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New approach for the damage mechanisms identification in the glass-epoxy composites

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The aim of this work is to introduce a new approach for clustering acoustic emission data occurring during the fracture process of glass fibre reinforced polymer (GFRP) plates. In particular, we have developed signal processing techniques based on continues wavelet transform (CWT) in order to isolate acoustic signature corresponding to each damage mechanism (fibre breakage, matrix cracking, etc.). Entropy criterion was used to provide selection of most significant wavelet coefficients of AE signals. Models are established in the form of dictionaries, whose elements are the waveforms collected during specific experiments in which the created damage mechanisms are well known. Dictionaries should be used to classify acoustic emission signals recorded when polymer composites are under load.

1 Introduction

Glass fibre reinforced polymer (GFRP) composite materials have grown an increasing interest in industry because of their superior weight to strength ratio and rigidity. However various damage mechanisms may appear during use of these materials. Acoustic emission (AE) technique is one of several diagnostic techniques developed to monitor defect formation and failure in composite structures. AE can be generated during the failure process of materials produced by spontaneous release of localized strain energy in stressed materials. This energy can be recorded by transducers which are put on the materials' surface and analyzed to study the involved failure mechanisms. Identification of damage mechanisms was the object of many research in literature. The main subject is to establish a tool for classification by exploiting parameters extracted from AE signals. In some works, distributions of AE signals' amplitudes are analyzed to correlate AE sources with failure modes [1,2]. Efforts were conducted to classify AE sources using statistical methods based on the use of several parameters such as counts, rise time, energy, etc. In this way, statistical supervised and/or unsupervised methods were proposed to identify damage mechanisms during calibrated mechanical tests [3,4]. Recent studies are addressed to analyse and discriminate AE events by using the frequency content of AE signals. These works considered that frequency of AE signal present a significant parameter for the identification of different type of damage. In references 5 and 6, a frequency analysis was performed by the mean of the Fast Fourier Transform. Failure modes are correlated with primary frequency content of signals. Some studies used a wavelet-based signal processing technique to attribute a damage mechanism to the received stress waves [7, 8]. In present work, a signal processing technique based on continues wavelet transform (CWT) is investigated to introduce a new approach for clustering AE events in composite materials. Experiences were performed on model specimens of GFRP composite in order to generate specific damage modes. Waveforms are determined for each damage mechanism while selecting the wavelet coefficients. Entropy criterion was used to extract waveforms basis which are used to establish dictionaries. A brief illustration of the procedure used to establish the dictionaries is shown in Figure 1. Based on results found in literature [9], the following hypotheses were taken on account :

- The quasi-static tensile test, applied to pure resin samples allows to generate only one damage mechanism, which is the matrix cracking.
- Each AE signal collected during quasi-static tensile tests of 90° unidirectional composite samples could not be ascribed to fibre breakage, it should be associated to matrix cracking or fibre-matrix debonding.

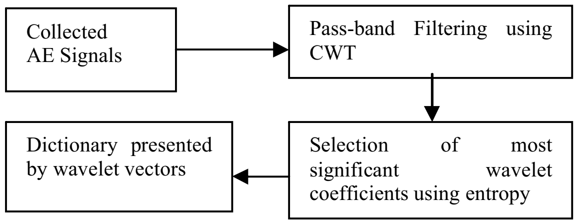

Figure 1: Schematic explanation of the methodology proposed to establish a dictionary of each mechanism damage.

2 Entropy and Wavelet Transform

The analysis of non-stationary signals involves a compromise between how well discontinuities or transitions can be described, and how finely long-term behavior can be identified. The wavelet transform provides an efficient analysis of signals combining occurrences of very different scales and frequencies. The analysis is performed using a single prototype function, called mother wavelet $\Psi(t)$, which can be thought of as a band pass filter, and it is a well-localized and oscillating function, of zero average [10]. The CWT is defined by:

$$CWT_f(u,s) = < f, \psi_{u,s} > = \int_{-\infty}^{+\infty} f(t) \frac{1}{\sqrt{s}} \Psi^*\left(\frac{t-u}{s}\right) dt,$$

Where $\Psi_{u,s}(t)$ functions are the wavelet atoms derived from the dilation of a mother wavelet Ψ by a scale factor and translation by a factor u. The analysis consists in the extraction of the information of the signal, with the wavelet coefficients $CWT_f(u,s)$, and the synthesis allows retrieving the function $f(t)$ using the same coefficients.

