CONTINUOUS DAMAGE MONITORING TECHNIQUES FOR LAMINATED COMPOSITE MATERIALS

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SUMMARY: The increasing use of composite materials in loaded structures and the typical distributed nature of damage in these materials has created a need for reliable and efficient damage monitoring techniques. Preferably, these techniques should have continuous detection capabilities as this makes it possible to eliminate the high cost of a periodic inspection scheme. This paper will discuss two different approaches to continuous damage detection : optical fibre technology and modal acoustic emission (MAE). By embedding optical fibres in composite materials and by continuously monitoring the changes in properties of light transmitted through these fibres, damage initiation and growth can be detected. This has been demonstrated by performing tensile tests on quasi-isotropic laminates and correlating the optical fibre observations with results obtained by the classic acoustic emission and replica techniques. Modal acoustic emission is a new approach to acoustic emission testing which uses plate wave theory as a theoretical background. Laboratory testing has shown that this new analysis procedure offers distinct advantages over the classic AE analysis techniques.

KEYWORDS: damage monitoring, continuous, optical fibre, acoustic emission, plate wave theory

INTRODUCTION

Because of their interesting properties, composite materials based on polymer matrices have received considerable attenation during the last decades. This material class is nowadays increasingly being used in a variety of applications, e.g. military and civil aircrafts, chemical storage tanks, sport articles,...

One of the main difficulties that has to be tackled before composite materials can be used in a safe manner in loaded structures, lies in the damage evolution sequence. In contrast to monolithic materials, composites exhibit a variety of damage modes (matrix cracking, fibre fracture, delamination,...) which are spatially distributed. Both factors make it difficult to quantify the damage state during the service life of a composite component. Nevertheless, damage quantification is necessary to be able to determine the residual properties of the structure.

Up to now, damage detection in composite materials has been performed by using the classic

NDT techniques like visual inspection, ultrasonic testing or radiography. These techniques do, however, require a high accessibility to the structure which makes it necessary to take the structure out of service. With these techniques, inspection can therefore only be done on a periodic basis : the structure is in service for a certain period and is then taken out of service to be completely inspected. The time between two subsequent inspection intervals is such that a critical damage state can not form inbetween.
The problem with a periodic inspection scheme is the high cost. Taking a structure out of service leads to a loss of production profits. Moreover, in this way the first inspection intervals can be spent completely searching for damage that isn’t present, since it is not known a priori if damage has formed.
The high cost involved in periodic inspection could be avoided if adequate techniques were available that can continuously monitor a composite structure in service. In this way, damage could be detected at the moment of its occurrence after which additional inspection or repair could be undertaken. Composite materials could thus gain substantial added value if it were possible to equip them with a system that can continuously monitor its damage state.
The main aim of this work was to investigate the possibilities of two concepts for continous damage monitoring of composite materials : optical fibre technology and modal acoustic emission. Optical fibres can be embedded in composite materials during production. By continuously monitoring the properties of light transmitted through these fibres, damage initiation and growth can be detected. In this work, a novel detection concept based on microbending and intensity modulation was used. Modal acoustic emission (MAE) is a new approach to acoustic emission testing which uses plate wave theory as a theoretical background. By performing laboratory experiments, it was demonstrated how this technique offers clear advantages over classic acoustic emission analysis procedures.

OPTICAL FIBRE TECHNOLOGY

Material and experimental techniques

Throughout the work a carbon (Torayca T400H)/epoxy (Vicotex 6376) prepreg was used as the base material. The work concerning optical fibre technology used an 8-ply quasi-isotropic lay-up : $[0, 45, -45, 90]_s$. During production optical fibres (core diameter 50 µm, cladding diameter 125 µm, coating diameter 140 µm) were embedded along the 90-direction in the different interfaces of the laminate. This resulted in five material types :

- type A : no embedded optical fibres, reference material
- type B : one optical fibre embedded in each 0/45-interface
- type C : one optical fibre embedded in each 45/-45-interface
- type D : one optical fibre embedded in each -45/90-interface
- type E : one optical fibre embedded in the 90/90-interface

Tensile specimens were produced having a length of 200 mm, a width of 5 mm and a thickness of 1 mm. Damage was introduced in the specimens by performing tensile tests. All tests were performed on a MTS 810 loading frame equipped with hydraulic grips.
The tests were simultaneously monitored with three techniques. First there was the optical system : the optical fibres were led out of the specimen and were attached to a laser light source at one end and to a photodiode at the other end. In this way the intensity of the transmitted light could be continuously monitored throughout the test. In addition to this, information about the damage evolution was obtained by using the classic acoustic emission technique. To this extent, two broadband AE sensors (Digital Wave Corporation, type B1025) were attached to the specimen and were connected to a Vallen AMS3 acoustic emission

system (Vallen Systeme GmbH). Some tests were also monitored with the edge replication technique.

