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Structural Health Monitoring of Smart Composite Material by Acoustic Emission

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This paper presents a health monitoring study of composites incorporating integrated piezoelectric sensors. Firstly, experimental research is focused on examining the effects of the embedded sensors on the structural integrity of composites subjected to flexural loads. A series of specimens of composite with and without embedded piezoelectric sensors were fabricated in E-glass fibre/epoxy with a unidirectional play laminate. The composite specimens with sensors embedded in the mid-plane and without sensors were tested in three-point bending tests in static and creep loading while continuously monitoring the response by the acoustic emission (AE) technique. The AE signals were analysed using the classification *k*-means method in order to identify the different damages and to follow the evolution of these various mechanisms for both types of materials (with and without sensors). The static flexural tests indicate that the ultimate strength of the embedded composites is reduced, while the elastic modulus is not significantly affected. The acoustic emission analysis shows that the integration of the sensor presents advantages of the detection of the acoustic events.

1 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 analyse 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 composite materials. They identified three types of signals: A, B and C which correspond respectively to the matrix cracking, debonding in the fibre-matrix interface and fibres breakage.

The mechanical behaviour of composite materials has been studied by several researchers. For example, in the lab El Mahi et *al.* [11-13] have studied the mechanical behaviour in three-point bending in static and fatigue of different composite laminates. The static study has allowed to know the effect of stacking sequences and reinforcement types on the strength, modulus and damage mechanisms causing failure materials. Several loading ratio were used in fatigue tests. The analysis of stiffness degradation and identification of damage mechanisms during and after fatigue test have been performed.

In this paper, three-point bending tests are applied to the unidirectional composites specimens with and without embedded piezoelectric sensors made from glass fibres and polymer matrix. Tests applied to the material integrated with piezoelectric sensors are conducted in order to characterize the effects of introducing the sensors into the host composite material. The results of mechanical tests and AE signals collected during tests for specimens with and without integration were compared. The *k*-means method is applied to classify the signals emitted by damages mechanisms using the Noesis software [14].

2 Material and experimental procedure

The materials considered in this work were manufactured in the laboratory. The material is a unidirectional $[0_{24}]$ laminate composites fabricated by hand lay-up process from E-glass fibres 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 composite, in a way to result in 45 mm from the edge of the specimen. The dimensions of PZT disc sensors 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 specimens of both composites are: L = 150 mm, w = 30 mm and th = 8 mm, where L, w and th are respectively the length, width and thickness of the specimens.

The effect of embedding the sensors on the stress-strain of the composite was studied in flexural tests. At ambient temperature, the specimens are subjected to three-point bending 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 are tested for each test in order to check the repeatability of the results. Experimental set-up is shown in figure 1.

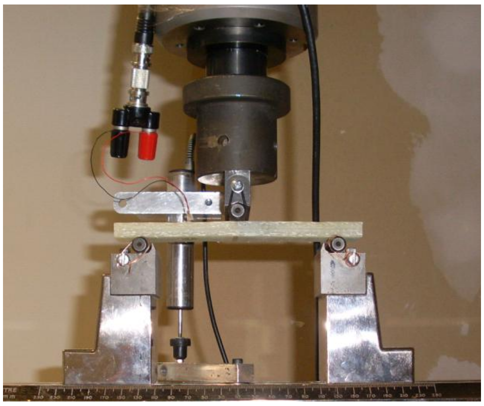


Figure 1: Experimental set-up of three-point bending test

The specimens were tested in static three-point bending until fracture at a constant rate of 2 mm min^{-1}. The load and displacement of specimen was recorded during tests.

In creep tests, the specimens were loaded to a given load and maintained in isotherm condition. Then we recorded the increase displacement in time. These tests were done for applied load levels r (F_a / F_u) equal to 0.75, where F_a is the applied load to the specimen during the creep tests and F_u is the ultimate failure in static test.

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 pre-amplification. 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.

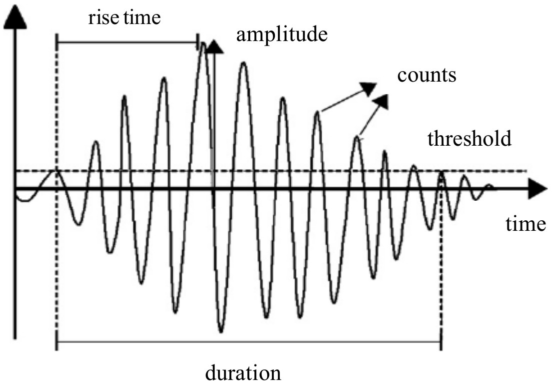


Figure 2: Common waveform descriptors calculated by the acquisition system for each AE event

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 [15]. The number of classes is optimized by taking the minimum value of the factor R_{ij} [15] by scanning a number of classes in a range from 2 to 5.