In current work, the entropy was used as a tool to extract the basis which could be used to reconstruct the more significant components of AE signals.

For a wavelet basis, the AE signal can be expressed as following:

$$f(t) = \sum_i^n \alpha_i \psi_i(t), \text{ where:}$$

α_i : basis coefficients

$\psi_i(t)$: wavelets or basis vectors

The entropy of Shannon of one signal (vector $f(t)$) on the basis decomposition $\psi_i(t)$ is defined as:

$$E = -\sum_{i} \frac{|\alpha_i|^2}{\|f(t)\|^2} Ln \frac{|\alpha_i|^2}{\|f(t)\|^2}$$

Theoretical dimension represents the dimension of the signal to be analyzed in the field of the transform: $d = e^E$ [11].

3 Experimentation

Composites made of glass fibre and epoxy matrix were manufactured by using the procedure of manual lay-up with compression moulding at room temperature. The Stacking sequence is 12 layers. Composites are in parallelepiped form and have dimensions 20 x 250 x 3 mm^3. Resin samples have a dumbbell shape and are 150 mm length.

Quasi-static tensile tests were performed on composite specimens at room temperature using an Instron loading machine with the load cell capacity of 100 KN (Figure 2). The rate of displacement of the machine crosshead was 0.5 mm/min. Tests were performed in the same conditions to ensure consistency of results. In this study two-channel data acquisition system Euro Physical Acoustics (EPA) corporation was used to record AE data. AE signals were detected by using two broadband piezoelectric sensor (EPA micro 80) (Figure 1.a), with 100 KHz-1 MHz bandwidth. Transition of acoustic energy between the transducer and the samples is achieved by using silicone grease. AE signals are conditioned and amplified at 40 dB using a preamplifier (EPA 1220 A) operating in the frequency range (100KHz-1 MHz). Preliminary measurements allowed determining the following acquisition parameters: PDT = 50 µs; HDT = 100 µs; HLT= 400 µs. Sampling rate was fixed at 5 MHz by taking 5021 points. Depending on the performed experiment, the threshold was fixed from 38 dB to 42 dB.

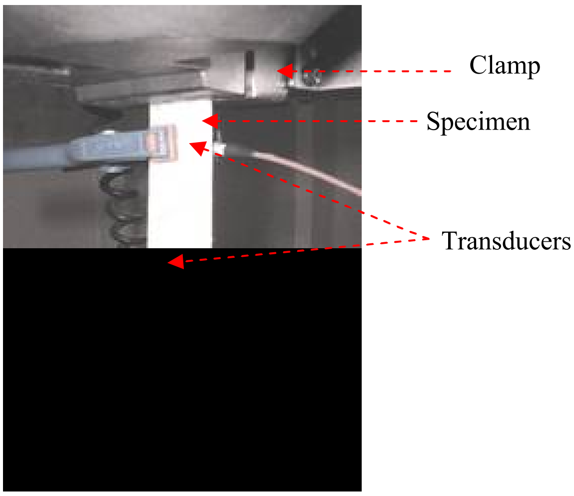

Figure 2: Monitored quasi-static tensile tests.

3 Result and discussion

Figure 4 illustrates the time evolution of the AE hits as a function of the applied load recorded during a quasi static tensile test performed on (a) resin specimen and (b) 90° unidirectional composite specimen (angle between fibres and load is 90°). The evolution of load for each specimen is characterized by a quasi-linear tendency which indicates that resin and 90° UD-GFRP have a fragile behaviour.

AE activity starts at the beginning of tests signifying the premature appearance of damage. It can be seen that a small number of events was detected for the resin. During the test applied to 90° UD-GFRP specimen, around 500 signals were detected. Amplitudes of collected signals are mainly distributed in the range: 38-60 dB for these two tests.