Preliminary research

Literature results concerning damage detection with optical fibre technology have shown that the development of a practical optical fibre sensor should systematically address the following subjects :

1) Is there a noticeable influence of the embedded optical fibres on the microstructure of the laminates ? [1, 2]
2) Are the mechanical properties of the laminates degraded by the presence of the embedded optical fibres ? [3, 4, 5, 6]
3) What type of optical fibre sensor will be used for damage detection ? [7]
4) Can damage formation be detected with the chosen configuration ?

Preliminary research [8] performed by the authors showed that major disturbances of the microstructure resulted from embedding optical fibres in the 0/45 (type B) and 45/-45 (type C)-interfaces ((ply bending, formation of a resin rich area) and to a lesser extent in the -45/90 (type D)-interface (resin rich area in the interface). An extensive investigation of the mechanical properties [9] exhibited significant degradations of the tensile strength, the bending strength and the fatigue properties for the type B material, a degradation of the bending strength for the type C material and a degradation of the fatigue properties for the type D material. The only material type that didn’t exhibit any degradation in mechanical properties was the type E material. Therefore it was decided to use this material type in the further development of the optical fibre sensor.

Choice of an optical fibre sensor

Two types of optical fibre sensors have been mainly used in literature for damage detection in composite materials : an intensity modulated concept based on optical fibre fracture which can only be used for the detection of damage initiation and a phase modulated concept which can be used as an alternative to a piezo-electric sensor for the detection of acoustic emission signals. In this work a novel intensity modulated concept was used, based on microbending of the optical fibre. The working principle of the sensor is schematically illustrated in Fig. 1. The optical fibre is embedded in the 90-layers, transversely to the loading direction in a tensile specimen. The left part of the figure shows the material and the embedded optical fibre in its undamaged state. The stress fields in the 90-layer above and below the optical fibre are identical and thus the optical fibre remains straight upon loading. The right part of the figure shows the material after damage, in the form of 90-matrix cracks, has been introduced. Generally, the average stress in the 90-layer in the vicinityof the matrix cracks will be lower. The stress fields above and below the optical fibre will therefore no longer be indentical and the optical fibre will start bending. Due to the microbending principle, light will be lost through the cladding because the condition of total internal reflection is no longer satisfied. The initiation of damage should therefore correspond to a decrease in the intensity of the transmitted light.

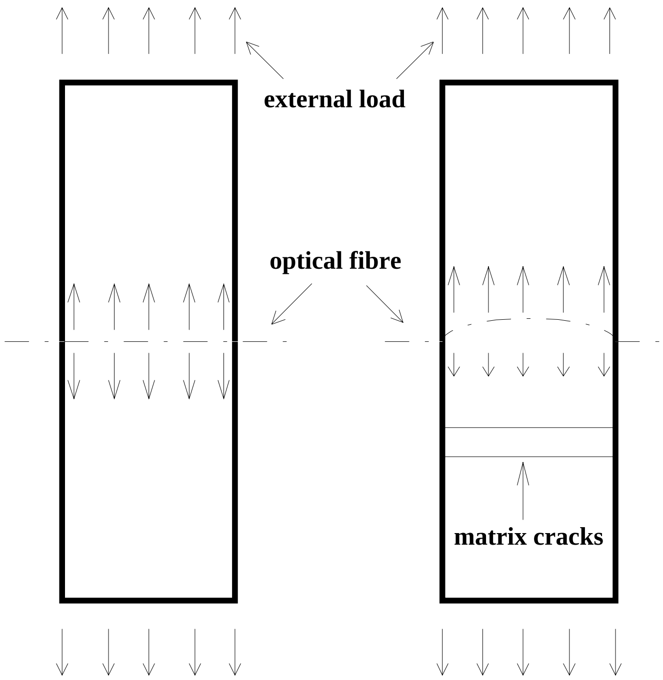

Fig. 1 : Schematic illustration of the optical fibre sensor working principle

This novel optical fibre sensor concept, which hadn't been demonstrated in literature before, combines the robustness of an intensity modulated sensor with the possibility to detect gradual damage evolution and not just damage initiation. In a next step, the feasibility of this concept was demonstrated by performing tensile tests and monitoring the damage evolution with the optical system, the classic AE technique and edge replication.