3 Results and analysis

3.1 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 stress 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 each stress/displacement curve is divided into two zones: the first one is linear, which is elastic, is large and allows measuring the Young's modulus in three-point bending test. The second zone is nonlinear until the rupture of specimen material. The behaviour of the three types of specimens was similar. The integrated specimen with small sensor (SS) reach the break at the same time of the specimen without integration, but the integrated specimen with large sensor (LS) reaches the break before the other specimens.

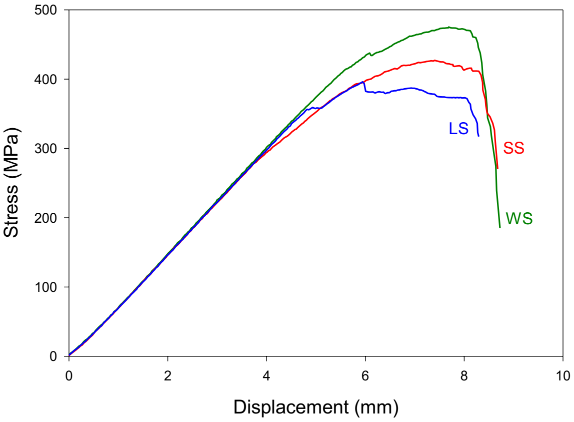


Figure 3: Stress-displacement curves measured in three-point bending static tests for three types of specimens: without sensor (WS) and with integrated small (SS) and large (LS) sensors

Table 2 show the mechanical characteristics of material obtained in flexural static tests. By increasing the size of integrated piezoelectric sensors, the strength decrease, the failure displacement decrease slightly and the flexural Young's modulus (calculated with the NE 63) 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 flexural static tests

Specimen	WS	SS	LS
Flexural failure stress (MPa)	475	427	387
Flexural failure displacement (mm)	7,7	7,4	7
Flexural Young's modulus (GPa)	16,6	16,5	16,5

The three-point bending creep tests were carried out on the identical specimens tested in static. A comparative study of composite specimens with and without embedded PZT sensors is shown in figure 4. This figure illustrates the evolution of normalized displacement in time. Integrated specimens are broken up but specimen without integration is not broken after more than 3 hours. It should be noted in creep test, that incorporation of sensors within composite causes a significant degradation in mechanical properties in creep loading.

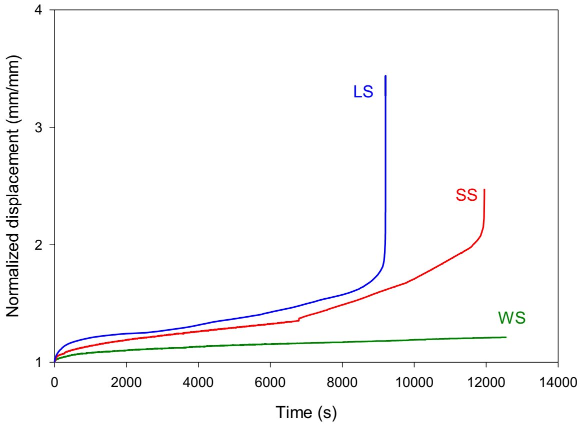


Figure 4. Normalized displacement vs time in creep tests for three types of specimens: without sensor (WS) and with integrated sensor (SS and LS)

Evolution of displacement according the time for integrated specimens can be divided in three distinct phases: the first one is short; the application of the load at zero time causes instantaneous elastic deformation, followed by a deformation depending on time. Second zone is very spread in time and represents the dominant part during test. Finely zone 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.

The integrated specimen with large sensor (LS) reaches the break before the integrated specimen with small sensor (SS).

3.2 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.

Figures 5 and 6 show the classification of AE signals for composite specimens without sensor (WS). These figures give the distribution of amplitude versus time (Fig.5) and time dependency of the identified damage mechanisms (Fig.6). We have observed the presence of three types of damage: matrix cracking (A class), fibre-matrix debonding (B class) and fibres breaking (C class). The waveforms of the three damage mechanisms are given in table 3. The acoustic signature of matrix cracking is characterised by slowly rising waveform and low amplitude and energy, for B class signals the waveforms quite different from the waveforms of A class signals, with shorter decay time and higher amplitude and energy. Signals for C class are a very short time and very high amplitude and energy.