At first, a pass-band filter ranging from 50 KHz to 1.5 MHz is applied to AE data using wavelet transform. This filter contributes to increase the signal-to-noise ratio thus to improve AE analysis. An example is shown in Figure 3.

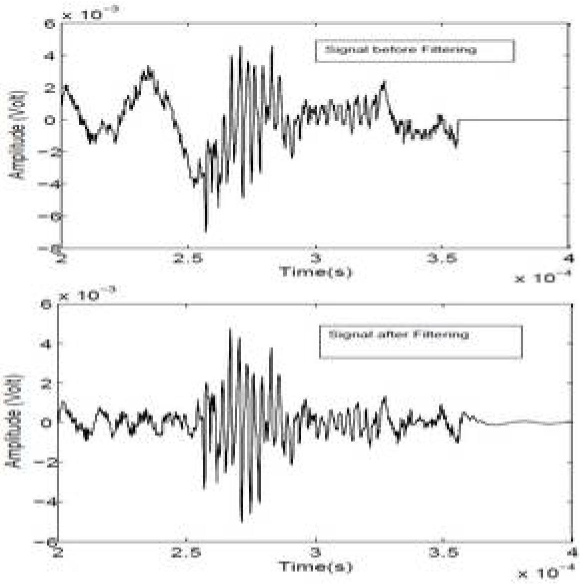

Figure 3: Effect of the wavelet transform filtering.

CWT was used to analyse AE signals in term of time-frequency content. The visual observation of AE signals obtained on the tested resin samples allows to identify two typical models which correspond to the majority of AE hits. As shown in Figure 5, for the first signal (A= 41 dB), it can be seen that energy is concentrated in frequency range from 260 KHz to 320 KHz. For the second (A= 40 dB) energy is localized in the frequency range from 80-100 KHz. These signals should be ascribed to matrix cracking mechanism, according to our experimental assumptions (supported by the literature).

Typical models of AE events are shown in Figure 6, for tests on unidirectional composite specimens (90°). It can be observed on first signal (53 dB) that frequency content can reach a value of 1 MHz. This kind of signal does not appear in resin tests, it should be associated to matrix-fibre debonding damage. Indeed, as mentioned earlier, for 90° UD-GFRP samples only debonding and matrix cracking mechanisms can be generated.

The second signal (A= 44 dB) must be ascribed to matrix cracking mechanism , since energy distribution is well localized in the frequency range from 270 KHz - 350 KHz. This signal has similar frequency characteristics compared to AE signals recorded from resin tests (cf Figure 4, b).

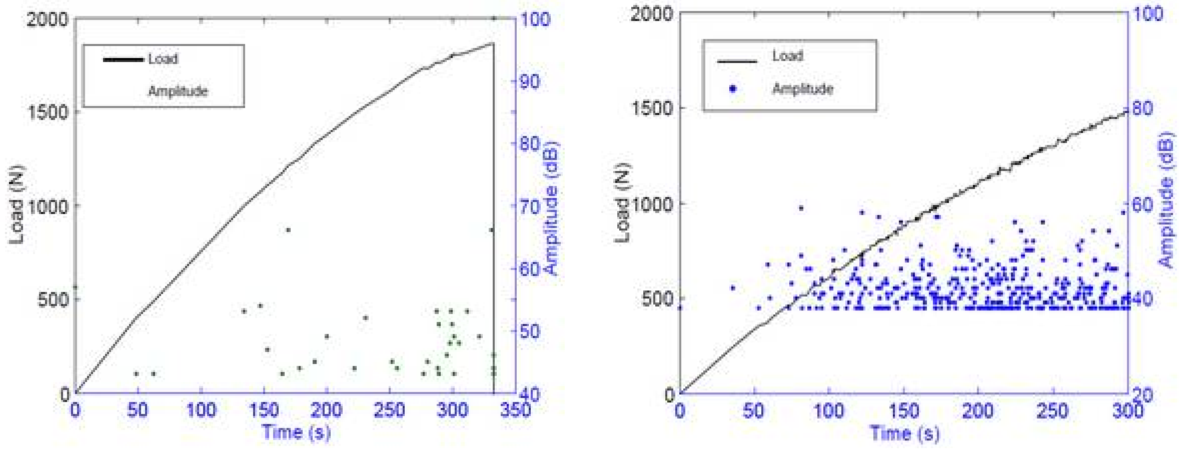

Figure 4: Load and AE hits amplitude for (a) resin specimen and (b) composite specimen $[90°]_{12}$.