Damage monitoring with an optical fibre sensor

An example will be shown here that demonstrates the feasibility of using the novel sensor concept for continuous damage monitoring in composite laminates. An interrupted tensile test was carried out : the specimen was loaded to an initial stress level, unloaded and reloaded again to a higher stress level. This cycle was repeated until specimen failure occurred.
During the initial two cycles to 400 and 500 MPa no evolution was noticed in the optical sensor signal. Fig. 2 shows the results of the cycle to 600 MPa. Four graphs are shown : the top left graph shows the cumulative number of AE events observed during the test, the top right graph shows the load as a function of time, the bottom left graph shows the evolution of the optical signal as a function of time and the bottom right graph shows an AE location graph.
The optical signal exhibits a gradual increase, corresponding to a decrease in transmitted light intensity, from about 100 seconds onwards. This increase corresponds reasonably well to the initiation of the AE activity which is a first illustration of the fact that the optical fibre sensor does indeed sense damage initiation. Further evidence was provided by investigating the damage state of the laminate with the edge replication technique. The results of this investigation [8] showed that matrix cracking does indeed initiate at 600 MPa in this laminate. Thus, the three techniques are in good agreement which gives strong evidence for the fact that the optical fibre sensor can sense matrix crack initiation in these laminates.

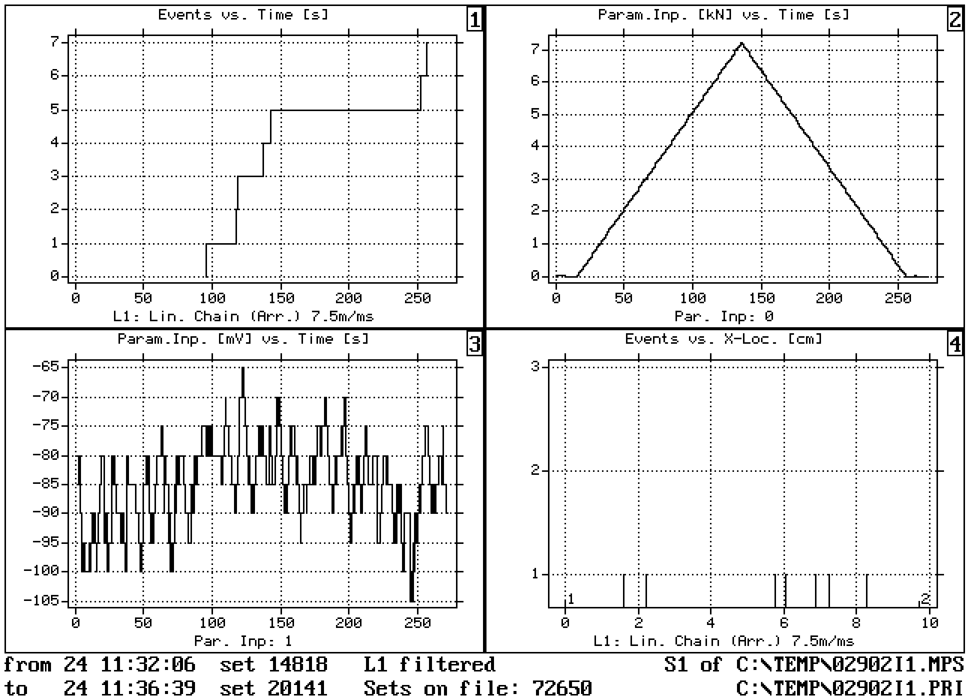

Fig. 2 : Tensile testing to 600 MPa : the optical signal shows a gradual increase corresponding to the initiation of the AE activity

This example illustrates the feasibility of using an intensity modulated concept for the detection of gradual damage evolution in composite laminates. More research needs to be carried out before practical applications can be developed. Research should, amongst other items, focus on the reproducibility of the measurement, on the sensitivity of the technique and on establishing quantitative relations between the active damage phenomena and the observed intensity drops.

