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Integration of piezoelectric sensors for structural health monitoring of composite materials

S. Masmoudi[1, 2], A. El Mahi[1], R. El Guerjouma[1], S.Turki[2]

[1.] LUNAM University: Maine University, Acoustic Laboratory of Maine University (LAUM), CNRS UMR 6613, Avenue Olivier Messiaen, 72085 Le Mans Cedex 9, France
[2.] Sfax University, Sciences Faculty of Sfax, Physics Department, BP1171, 3000 Sfax, Tunisia

ABSTRACT —This work presents a health monitoring study of composites incorporating an integrated piezoelectric sensor. Firstly, experimental research is focused on examining the effects of the embedded sensors on the structural integrity of composites subjected to tensile loads. A series of specimen composites with and without embedded piezoelectric sensors were fabricated in E-glass fiber/epoxy. The composite specimens with PZT sensors embedded in the mid-plane were tested in tensile static and creep loading while continuously monitoring the response by the acoustic emission technique. The acoustic signals were analyzed using the classification k-means method in order to identify the different damage and to follow the evolution of these various mechanisms for both types of materials (with and without sensor).

Keywords *Composite, integrated NDT, piezoelectric sensor, acoustic emission, tensile tests*

I. Introduction

In order to increase security, to reduce delays of airplane maintenance and to lower the repair costs, integrated monitoring could be envisaged in a permanent or semi-permanent way, for the evaluation of the degradation state of composite structures. This could provide information about damage state. The embedment of sensors within composite structures gives the opportunity to develop smart materials for health monitoring systems.

The future of smart structure technology is very promising [1-4]. There has been considerable interest in the use of piezoelectric materials in conjunction with the light-weight and high-strength/modulus polymeric laminated composites as one type of smart structures.

Smart structures incorporating piezoelectric sensor have many advantages for engineering applications: such as vibration control, noise suppression and structural health monitoring [1,3]. Several studies [5, 6] were carried for the development of non-destructive testing methods to detect damage in composite materials.

Acoustic emission method was used to analyze the different damage mechanisms detected in composites. This technique represents the generation of transient ultrasonic waves due to damage development within the material under load [5, 7]. The phenomena origins of acoustic emission are the propagation of cracks, delamination, friction, etc [8]. Any generated AE signal contains useful information on the damage mechanism. One of the main issues of AE is to discriminate the different damage mechanisms from the detected AE signals. Multi-parametric classification of the main parameters extracted from the signals of AE is increasingly used to separate and identify the different mechanisms sources. In this context, many studies [9,10] were conducted on

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Corresponding author: Sahir Masmoudi,
Research field: Non-destructive testing,
Adress: Acoustic Laboratory of Maine University (LAUM), CNRS UMR 6613, Avenue Olivier Messiaen, 72085 Le Mans Cedex 9, France.
E-mail: Sahir.Masmoudi.Etu@univ-lemans.fr

composite materials. They identified four types of signals: A, B, C and D which correspond respectively to the matrix cracking, debonding in the fiber-matrix interface, fibers breakage and delamination.

In this paper, tensile tests are applied to the cross composite specimens with and without embedded piezoelectric sensor made from glass fibers and polymer matrix. Tests applied to the material integrated with piezoelectric sensor are conducted in order to characterize the effects of introducing the sensor into the host composite material. Then, *k*-means method is applied to classify the signals emitted by damages mechanisms using the Noesis software [11]. The results of mechanical tests and AE signals collected during tests for specimens with and without integration were compared.

II. Material and experimental procedure

II.1. Material

The material considered in this work was manufactured in the laboratory. The material is a cross $[0_3/90_3]_s$ laminate composites fabricated by hand lay-up process from E-glass fibers of weight 300 g m^{-2} and resin epoxy of type SR1500/SD2505. Composite plates were cured at room temperature with pressure by using vacuum bagging technique. The embedded transducer, constructed from the piezoelectric ceramic was placed within the plies on the neutral plane of the laminate, in a way to result centered in plane global axis of the final specimens. Two-dimensional of PZT sensors is used, their dimensions are given in table 1.

Table 1.Dimensions of piezoelectric sensors embedded in the composite materials

Piezoelectric sensors	*Small Sensor: SS*	*Large Sensor: LS*
Diameter (mm)	5	10
Thickness (mm)	0.5	1

The composite specimens with and without sensors have been cut up using a diamond disc from laminate plates of 300x300 mm². The dimensions of specimens are: L = 250 mm, w = 30 mm and th = 4 mm, where L, w and th are respectively the length, width and thickness of the specimens.