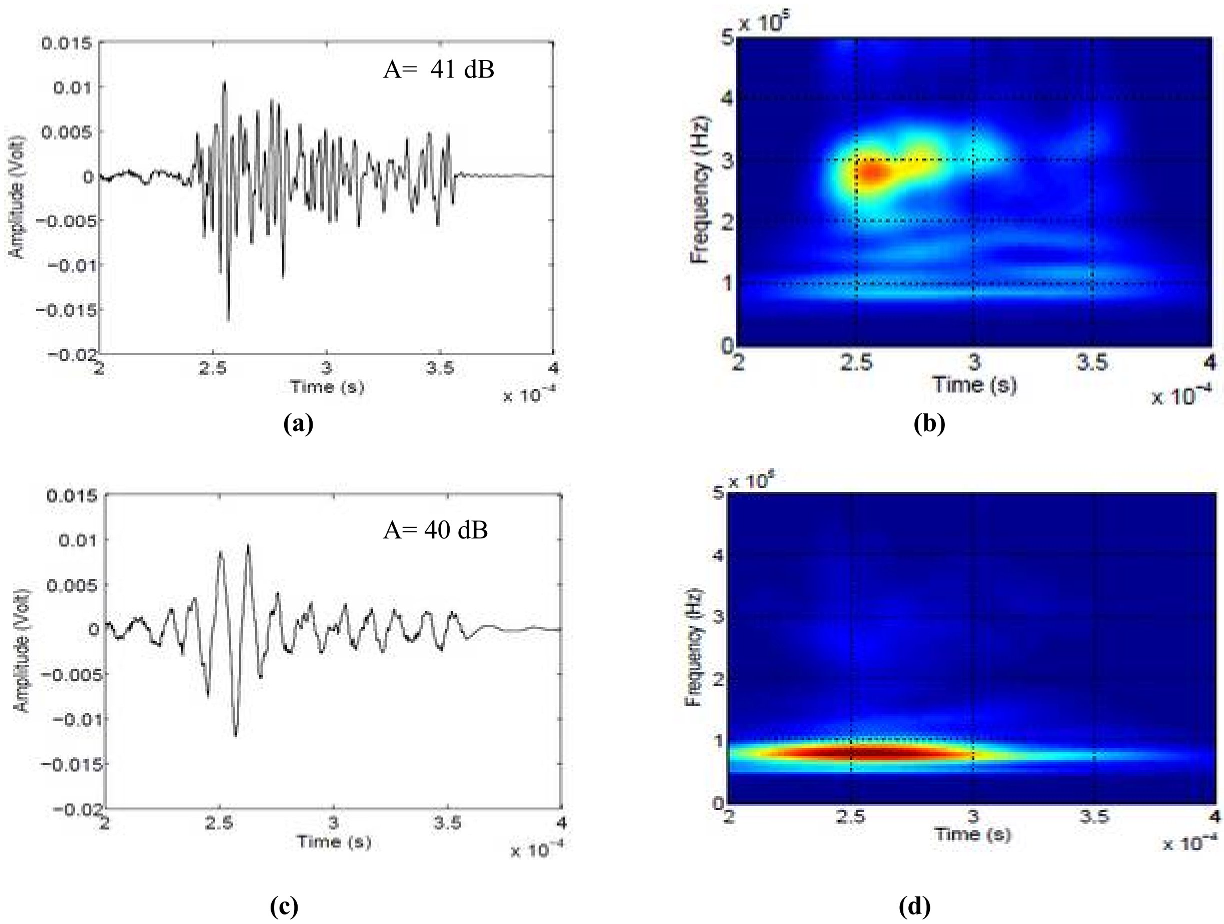

Figure 5: Time-amplitude representation (a, c) and Time-frequency content (b, d) of typical AE signals recorded from resin test. The two signals are related to matrix cracking mechanism.

