

Health Monitoring of FRP using Acoustic Emission and Fibre Optic Techniques

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by

Rui Fernando da Costa Oliveira

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Abstract

In this dissertation is proposed a procedure for continuous damage monitoring of FRP (fibre reinforced plastics), from the rapid release of elastic strain energy, generated at damage, in the form of elastic waves (acoustic emission). Two materials were studied in order to associate the acoustic emission waves to the damage mechanisms source: the single fibre specimen and cross-ply laminate. Those materials were chosen for having well established damage sequence. For these materials, the fracture process could be controlled, with a reasonable efficiency, changing some tests conditions. Once the damage conditions changed it was possible to establish relationships with the detected acoustic emission waves.

A hybrid processing of acoustic emission signals was implemented based on waveform and frequency analysis. Unsupervised artificial neural networks were used for automated clustering of transient acoustic emission signals detected during testing of the cross-ply laminates. A time-frequency representation of the classified signals was implemented using the wavelet transform for signal characteristics enhancement. Damage mechanisms could be identified from the modal analysis of the acoustic emission waves.

An optical fibre sensor system was conceived for acoustic emission waves detection based on an optical fibre Fabry-Pérot interferometer. Two original interrogation procedures based upon the generation of two quadrature-shifted signals for phase recovery were proposed. The capability of the optical fibre sensor system to detect simulated acoustic emission waves was shown.

Resumo

Nesta dissertação é proposta uma metodologia de forma a monitorizar, em contínuo, o dano em PRF (plásticos reforçados com fibras) a partir da rápida libertação de energia de deformação elástica, gerada no processo de dano, sob a forma de ondas elásticas (emissão acústica). Dois materiais foram estudados com o objectivo de associar as ondas de emissão acústica com os mecanismos de fonte de danificação: o provete monofilamentar e o laminado cruzado. Esses materiais foram escolhidos por terem uma sequência de deterioração bem estabelecida. Para esses materiais, o processo de fractura pode ser controlado com razoável eficiência, mudando certas condições de ensaio. Uma vez modificadas as condições de dano, foi possível estabelecer relações com as ondas de emissão acústica detectadas.

Foi implementado um tratamento híbrido dos sinais de emissão acústica baseado na análise da forma das ondas e do seu conteúdo de frequências. As redes neuronais de aprendizagem não supervisionada foram utilizadas na classificação automática dos sinais transientes de emissão acústica detectados durante o ensaio dos laminados cruzados. Uma representação tempo-frequência dos sinais classificados foi implementada utilizando a “Wavelet transform” de forma a realçar as características dos sinais. Os mecanismos de dano puderam ser identificados a partir da análise modal dos sinais de emissão acústica.

Foi concebido um sistema de sensor em fibra óptica baseado num interferómetro de Fabry-Pérot com o intuito de detectar as ondas de emissão acústica. Foram propostos dois processos originais de interrogação da cavidade baseados na geração de dois sinais em quadratura de fase a fim de recuperar a fase. Foi demonstrada a capacidade do sistema de sensor em fibra óptica na detecção de ondas simuladas de emissão acústica.

Résumé

Dans cette dissertation est proposée une procédure pour le suivi en continu de l'endommagement dans les PRF (plastiques renforcés de fibres) à partir de la rapide libération d'énergie de déformation élastique, générée à l'endommagement, sous la forme d'ondes élastiques (émission acoustique). Deux matériaux ont été étudiés afin d'associer les ondes d'émission acoustiques aux mécanismes d'endommagement source : l'éprouvette monofilamentaire et le stratifié croisé. Ces matériaux ont été choisis pour avoir une séquence d'endommagement bien établie. Pour ces matériaux, le processus de fracture a pu être contrôlé, avec une raisonnable efficacité, en changeant certaines conditions d'essais. Une fois les conditions d'endommagement changées il a été possible d'établir des relations avec les ondes d'émission acoustique détectées.