II.2. Experimental procedure

The effect of embedding the sensor on the stress-strain of the composites was studied in tensile tests. At ambient temperature, the specimens were subjected to tensile tests in static and creep until failure, which enables to put in evidence the damage phenomena as function of the time. Experimental tests were carried out on a standard hydraulic machine INSTRON 8516 of 100 kN capacity. The machine is interfaced with a dedicated computer for controlling and data acquisition. Three to five specimens were tested for each test in order to check the repeatability of the results. Experimental set-up is shown in figure 1. The specimens were tested in static tensile until fracture at a constant rate of 1 mm min^{-1}. The load and displacement of each specimen was recorded during tests.

In creep tests, the specimens were loaded to a given load and maintained in isotherm condition. Then the increase displacement was recorded in time. These tests were done for applied load levels r (F_a/F_u) equal to 0.7, where F_a is the applied load to the specimen during the creep tests and F_u is the ultimate failure in static test.

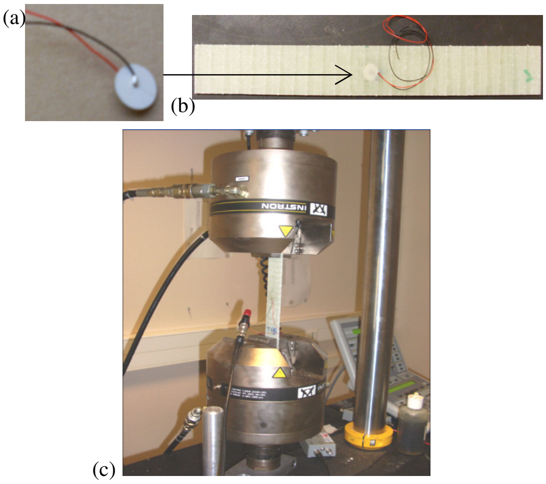


Fig. 1 a) Experimental set-up of tensile test, b) Piezoelectric sensor and c) Specimen with embedded piezoelectric sensor

During loading, acoustic emission signals were recorded. The acquisition of the signals is carried out using software AEWin from Euro Physical Acoustics (EPA) Corporation with a sampling rate of 5 MHz and 40 dB preamplification. AE measurements are achieved by piezoelectric sensor with a frequency range 100 kHz–1 MHz. The amplitude distribution covers the range 0–100 dB. Several descriptors are calculated by the acquisition system for each AE event (Figure 2): amplitude, energy, duration, rise time, counts, etc.

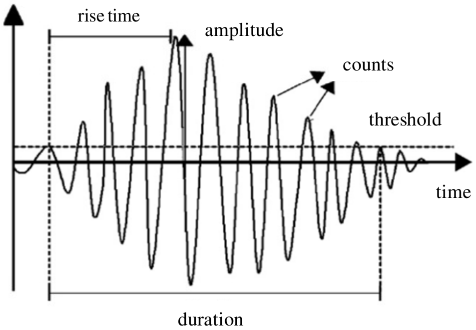


Fig. 2 Common waveform descriptors calculated by the acquisition system for each AE event

The collected parameters are used as input descriptors in the proposed classification method. The AE signals are classified by the *k*-means method using the Noesis software [11]. The number of classes is optimized by taking the minimum value of the factor R_{ij} [12] by scanning a number of classes in a range from 2 to 5.

III. Results and analysis

III.1. Influence of integration of the piezoelectric sensor on the mechanical properties

Figure 3 presents a comparative study of composite specimens with and without embedded sensors. This figure gives the evolution of the load versus displacement for three types of composites: specimen without sensor (WS), specimen with integrated small sensor (SS) and specimen with integrated large sensor (LS).

The curves show two different linear zones. The first region represents an elastic behavior of the material for small displacements, which used to measure the elastic characteristics of the materials tested. The second zone is also linear up to rupture which is brittle. This zone is characterized by the initiation and development of micro-cracks in the material. It was found that the instrumented composites reach their break before the composite without instrumentation.