MODAL ACOUSTIC EMISSION

Background

The classic acoustic emission (AE) technique has been the prime candidate for continuous damage monitoring in loaded structures since the 1970's. The number of well developed and generally accepted industrial applications of this technique has, however, up to now remained relatively limited. The main reason for this has to be found in the inherent limitations of the classic AE analysis procedures which mainly focused on an analysis of the AE activity (number of detected AE events per unit of time) and some simple wave parameters (peak amplitude, duration, energy, counts). These analysis procedures make it difficult to extract valuable information from the large data sets that are typical for a practical application. Moreover, the elimination of noise signals has always proven to be very difficult and there is no way to take into account the effects of wave propagation on the signal parameters. This has made AE mainly a trial and error technique based on empirical correlations which lacks an accurate, yet practical, theoretical foundation.
One possible way of solving this problem was introduced in the early 1990's by Gorman and his co-workers. The technique is now known as modal acoustic emission (MAE). MAE starts from the basic observation that AE signals are actually mechanical waves and that they should therefore be analysed according to their nature. This implies the use of wave propagation theory. MAE uses the additional observation that many composite structures are plate-like,

meaning that they have one dimension which is much smaller than the other two. As a result, a simplified version of general wave propagation theory, classical plate wave theory, can be used for the analysis of AE signals. The first literature results concerning the use of this theory in the field of composite materials have dealt with the detection of transverse matrix cracking [10, 11] and the monitoring of composite pressure vessels [12].

Here, first the main results of the classical plate wave theory will be presented. Following this, it will be demonstrated how this theory can be used in the analysis of AE signals and how this offers distinct advantages over the traditional AE analysis procedures.

Plate wave theory

A comprehensive overview of wave propagation theory as it applies to solid materials can be found in reference 13. Solutions to wave propagation problems in structures of arbitrary geometry can be obtained by using the three-dimensional equations of the elasticity theory. In the case of plate-like structures, however, a simpler theory can be used, i.e. classical plate wave theory. According to this theory, mechanical waves propagate through plate-like structures in three modes : the extensional mode (particle displacement in the plane of the plate and in the direction of wave propagation), the flexural mode (particle displacement perpendicular to the plane of the plate) and the shear mode (particle displacement in the plane of the plate and perpendicular to the direction of wave propagation). MAE has up to now made extensive use of the extensional and the flexural mode.

Based on the classical plate wave theory, the velocities of propagation of both modes can be calculated. Plate wave theory predicts a dispersionless extensional mode : all frequency components of this mode propagate at the same velocity. Although practical results show that this is a reasonable approximation, it will not be satisfied completely. An analysis of the extensional mode based on higher order theories shows that the extensional mode exhibits limited dispersive behaviour in which the velocity of propagation decreases with increasing frequency. For the flexural mode, plate wave theory predicts dispersive behaviour in which the velocity increases with increasing frequency.

Material and experimental techniques

The work dealing with MAE used the same prepreg that was mentioned above. Three different 8-ply cross-ply lay-ups were produced : $[0, 90_3]_s$, $[0_2, 90_2]_s$ and $[0_3, 90]_s$. Tensile samples were used having a length of 150 mm, a width of 12 mm and a thickness of 1 mm.

Tensile tests were performed on the MTS 810 loading frame. All tests were monitored by attaching two broadband AE sensors (Digital Wave Corporation, B1025) to the specimens. The AE signals captured by these sensors were fed into a Fracture Wave Detector (Digital Wave Corporation) system. This system is specifically designed for MAE applications.

Wave mode recognition

Fig. 3 shows a signal that was generated by transverse matrix cracking in a $[0, 90_3]_s$ laminate. The figure shows both the time and frequency domain of the signal. As is indicated on the time domain graph, the signal can generally be divided in two zones. The wave package that arrives first at the sensor shows a behaviour in which the period of the subsequent cycles decreases with increasing time. The frequency content of this mode increases with increasing time which also means that the lower frequency components arrived first at the sensor and propagated at the higher velocities. As was discussed before, this dispersion behaviour is typical for the extensional mode.