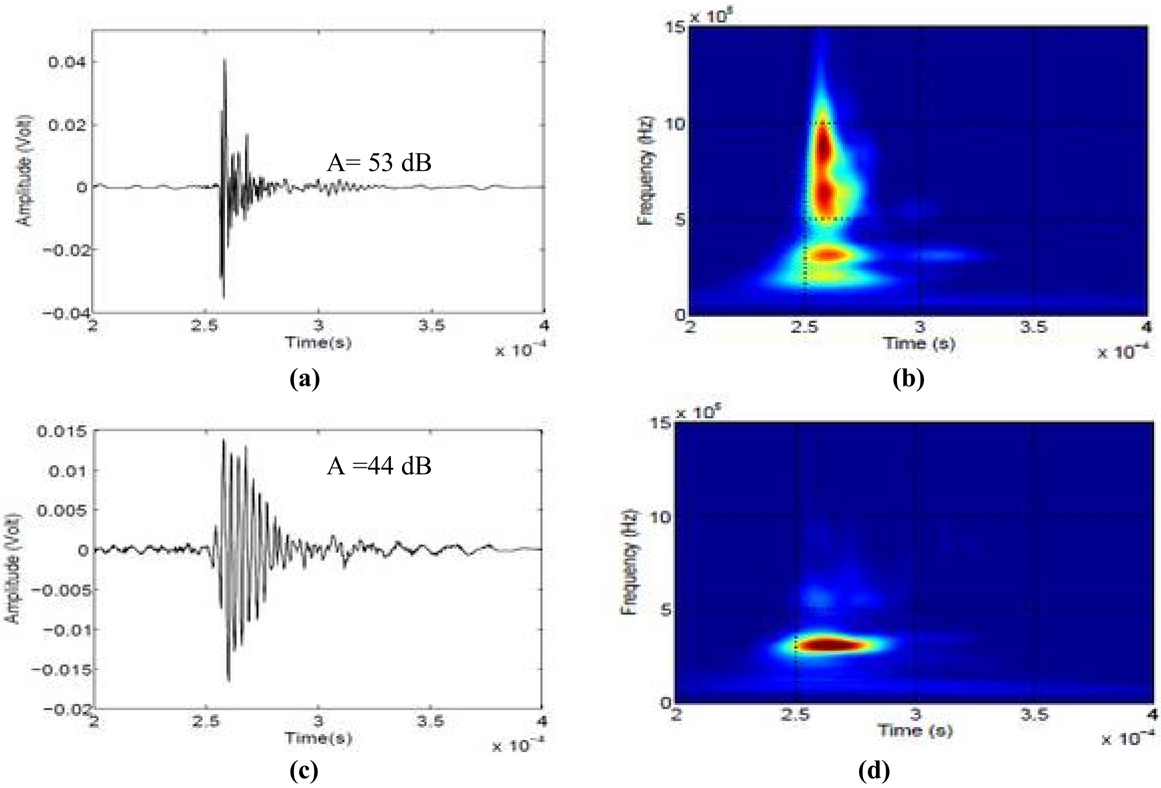

Figure 6: Time-amplitude representation (a, c) and Time-frequency content (b, d) of typical AE signal recorded from 90° specimen test. The first signal is related to interfacial damage, the second is relate to matrix cracking damage.