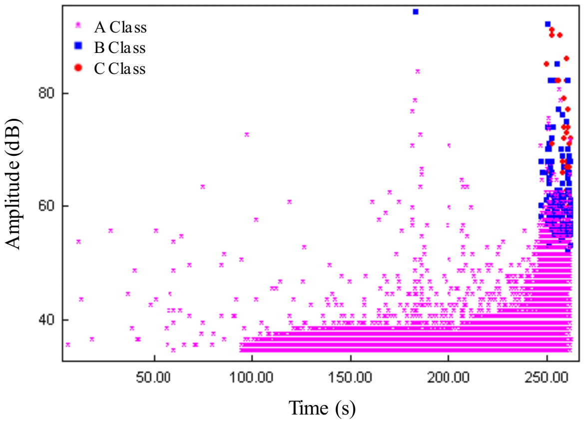


Figure 5. Distribution of amplitude vs time for specimen without integration (WS) in static test

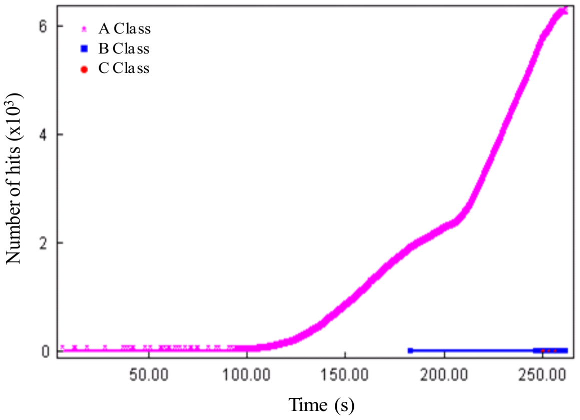


Figure 6. Time dependency of the identified damage mechanisms for specimen without integration (WS) in static test

Figures 7 and 8 show the classification of AE signals for integrated specimens with large sensor (LS). These figures give the distribution of amplitude versus time (Fig.7) and time dependency of the identified damage mechanisms (Fig.8). Also we have observed the presence of three types of damage (A, B and C class).

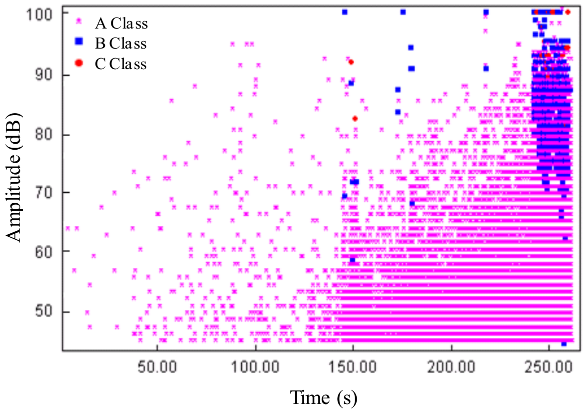


Figure 7. Distribution of amplitude vs time for specimen integrated with large PZT sensor (LS) in static test

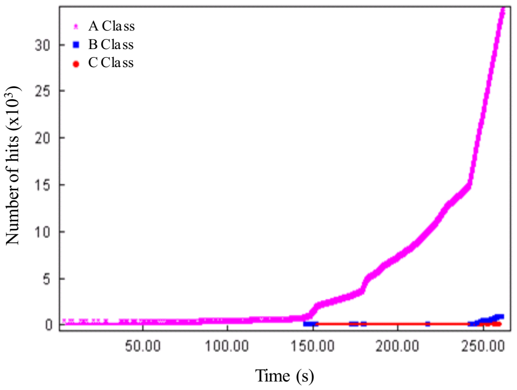


Figure 8. Time dependency of the identified damage mechanisms for specimen integrated with large PZT sensor (LS) in static test

Results show that the initiation of damage in both types of composites is ensured by the matrix cracking (A class) which continued until failure of the material. The fibre-matrix debonding (B class) and fibres breaking (C class) appears approximately in the middle of the test. The events amplitude and the number of hits for material with embedded sensor are higher than those observed in material without embedded. The high amplitude events for material with embedded sensor started before, almost at the middle of the load applied (Fig.7).

Once the patterns are labelled in terms of damage mechanisms and since the arrival time of each AE event is stored, it is possible to show the time occurrence of the events provided by the different damage mechanisms (Figs. 6 and 8). This visualization shows that before failure, the matrix cracking (A class) is the most dominant damage mechanism as it begins from the start of the tests and involves much more numerous AE events than the other mechanisms do. The fibre-matrix debonding (B class) appears in the middle of the experiments. The fibres breaking (C class) mainly occur at the end of the tests and lead to the failure of the material.

Similarly to static tests, the classification of AE signals obtained during creep tests are shown in figures 9 to 12. These figures gives the distribution of amplitude versus time (Fig.9 and 11) and time dependency of the identified damage mechanisms (Fig.10 and 12) for composites with and without integrated sensors (LS and WS).