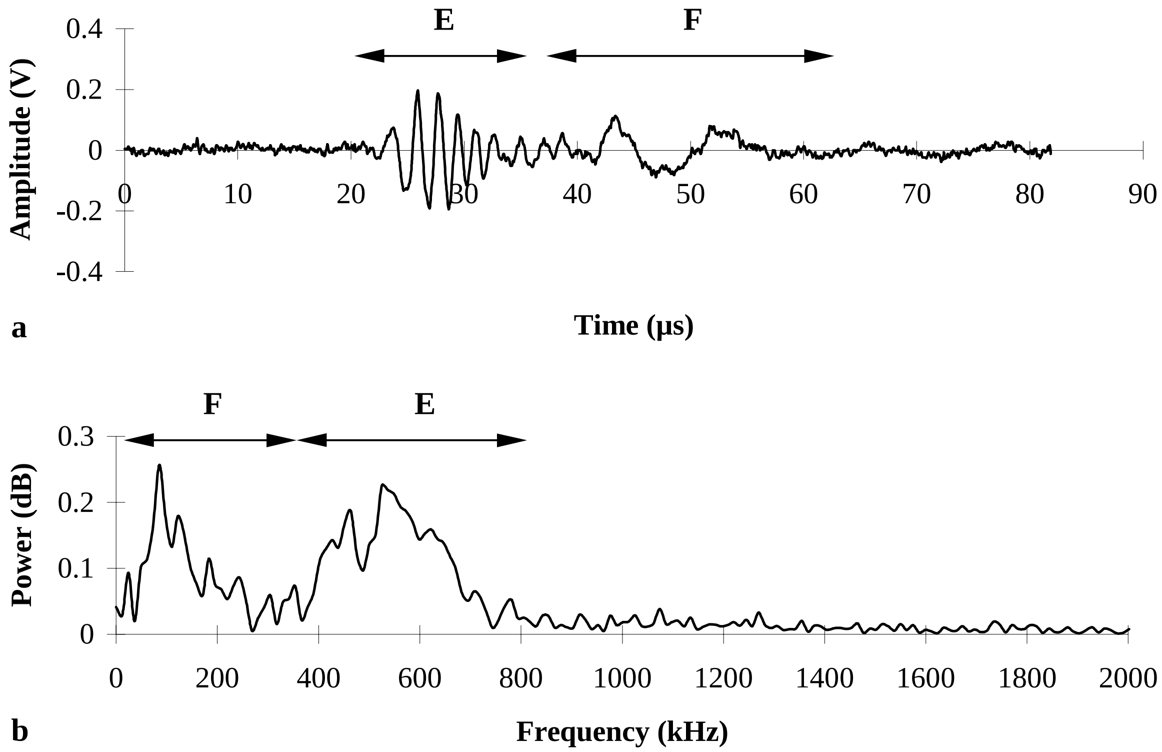

Fig. 3 : Matrix crack signal generated in a $[0, 90_3]_s$ sample : a) time domain, b) frequency domain (E : extensional mode, F : flexural mode)

The wave package that arrives at approximately 40 µs exhibits a behaviour in which the period of the subsequent cycles increases with increasing time. The frequency content of this mode decreases with increasing time and thus the higher frequency components arrived first at the sensor and propagated at the higher velocities. This dispersion behaviour is typical for the flexural mode.

Both plate wave modes can be recognised in this signal. Generally, the extensional mode propagates at a higher velocity than the flexural mode and exhibits a higher frequency content. As is indicated on the frequency domain graph, the range between 400 and 800 kHz corresponds to the extensional mode and the range between 0 and 200 kHz to the flexural mode.

Discrimination between damage phenomena

The two main damage phenomena that are active during tensile testing of a cross-ply composite laminate are transverse matrix cracking at the early stages of testing and fibre fracture during the later stages of testing. An example of a matrix crack signal as it was generated in the $[0, 90_3]_s$ lay-up was given in Fig. 3. Further investigation of the matrix crack AE signals revealed that the frequency content of these signals increased as the 90-ply thickness decreased.