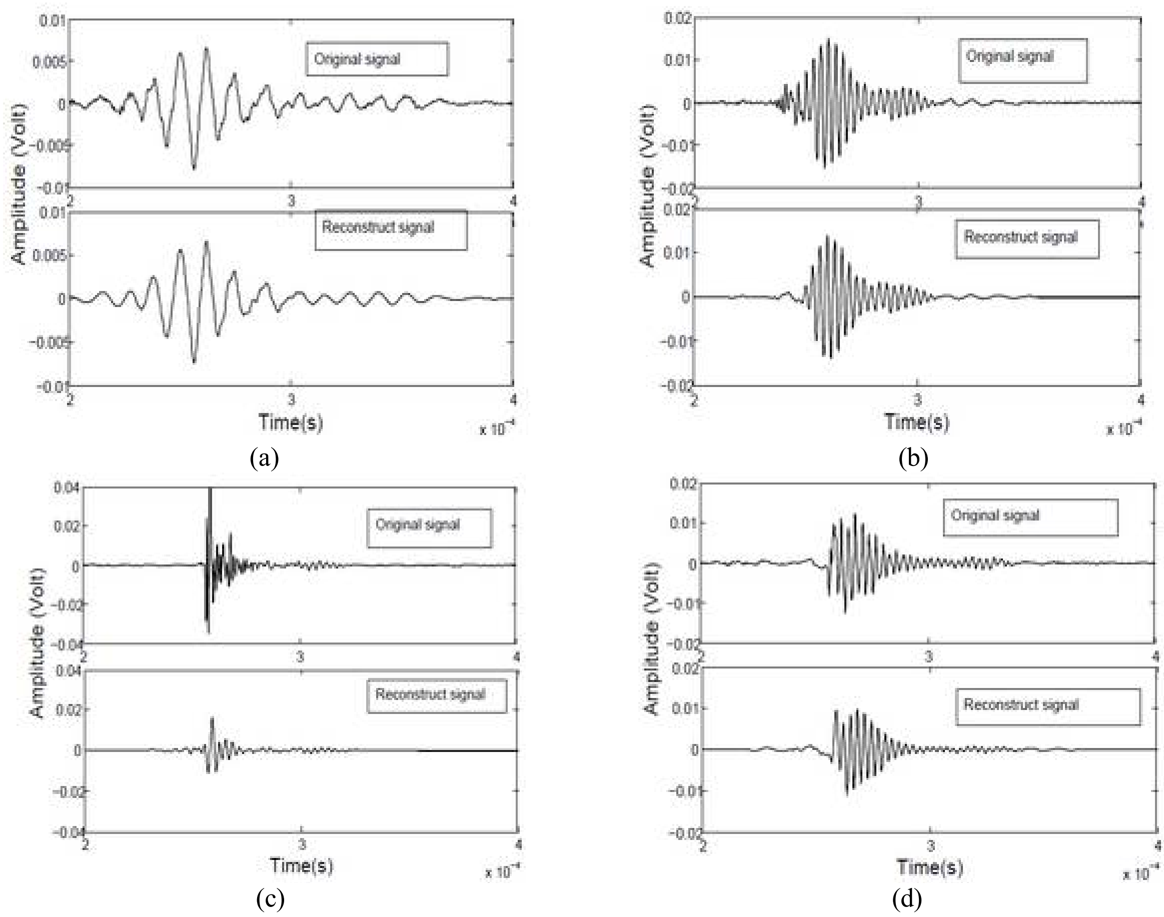

Figure7 : Reconstruction of AE signals: Projection on the matrix cracking dictionary, (a, b) model signals acquired from test on resin, (c, d) model signals acquired from test on 90° UD-GFRP composite.

In order to determine the waveforms which constitute the basis related to matrix cracking, the average of the wavelet coefficients modulus was calculated for 120 signals acquired during 4 tests applied to the resin. Calculation of theoretical dimension give most significant waveforms, by which the synthesis of each signal associated to matrix cracking could reproduce the maximum of signal energy. As a result, 102 wavelets were selected from 53X1000 wavelets . After establishing the matrix cracking (MC) dictionary , we compare AE signals' energies before and after projection on MC dictionary. Projection was realized by reconstruction of AE signals using both wavelet coefficients related to MC dictionary and original wavelet coefficients.

Results presented in Figure 7 illustrate comparison between original and reconstructed signals acquired from two tests. For test on resin (which generate only matrix cracking), we note that signals are well reconstructed thanks to MC dictionary, the two signals (a) and (b) were reconstructed with 89% and 77% energy percentage respectively. Projection of signals acquired from test on 90° UD-GFRP composites is shown in Figure 7,c and 7,d. First signal was partially synthesised using MC dictionary, 23% of original signal energy was reproduced. For the signal on the right (Figure 7,d), the percentage of energy reconstruction is 79%. This result demonstrates that the first signal can not be related to matrix cracking contrary to the second signal.