Un traitement hybride du signal d'émission acoustique a été implémenté basé sur l'analyse de la forme d'onde et le contenu fréquentiel. Les réseaux de neurones à apprentissage non supervisé ont été appliqués à la classification automatique des signaux transitoires d'émission acoustique détectés au cours de l'essai des stratifiés croisés. Une représentation temps-fréquence des signaux classifiés a été implémentée en utilisant la transformée en ondelette afin de rehausser les caractéristiques des signaux. Les mécanismes d'endommagement ont pu être identifiés à partir de l'analyse modale des signaux d'émission acoustique.

Un système de capteur à fibre optique basé sur un interféromètre de Fabry-Pérot à fibre optique a été conçu afin de détecter les ondes d'émission acoustique. Deux procédures originales d'interrogation de la cavité basées sur la génération de deux signaux en quadrature de phase ont été proposées afin de récupérer la phase. La capacité du système de capteur à fibre optique à détecter les ondes de émission acoustiques simulées a été montrée.

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Chapter 1

Introduction

The composite systems are formed by the intimate combination of a matrix (polymer) and a reinforcement (fibre). This combination uses the physical properties of the resin, in order to protect physically and chemically the reinforcement. The resin assures the connection between fibres and, during loading, transmits the stress to the fibres. The fibres increase the stiffness and strength of the composite material and act as centres to suppress the propagation of cracks and defects within the material. The obtained system allies high mechanical performances for lower weight than the conventional materials.

One of the major interests of composite materials is the possibility to produce a material adjusted to the desired application. Varying the architecture, the process of manufacture, the constituent (e.g. nature of the resin and fibres) the material will be more adjusted to the predefined kind of solicitations it will be submitted to.

Composite material structures are sensible to their conditions of manufacture, as well as to their conditions of service. The application of the composite materials in the leading industries (e.g. aeronautics, naval, automotive) implies the necessity of a good knowledge of their mechanical behaviour. The long-term behaviour of a composite structure can be predicted from numerical and experimental models. But in order to insure its integrity during its life, a meticulous monitoring of its deterioration requires the use of non-destructive evaluations.

Different non-destructive techniques are available, each one having its own characteristics and potentialities. The choice of the more appropriate technique will depend on the required information: determination of the presence of defects in the structure, its location, the prediction of the resistance of the structure to a certain type of solicitation, determination of the damage mechanisms, etc.

In this dissertation, is reported the elaboration of an automated system of detection, acquisition, and identification of damage in composite materials. The acoustic emission technique has been chosen, due to its ability to monitor, in real-time, evolutive defects.

Acoustic emission is the phenomenon of emission and propagation of stress wave resulting from local modifications (e.g. cracking, dislocations) in a material submitted to a mechanical loading. Acoustic emission results from local rupture processes, produced when a part of the strain energy stored in the material is rapidly released, creating a temporal discontinuity of the deformation called acoustic emission event. The acoustic emission event generates a mechanical wave in the structure. Traditionally, the stress waves are detected at the surface of the structure by piezoelectric transducers, transforming the stress wave in an electric signal.

Acoustic emission has been widely presented in the literature to monitor, in real-time, the formation and propagation of cracks in pressure vessels, the corrosion process, the martensitic transformation, the leak existence or the machining of materials. It is a global method of control which allows the establishment of a relationship between the global macroscopic state and microscopic defects in the material. Associated with other more local techniques (e.g. ultrasound, radiography, microscopic observations), it is possible to correlate the acoustic emission data with the mechanical damage sources.

In the case of composites materials, acoustic emission is promising because those materials emit high amplitude signals. Acoustic emission results enable the knowledge of the state of the extended volume. This technique is one of the rare allowing the detection and initiation of defects and the observation of propagation of those defects, in real-time.

The acoustic emission technique is most often considered as a qualitative non-destructive technique. It is usually used for the determination of damage initiation in a structure and for its location.