Fig. 4 shows a signal that was attributed to fibre fracture, due to the load level at which it appeared. The signal exhibits a dominant extensional mode and its main feature is its higher frequency content as compared to the matrix crack signal. This is reflected in the frequency domain : the signal exhibits large frequency components above 1000 kHz. This is in contrast with the matrix crack signal (see Fig. 3) in which no significant content could be observed above 1000 kHz. It thus seems feasible to base a discrimination between different damage phenomena on the properties of the plate wave modes.

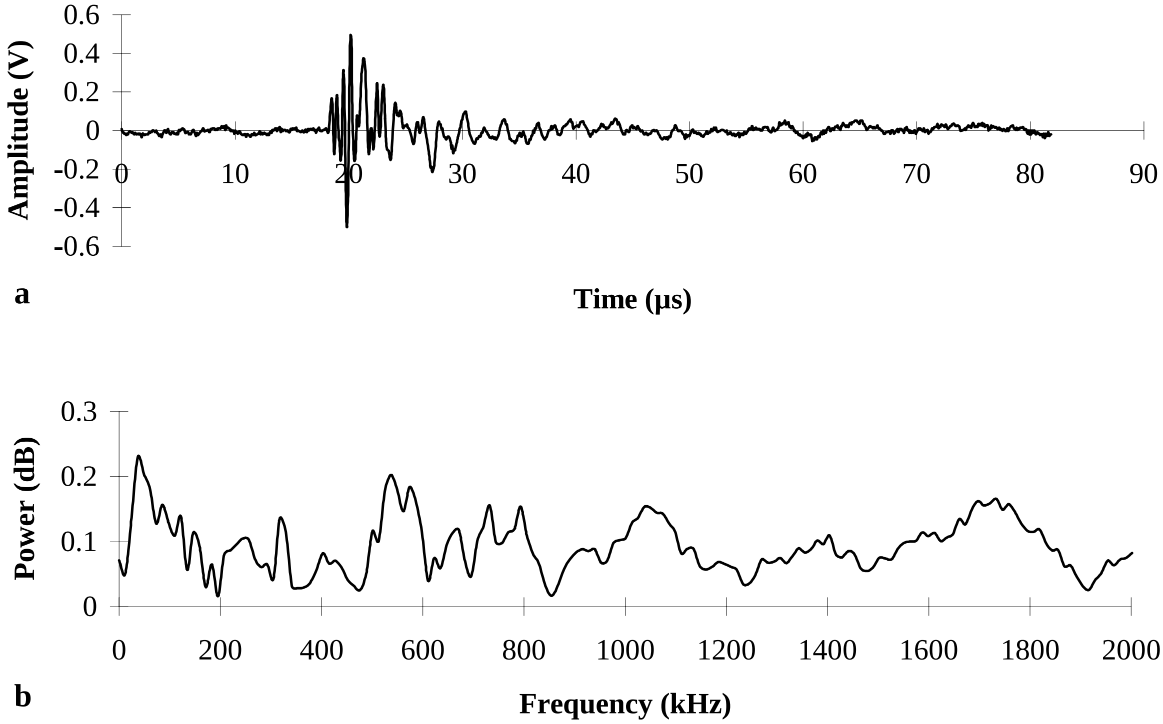

Fig. 4 : Fibre fracture signal generated in a $[0, 90_3]_s$ sample :
a) time domain, b) frequency domain

Noise elimination

One of the main problems preventing the widespread use of AE in practical applications is the elimination of noise signals from the data set. Based on the classic parameter based analysis procedures, this elimination has proven to be very difficult. As will be shown here, noise signals can be eliminated in a more consistent manner based on the complete waveform and the modal properties.

The main noise phenomena that are active during laboratory type tensile tests are EMI (electro magnetic interference) and grip noise. Fig. 5 shows an example of an EMI signal as it was measured by two sensors. The shape of these waves is quite different from the ones shown above. Both signals are detected at exactly the same time. Additionally, the signals are very high frequent in nature and do no exhibit plate wave characteristics or propagation effects. It should be noted here that a traditional AE analysis would have treated this signal as a signal with an amplitude comparable to the one of the real damage signals, a short duration and a high number of counts. Reducing the wave to these parameters would have made it very difficult to eliminate this noise type.

