 \sum_{i=1}^{N} y_2(i+s)^2}} \tag{4}$$

where s is the time shift between signals and N is the number of samples. The time shift s is obtained for the maximization of the function $R(s)$. Fig. 10 depicts the time shift between the reference signal and the signal after the 19th impact carried out on sample A. The damage area versus time shift is shown in Fig. 11. It is observed an increase of the time shift with the damage severity, which is related to the plate deformation and changing of the ultrasound wave propagation path. Again a good liner correlation (R^2=0.936) was achieved.
Both amplitude and time shift approaches were also applied to the samples B, C and D. The results are summarized in Table 3 in terms of R^2.

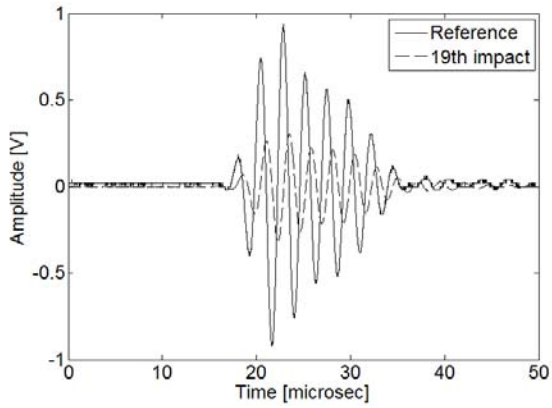


Fig. 10. Reference signal and after 19th impact for plate A.

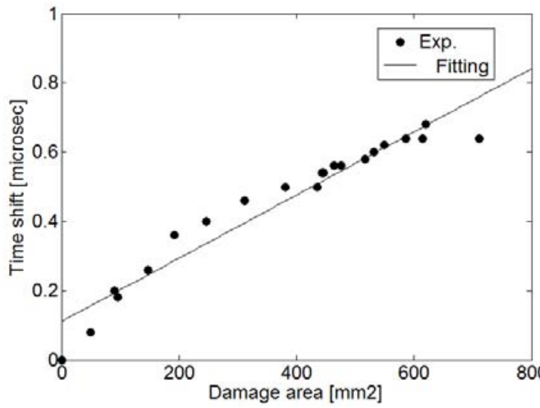


Fig. 11. Time shift versus damage area for sample A.

Table 3 – Values of R^2 for all samples.

Sample	R^2	
	Amplitude	**Time shift**
A	0.968	0.936
B	0.182	0.790
C	0.895	0.988
D	0.190	0.992

The amplitude measurements show good linear correlation with the defect dimensions only for samples A and C. Looking at the photographs of the impact damages, it is clear for these samples that fibre breakage exists from the beginning of the impact test sequence (1^{st} impact for sample A and 3^{rd} for sample C), while for the other samples the fibre breakage appears only for high order impacts (23^{rd} impact for sample B and 14^{th} impact for sample D). This allows concluding that amplitude measurement could be used to predict defect size, whenever fibre breakage occurs after impact.
From time shift data presented in Table 3, high linear correlation with defect size for samples A, C and D and moderate for sample B is observed. Even for the sample B, the value of R^2 is higher than the one obtained by the amplitude measurement. From the presented values, apparently, time shift seems to be the better parameter when damage size prediction is demanded, even when delaminations, matrix cracking or fibre breakage is present.

CONCLUSION

The presented work demonstrates the suitability of PZT sensors for impact defects evaluation in fibre glass composite plates. Experiments using conventional ultrasonic transducers with variable inclination, together with phase spectrum method allowed identifying S_0 Lamb wave mode in low frequency regime. An appropriate setup was used for S_0 mode tuning of PZT sensors bonded in aluminium and fibre glass plates giving results according to the theory. Different types of samples fabricated with different stacking sequences were impacted using a pressure-assisted drop-weight testing machine. It was observed that the absorbed energy increases with the number of impacts with the consequent increase in the delamination size. This phenomenon can be explained by the higher displacement induced on the sample. The stacking sequence influences the damage area due to the increased number of interfaces between layers with different orientations, which can promote the appearing and propagation of delaminations.