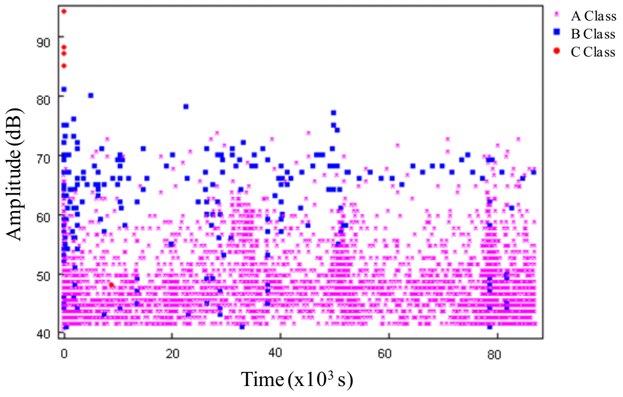


Figure 9. Distribution of amplitude vs time for specimen without integration (WS) in creep test

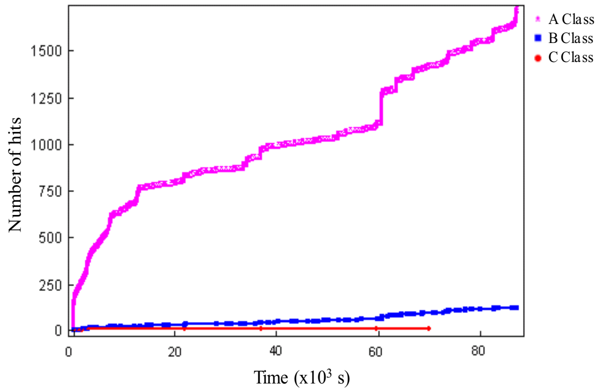


Figure 10. Time dependency of the identified damage mechanisms for specimen without integration (WS) in creep test

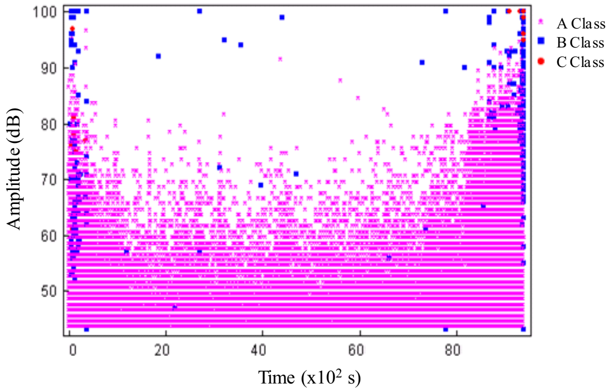


Figure 11. Distribution of amplitude vs time for specimen integrated with large PZT sensor (LS) in creep test

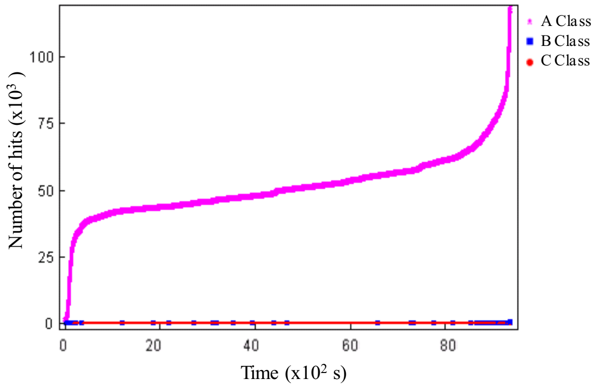


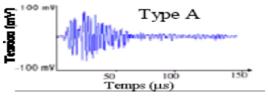
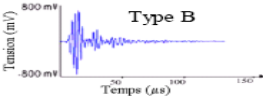
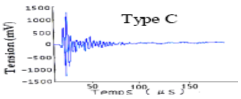
Figure 12. Time dependency of the identified damage mechanisms for specimen integrated with large PZT sensor (LS) in creep test

The results obtained for integrated specimen (LS) shows that the acoustic activity is divided on three phases (Fig 11): 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.

For specimen without integrated sensors (WS), we observed only the first two phases (Fig 9) because it is not broken.

Similar to static tests, the events amplitude and the number of hits for material with embedded sensor are generally more and higher than those observed in material without integration.

Table 3. Waveform of damage mechanisms

Damage mechanisms	Waveform
Matrix cracking (A class)	
Fibre matrix debonding (B class)	
Fibres breaking (C class)	

5 Conclusion

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

- The mechanical behaviour of composites with and without integrated sensors shows no difference in the form. The incorporation of piezoelectric sensor influences specially the fracture strength and causes low degradation of mechanical properties of material. The same conclusions apply to creep tests, embedding of PZT causes low decrease on the evolution of stiffness of the composites.

- The analysis and observation of AE signals sets three acoustic signatures of three damage modes in composites: matrix cracking, fibre matrix debonding and fibre 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 events amplitude and the number of hits for material with embedded sensor are generally higher than those observed in material without embedded and began early. This is certainly due to the integration of the sensors which leading to the discontinuities between the folds of the composite and hence contributes to the initiation of the damage and the loss of rigidity for the composite.

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