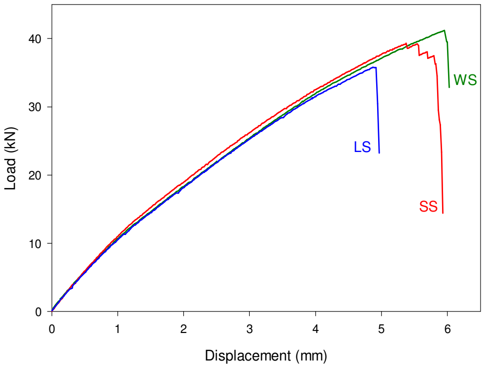


Fig. 3 Load-displacement curves measured in tensile static tests for three types of specimens: without sensor (WS) and with integrated small (SS) and large (LS) sensors

Table 2 shows the mechanical characteristics of material obtained in tensile static tests. By increasing the size of integrated piezoelectric sensors, the strength decrease, the failure displacement decrease slightly and the rigidity is founded identical for all type of specimens studied. As a general comment, the incorporation of piezoelectric sensors in the composites causes low degradation of mechanical properties.

Table 2. Mechanical characteristics obtained in tensile static tests

Specimen	*WS*	*SS*	*LS*
Failure load (kN)	41	40	36
Failure displacement (mm)	6	5,6	4,9
Rigidity (kN/mm)	10	10,6	10

The tensile creep tests were carried out on the identical specimens tested in static. A comparative study of composite specimens with and without embedded PZT sensor is shown in figure 4. This figure illustrates the evolution of normalized displacement in time. All specimens are broken up. Specimen integrated with the small sensor (SS) resisted more than the non-integrated specimen (WS) while the specimen integrated with a large sensor (LS) reached the break before the other specimens. The evolution of displacement according the time for all specimens can be divided into three distinct phases:

- The first one is referred as a region of primary creep and has very short duration as compared to rest of creep curves during which decrease in stiffness degradation is rapid.
- The second phase is very spread in time and represents the dominant part during test corresponds to a gradual decrease in stiffness with time and it is slower than the first region.
- The third phase is characterized by a brutal and continuous acceleration of deformations rates. It is associated to the more active damage until the final failure of the specimen material.

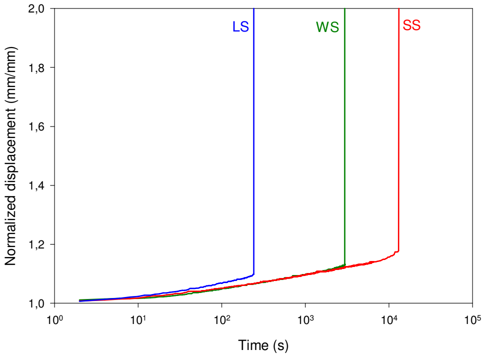
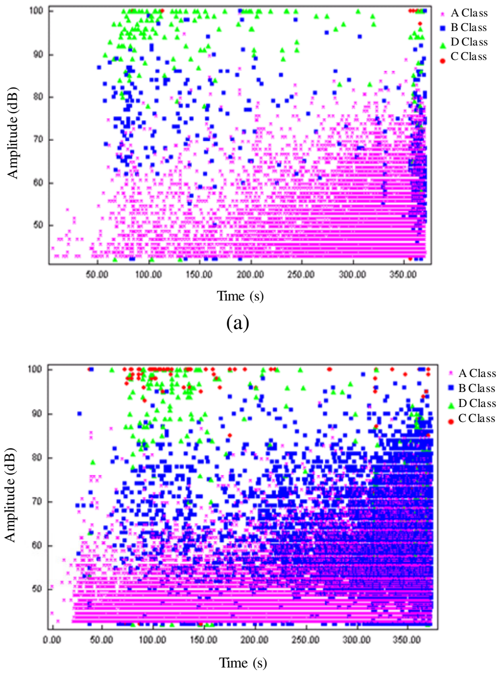


Fig. 4 Normalized displacement vs time in creep tests for three types of specimens: without sensor (WS) and with integrated sensor (SS and LS)

III.2. Acoustic emission analysis

The acoustic signals collected during tests were analysed by multi-parameters classification method (*k*-means). This analysis is achieved in order to identify the acoustic signals emitted by different type of damages, also to compare evolution of these various mechanisms in materials with and without instrumented sensor during tests. Two to three specimens are tested for each test in order to check the repeatability of results.

Figure 5 shows the classification of AE signals for composite specimens with and without sensor (SS and WS). This figure gives the distribution of amplitude versus time. We have observed the presence of four types of damage: matrix cracking (A class), fiber-matrix debonding (B class), fibers breaking (C class) and delamination (D class).