Conventional acoustic emission analysis is based on the study of the acoustic emission signals parameters, such as duration, amplitude, and energy. However, single parameter analysis for mechanism fracture identification in the case of composite fracture is not reliable enough. The existence of a relation between amplitudes distributions and the mechanism of rupture in composite materials is reported in the literature [1,2]. Typically, signals whose amplitude values are within a range of 40-60 dB, are attributed to matrix cracking, whereas, signals whose amplitude values are within a range of 70-100 dB are attributed to fibre breakings. Those results are highly variable from one material to another, and the information about the physique source is limited. Multiparameter analysis has permitted to obtain more reliable results when associated to pattern

recognition algorithms but it does not contribute to get a deeper physical understanding of the acoustic emission phenomenon.

An alternative treatment considering the acoustic emission signals as mechanical waves (modal acoustic emission) has demonstrated to provide more quantitative information about the mechanism source [3,4]. Gorman et al. [5] could so derive the orientation of the source event. Prosser [3] observed that matrix cracks in thin-plate graphite/epoxy composite appeared to generate typical extensional Lamb wave mode, whereas signals caused by grip noise produced low frequency flexural Lamb wave mode.

The acquisition of acoustic emission waves is another important factor to consider in the investigation of the physical process associated to the detected acoustic emission signal. Acoustic emission signals are highly dependent on the transducer sensitivity and its frequency response. Typically, acoustic emission sensors are resonant piezoelectric transducers. Broadband transducers with a nearly flat frequency response in the frequency range of 50 kHz to 1.5 MHz have demonstrated to be more reliable to the physical source. Detected waveforms from those transducers show significant differences in both shape and frequency content for different types of sources, whereas relatively small differences in shape and frequency content are seen in resonant-sensor waveforms from the same sources [6].

Piezoelectric transducers have also some limitations (e.g. they have a limited bandwidth, they can't be used at high temperature, and are sensible to electromagnetic interferences). The stress wave being detected at the surface of the material, the acoustic emission waveform is highly dependent on the wave propagation across the material, i.e. attenuation, reflections, mode conversions.

According to Claus et al. [7], optic fibres are serious candidates for the detection of elastic waves in composite. The workability of composite materials allows the embedding of optic fibres sensors in the material during the fabrication. Using a single optic fibre sensor, it is possible to measure at the same time different physical parameters such as the strain, the temperature, and the vibrations into the material. They are a powerful tool to the conception of "smart materials", that are capable to sense alterations occurring inside them, to interpret them and to react to them by means of actuators.

In this dissertation, it is intended to improve the understanding of the relation between the acoustic emission waves and the damage source. A hybrid processing of acoustic

emission signals is implemented based on waveform and frequency analysis. A broadband transducer is used for detection of stress waves, for the reasons presented above. Considering that the acoustic emission signals are highly dependent of the propagation in the material, the transfer function of the acquisition system and the transducer, the association of the acoustic emission waveforms to a given damage mechanism is rendered complicated. To overcome these difficulties, it is here intended to control the damage process and to establish relations with the observed acoustic emission signals.

Two configurations are studied. In the first case, a single fibre embedded in epoxy resin is submitted to tensile loading. The damage mechanisms induced are well known [8]: multiple fibre ruptures, decohesion of the interface between the fibre and matrix, cracking of the matrix. Varying parameters such as the surface nature of the fibre, by surface treatments, or the diameter of the fibre, it is possible to control the induced damage processes and then to establish relations with the acoustic emission signals.

The second type of materials studied are composite laminates, designed as $[0/90_n]_s$ laminate or cross-ply laminate, constituted of unidirectional layers oriented alternately at 0° or 90° to the reference direction of the laminate. When cross-ply laminates are subjected to mechanical loading, different failure mechanisms are induced [9]: transverse matrix cracking in 90° plies, delamination between 0° and 90° plies, longitudinal matrix cracking which develops along the fibre direction of 0° plies, fibre fracture in 0° plies. Different parameters (the laminate lay-up, the ply thicknesses, and the specimen width) have an influence on the initiation and the evolution of the transverse matrix cracking. While changing those parameters, it is possible, with a reasonable efficiency, to control the fracture process. In this study, different test configurations (stacking sequence, ply thicknesses, specimen width) are considered as a change in the conditions of the transverse matrix cracking in order to analyse their influence on the acoustic emission waveforms.