5 Conclusion

In this work a methodology was presented in order to discriminate damage mechanisms in fiber reinforced composite materials. The procedure consists in creating a waveform dictionary for each damage mode mechanism. Experiences were performed on two model-materials: pure resin where only matrix cracking damage are generated, so tests on 90° UD-GFRP composites allowed to generating matrix cracking and matrix-fiber deboning mechanisms. Matrix cracking dictionary was created by using signals acquired from tests on pure resin. First it was necessary to filter the AE signals by using wavelet transform in order to increase the signal to noise ratio thus optimizing the waveforms dictionary. Wavelet transform associated to the entropy criterion was used to determine the wavelet vectors by which the dictionary was made. The MC dictionary was examined for signals acquired from both tests. AE signals were reconstructed using MC dictionary. The reconstructed signals energy should be important for AE signals related to matrix cracking contrary to the debonding mechanism. This condition was confirmed by the result presented in figure 7. Finally, this work will be developed by holding account of signals whose amplitudes are below the fixed threshold (ex. from 30 dB to 25 dB), which are usually neglected [12]. The creation of new dictionaries describing other damage mechanisms (ex. delamination) in order to make automatic classification of damages possible is also under consideration.

References

[1] A. Laksimi, X.L. Gog and M. Benzeggah, "Analysis of damage mechanisms in a centrally notched glass-fibre/epoxy plate", *Composite Science and Technology.* 52, 85-91 (1994).

[2] D.Valentin. "A critical analysis of amplitude histograms obtained during acoustic emission tests on unidirectional composites with an epoxy and a PSP matrix", *Composites*. 16(3), 225-230 (1985).

[3] A. Marec, J.H. Thomas, and R. El Guerjouma, "Damage characterization of polymer-based composite materials: Multivariable analysis and wavelet transform for clustering acoustic emission data", *Mechanical Systems and Signal Processing.* 22, 1441–1464 (2008).

[4] M.G.R. Sause, A. Gribov, A.R. Unwin, S.Horn, "Pattern recognition approach to identify natural clusters of acoustic emission signals", *Pattern Recognition Letters,* 33, 17-23 (2012).

[5] C.R. Ramirez-Jimenez, N. Reynolds, T.H. Gan, P. Purnell, M. Pharaoh, "Identification of failure modes in glass/polypropylene composites by means of the primary frequency content of the acoustic emission event", *Composite Science and Technology.* 64, 1819-1827 (2004).

[6] T.H. Loutas, V. Kostopoulos, C. Ramirez-Jimirez, M. Pharaoh, "Damage evolution in center-holed glass/polyester composites under quasi-static loading using time/frequency analysis of acoustic emission monitored waveforms", *Composites Science and Technology.* 66, 1366-1375 (2006).

[7] A. R. Oskouei, M. Ahmadi, M. Hdjikani, "Wavelet-based acoustic emission characterization of damage mechanism in composite materials under mode I delamination at different interfaces", *Express Polymer Letters. 3*, 804-813 (2009).

[8] H. Suzuki, T. Kinjo, Y. Hayashi, M. Takemoto, K. Ono, Y. Hayashi, " Wavelet transform of acoustic emission signals", *J. Acoustic Emission.* 14 (2), 69-84 (1996).

[9] N. Godin, S. Huguet, R. Gaertner, "Clustering of acoustic emission signals collected during tensile tests on unidirectional glass/polyester composite using supervised and unsupervised classifiers", *NDT and E International*. 37, 253-264 (2004).

[10] I S. G. Mallat, A wavelet tour of signal processing. San Diego: *Academic Press*. (1999).

[11] I. Abdallah, S. Montrésor, M. Baudry, "Speech Signal Detection in Noisy Environment using a Local Entropic Criterion", *5th European Conference on Speech Communication and Technology EUROSPEECH'97.* 5, 2595-2598 (1997).

[12] A. Satour, S. Montrésor, M. Bentahar, R. Elguerjouma, F. Boubenider, "Improved acoustic emisssion to diagnostic damage" (JASA-EL, 2012, submitted).