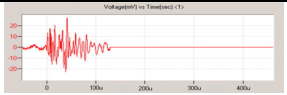
(a)

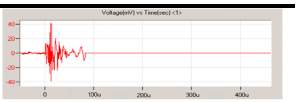
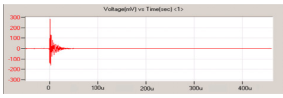
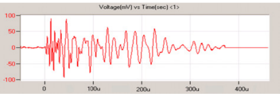
(b)

Fig. 5 Distribution of amplitude vs time for cross-ply laminates in static tests: a) specimen without integration (WS) and b) specimen with integration (SS).

The waveforms of the four damage mechanisms are given in table 3. The acoustic signature of matrix cracking is characterized by slowly rise time, low amplitude and low energy. For B class signals, the waveform is characterized by a shorter rise time, higher amplitude and higher energy. Signals for C class have a very short time, quickly rise time, high amplitude and high energy. Signals for D class have a very long duration, slow rise time and higher energy.

Table 3. Waveform of damage mechanisms

Damage mechanism	***Form of signal***
Matrix cracking (A class)	

Fibre-matrix debonding (B class)	
Fibres breaking (C class)	
Delamination (D class)	

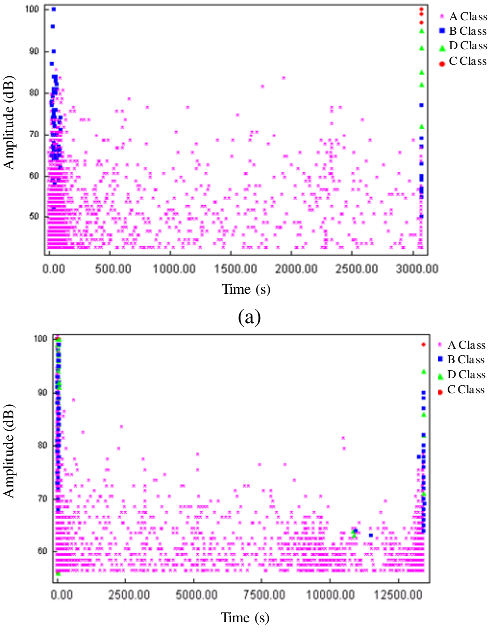
Results show that the matrix cracking (A class) starts early and involves more acoustic events. In the case of WS material, the matrix cracking is followed by the fiber-matrix debonding (B class) and delamination that occur simultaneously. After a few moments, the fiber breakage signals occur. In the case of SS material, the matrix cracking is followed by the debonding, delamination and fibers breaking, which appear in parallel. These microcracks continue to appear during tests and result the failure of the materials. The presence of the AE sensor into the structure promotes especially the detection of matrix cracking signals and the debonding.

Similarly to static tests, the classification of AE signals obtained during creep tests are shown in figure 6. In creep tests, we have also observed the presence of four types of damage (A, B C and D class).

The results obtained shows that the acoustic activity is divided on three phases:

- In the first one, the acoustic activity is very significant at the beginning of the test. This activity corresponds to the initiation and the multiplication of micro-cracks in the specimen. The amplitudes of these signals are in the range of 42 to 100 dB.
- In second phase, it's observed a reduction in the acoustic activity where the signals have amplitude in the range of 42 to 75 dB. This phase is due to the propagation of matrix-cracking, and corresponds to the totality of the life anticipation of the material.
- In the third phase, the acoustic activity becomes after very significant and very energetic. The amplitude reaches until 100 dB. This phase, very short, corresponds to the fast propagation of the cracking which becomes more localized, caused hence the final failure of the specimen. The acoustic activity of this phase covering all the ranges of amplitudes corresponds to several damage mechanisms.

Similar to static tests, the number of hits for material with embedded sensor is higher than that observed in material without integration.



(a)

(b)

Fig 6. Distribution of amplitude vs time for cross-ply laminates in creep tests: a) specimen without integration (WS) and b) specimen with integration (SS).

IV. Conclusion

The effects of embedded piezoceramic (PZT) sensor on the integrity and mechanical response of the E-glass/epoxy composites have been presented. Tensile static and creep tests were performed on specimens while constantly monitored the response by the acoustic emission technique. The acoustic signals collected during tests were analyzed using a multi-parameters classification method. The following conclusions can be drawn:

- The mechanical behavior of composites with and without integrated sensors shows no difference in the form. The incorporation of piezoelectric sensor causes low degradation of mechanical properties of material.

- The analysis and observation of AE signals sets four acoustic signatures of four damage modes in composites: matrix cracking, fiber/matrix debonding, delamination and fiber breakage.

- One of the major differences between the two types of specimens is the intense acoustic activity for material with embedded sensor. In addition, the number of hits for material with embedded sensor is generally higher than those observed in material without embedded.

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