Specimens are loaded in tensile tests and acoustic emission signals are recorded from two acoustic emission transducers allowing the localisation of the acoustic emission events. Once the damage process is controlled, it is possible to analyse the characteristics of the acoustic emission signals. In order to find some patterns to relate the signals to the

damage processes, an unsupervised classification has been performed, using neural networks algorithms.

The unsupervised signal classification procedure was developed for faster and more reliable association of signals to the source. To be really efficient the classification must be automated and independent of human decision. A time-frequency representation of acoustic emission signals was implemented to enhance the singularities of the acoustic emission waveforms.

An optic fibre system was developed as alternative to the piezoelectric transducers for detection of acoustic emission waves to get a better insight about the translation process. Such optical fibre sensor can be embedded in composite structures at fabrication. The main difficulty with optic fibre sensors for acoustic emission wave sensing resides in the low signal-to-noise ratio. The interrogation process is crucial to improve the signal quality. In this dissertation, an original procedure for optical fibre sensor interrogation is proposed.

This dissertation is divided in nine chapters. In this first one, the principal objectives of this study have been presented. The second chapter is dedicated to the non-destructive testing of composite materials. Considering the limited literature on this subject existing in Portugal, the major non-destructive testing methods applied to composite materials are reviewed in this chapter. The vocation of this chapter is to give the reader an overview of non-destructive evaluation of composite materials. The third chapter is exclusively dedicated to the acoustic emission technique. The physical aspects are presented and are reported some studies involving acoustic emission with composite materials. In the fourth chapter, the case of the single fibre specimen is studied. The damage mechanisms are described. A visual classification of acoustic emission waveforms is performed. In the fifth chapter, are reported the principles of pattern recognition and the theory of neural networks. The unsupervised classifier used for acoustic emission classification is described. In the sixth chapter, the theory of time-frequency representation of non-stationary signals is reported. In the seventh chapter, the damage in cross-ply glass-fibre laminate is monitored by the acoustic emission technique. Special attention is devoted to transverse matrix cracking. An automated classification of acoustic emission waveforms is performed, in order to establish the relation between acoustic emission signals and the architecture of cross-ply glass-fibre/polyester laminates, varying the ply numbers, the ply

thicknesses, and the specimen width. In the eighth chapter is reported the conception of a Fabry-Pérot fibre optic sensor for acoustic emission signal sensing. A novel interrogation system, for recovery of the acoustic emission signal, is proposed based on the generation of two quadrature-shifted interferometric signals. In the last chapter, the conclusions are summarised and discussed.

Chapter 2

Non-destructive testing of composite materials

When composite materials are used in structures like pressure vessels, pipes, bridges or aircraft components, it is highly important to guarantee their safety to avoid eventual failure that would have catastrophic consequences.

Contrarily to conventional materials, which once damaged have a fast and fragile rupture, composite materials can, even damaged, still sustain high solicitations until a damage level for which the structure will catastrophically fail. As a consequence, if a significant damage is detected with sufficient advance the structure can be removed or even repaired by reinforcing the damaged area. In most countries, the manufacturers of such structures are obliged, by law, to guarantee the safety of the structure, at fabrication, by non-destructive inspections. In the same way, the structures must be periodically inspected during their service life. That is, nowadays, commonly performed in aircrafts or petrochemical structures, especially when those are located close to residential areas. However, these non-destructive testing often involve high costs that all companies can't always sustain, in equipments, peoples or losses due to the structure being out of service during the inspection or to the requirement of disassembling of the component to be inspected.

This dissertation deals exclusively with acoustic emission monitoring of composite materials. This technique has been chosen because it is a global technique that allows monitoring, in real-time, of evolutive damage in the structure and as a consequence can detect crack initiation and analyze crack growth. Acoustic emission inspections can be performed with the structure in service, what can significantly decrease the costs of the inspection. In the case of aircraft structures, in-service studies can be implemented using composite materials embedment facilities to integrate acoustic emission sensors inside the structures.