Multiple impacts were performed in each fibre glass composite samples to guarantee the same test conditions for different impact levels. After each impact, amplitude and time shift were measured. A high accuracy technique based on cross-correlation function was used to the time shift evaluation. Amplitude measuring shows high linear correlation with defect size only when fibre breakage exists. On the other hand, time shift seems to be a better parameter for defect size estimation, because it is sensitive to all damage parameters like delamination or matrix cracking. Together both approaches can be used to defect estimation and classification. Future work will be developed using others stacking sequence and different composite materials as the CFRP in order to evaluate the practicability of the used parameters for damage characterization.

ACKNOWLEDGMENTS

This research was also sponsored by FEDER funds through theprogram COMPETE – Programa Operacional Factores deCompetitividade – and by national funds through FCT – Fundação para a Ciência e a Tecnologia –, under the project PEst-C/EME/UI0285/2011.

REFERENCES

Adams RD, Cawley PD. A Review of Defects Types and Non-Destructive Testing Techniques for Composites and Bonded Joints. NDT Int 1998;21: 208-222.

Banks HT, Smith RC, Wang Y. Smart material structures: Modeling, estimation and control. Masson, Paris: John Wiley & Sons, 1996.

Chakraborty N, Rathod VT, Mahapatra DR, Gopalakrishnan S. Guided wave based detection of damage in honeycomb core sandwich structures. NDT Int 2012;49:27-33.

Collombet F, Bonini J, Lataillade JL. A Three-dimensional modelling of low velocity impact damage in composite laminates. Int. J Numer Meth Eng 1996; 39:1491-1516.

Foster SG, Embree PM, O'Brien WD. Flow Velocity Profile via Time-Domain Correlation: Error Analysis and Computer Simulation. IEEE Trans Ultrason Ferroelect Freq Contr 1990;37(3):164-175.

Giurgiutiu V. Structural Health Monitoring with Piezoelectric Wafer Active Sensors. Academic Press, 2008.

Hein IA, O'Brien WD, A Real-Time Ultrasound Time-Domain Correlation Blood Flowmeter: Part II. IEEE Trans Ultrason Ferroelect Freq Contr 1990;40(6):776-785.

Kessler SS, Spearing SM, Soutis C. Damage detection in composite materials using Lamb wave methods. Smart Mater Struct 2002; 11: 269–278.

Kim YH, Kim DH, Han JH, Kim CG. Damage assessment in layered composites using spectral analysis and Lamb wave. Compos: Part B 2007; 38: 800–809.

Río TG, Zaer R, Barbero E, Navarro C. Damage in CFRPs due to low velocity impact at low temperature. Compos Part B-Eng 2005; 36: 41-50.

Rose JL. A vision of ultrasonic guided wave inspection potential. In: Proceedings of the Seventh ASME NDE Topical Conference NDE-Vol. 20 2001. p. 1–5.

Sachse W, Pao YH. On determination of phase and group velocity of dispersive waves in solids. J Acoust Soc Am 1978; 49(8):4320-4327.

Santos M, Ferreira A, Perdigão J. Practical considerations on ultrasonic guided wave propagation: immersion and contact methods. Mater Eval 2004;62(4):443-449.

Su Z, Ye L, Bu X., A damage identification technique for CF/EP composite laminates using distributed piezoelectric transducers. Compos Struct 2002; 57: 465–471.

Su Z, Ye L, Su YL. Guided Lamb waves for identification of damage in composite structures: A review. J Sound Vib 2006; 295:753-780.

Toyama N, Noda J, Okabe T. Quantitative damage detection in cross-ply laminates using Lamb wave method. Compos Sci Tech 2003; 63: 1473–1479.

Watkins R, Jha R. A modified time reversal method for Lamb wave based diagnostics of composite structures. Mech Syst Signal Pr 2012;3:345-354.

Yeum CM, Sohn H, Ihn JB, Lim HJ. Instantaneous delamination detection in a composite plate using a dual piezoelectric transducer network. Compos Struct 2012; 94:3490-3499.