Fig. 6 shows an example of a grip noise signal. A clear signal was only observed at sensor 2. The signal appears not have propagated to sensor 1, which suggests that it originated outside the sensor region, at the sensor 2 side. The signal at sensor 2 does exhibit plate wave characteristics, but they are markedly different from the ones of the damage signals as the low frequency content is much higher.

Both examples demonstrate how a more consistent noise elimination should be based on the complete waveform and the modal properties of AE signals.

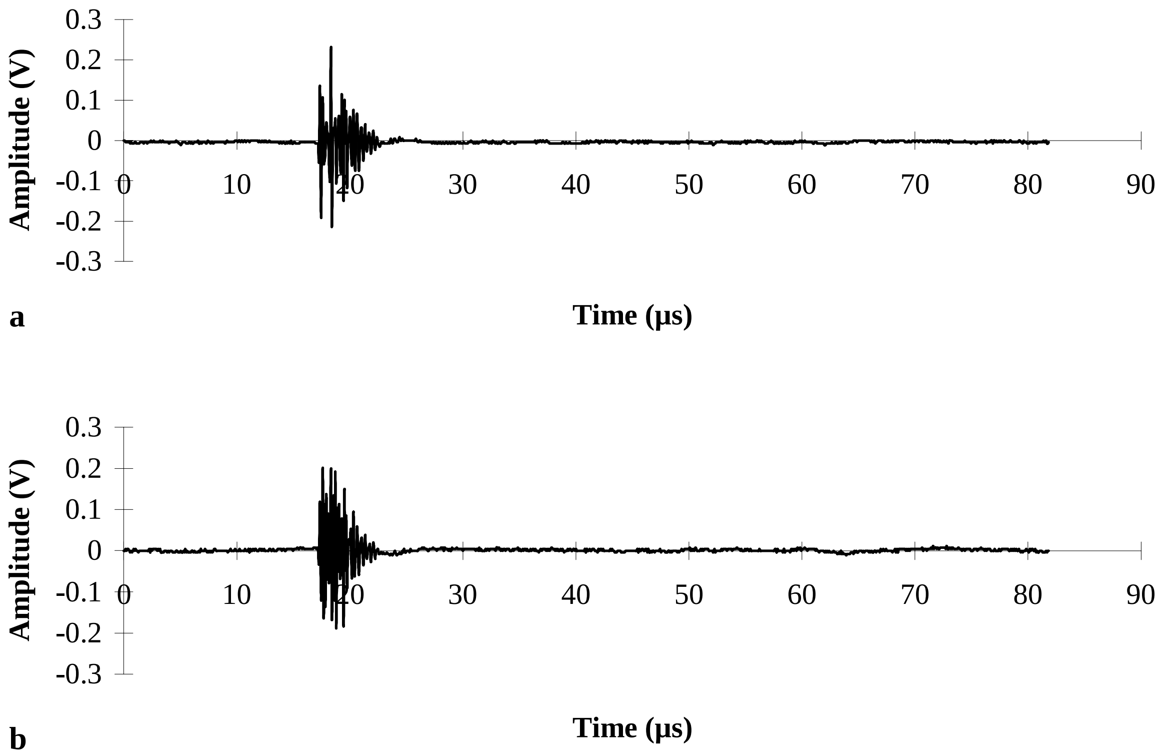

Fig. 5 : EMI noise signal : a) sensor 1, b) sensor 2

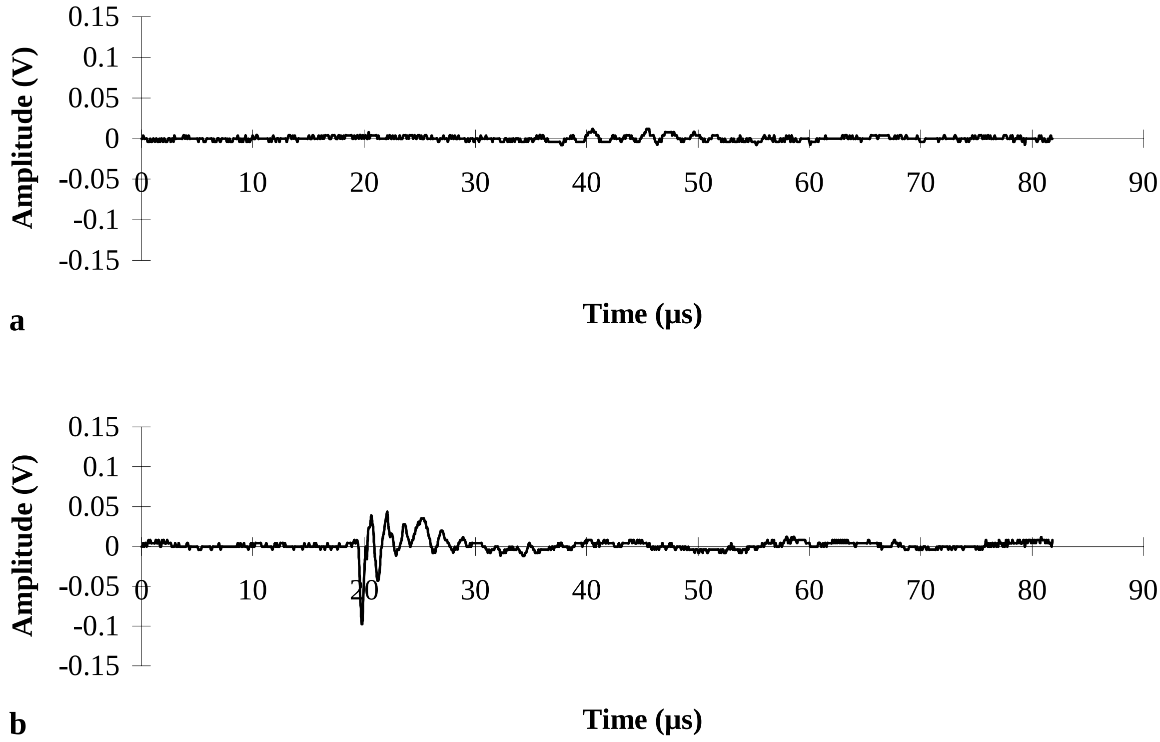

Fig. 6 : Grip noise signal : a) sensor 1, b) sensor 2

Source location

AE does not only offer the user the possibility to determine when damage occurs and what type of damage is active, but it also makes it possible to obtain information about the spatial location of the damage. Based on the arrival time of an AE wave at a limited number of sensors, a source location can be calculated, if the velocity of propagation in the material under study and the position of the different sensors are known.

The key element in a good and accurate location procedure is the determination of the arrival times of the AE wave at the different sensors. Arrival times are traditionally determined by using a fixed treshold value : the arrival time of a wave is the point where it first crosses the threshold. This procedure is prone to error as it doesn’t take into account the modal nature of the AE wave. Using a fixed threshold, one can never be sure which part of the wave is hit first by the treshold. A good location implies that the arrival times are determined on a part of the wave that has travelled with the same velocity to all of the sensors.

A detailed discussion of this problem can be found in reference 8. During the tests performed in this work, two sensors were used and a linear location procedure was applied. Some signals were observed that could pose problems to the classic AE location procedure as for some threshold values, the arrival times are determined on the extensional mode at one sensor and on the flexural mode at the other sensor. Using a fixed wave velocity, this led to location errors up to 35 %. This demonstrates that for an accurate source location, the modal nature of AE waves should always be taken into account.

CONCLUSIONS

In this work, two possible concepts for continuous damage monitoring in composite structures have been investigated. By embedding optical fibres in composite laminates during production, a material is obtained with an integrated sensor. A novel optical fibre sensor concept was proposed which was based on intensity modulations caused by microbending. By combining the results of three complementary damage detection techniques, the feasibility of this concept was demonstrated.

The modal acoustic emission (MAE) technique uses simple wave propagation concepts as a theoretical background to study AE signals generated in composite plates. Here, it was demonstrated how the plate wave modes can be recognised in real damage AE signals. Furthermore, a number of examples showed how the technique can discriminate between different damage phenomena, how it can be used to consistently eliminate noise signals from the data set and how it can improve on the location procedures as they are offered by traditional AE systems.

As a general conclusion, it can be stated that continuous damage detection with these techniques appears to be feasible. Further developement is, however, needed before the techniques will obtain widespread acceptance in the composite industry. Development should primarily focus on increasing the reproducibility of the measurements and on establishing quantitative relationships between the observed signals and the active damage phenomena.

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