Even if acoustic emission emerged as a non-destructive technique since the seventies, it is still in the evaluative phase. It is mostly used as a qualitative technique, which associated to other non-destructive techniques allows the identification of the damage type in the structure.

The evolution in acoustic emission equipments, the development of the physical concepts, acoustic emission data treatment, e.g. the use of signal processing or pattern recognition techniques, have allowed an improvement of the association of acoustic emission activity with the damage mechanisms sources. However, the technique still must be improved.

In this chapter, are briefly presented the non-destructive methods most applied to composite structures. A special emphasis is given to the basic concepts beyond those techniques, whose evolution in the last decades essentially consisted of hardware and software improvements leading to smarter, smaller, lighter and significantly more capable instruments. The requirements for non-destructive inspections continue to be driven by the need for lower cost methods and instruments with greater reliability, sensitivity, user friendliness and high operational speed. The trend towards a global market led to a growing recognition of the value of international standards for test procedures and personnel qualification, the inspector's decision process being a crucial element in the reliability of non-destructive testing. Advancement in instrumentation associated to improved analytical techniques led to transitioning non-destructive investigations from qualitative to more quantitative field. Inversion techniques were developed to determine flaw characteristics and material properties.

The difference between the methods will be underlined, considering that some of them are more appropriate to the detection of specific damage type, e.g. the ultrasonic inspection for delamination. The choice of the best non-destructive technique candidate depends on many factors like whether it is intended to inspect the surface or to assess damages occurred some distance below the surface, to locate the damage, to evaluate the damage extend, etc., considering that no single method can provide all the necessary information. However, their complimentary capabilities offer greater detectability and enhance the reliability.

With the concern to improve the legibility of this chapter, the different techniques have been arbitrary divided into two groups: the non-acoustic and acoustic techniques.

2.1. Non acoustic methods

2.1.1. Visual inspections

Visual inspection is a surface observation technique simple to implement. It is the leading non-destructive method and represents the highest percentage of the inspections that are applied to aircraft surface inspection [10]. It consists of a simple direct observation by naked eyes, but can also be enhanced by the use of equipments like mirrors, lenses, endoscopes, cameras, improved illumination techniques, when the structure is not directly accessible, when the sensitivity of the method is insufficient, or when an imaging record is required. Such technique is rapid and can give a general assessment about the structural integrity of a structure. However, considering that it provides only information about surface damage, it must be followed by a more sophisticated non-destructive technique for a more complete evaluation.

2.1.2. Liquid penetration inspection

Liquid penetration inspection is a method that is used to reveal surface breaking flaws by bleed out of a coloured or fluorescent dye from the flaw. The technique is based on the ability of a liquid to be drawn into a surface flaw by capillary action. These dyes fluoresce when exposed to ultraviolet making cracks and other surface flaws more readily visible to the inspector's eyes, increasing the contrast between the defect and the background.

The basic processing steps consist of the surface preparation, which must be free of oil, grease, water, or other contaminants that may prevent penetrant from entering flaws. Once the surface has been thoroughly cleaned and dried, the penetrant material is applied by spraying, brushing, or immersing the parts in a penetrant bath. The penetrant is left on the surface a sufficient time to allow as much penetrant as possible to enter into the defects. The excess of penetrant is then removed from the surface of the sample while removing as little penetrant as possible from defects. Different penetrant system, i.e. liquid, application time, etc., can be applied according to the material to be inspected, the defects to reveal, etc.

Compared to the other non-destructive methods, liquid penetration inspection has both advantages and disadvantages. The method is highly sensitive to small surface discontinuities, it can be applied to most of materials, large areas as well as complex geometric shapes can be inspected rapidly and at low cost. It provides a direct visual representation of the flaw. However, only surface flaws can be detected, only materials with a relative nonporous surface can be inspected, pre-cleaning is critical as contaminants can mask defects, the inspector must have direct access to the surface being inspected, surface roughness can affect inspection sensitivity, and multiple process operations must be performed and controlled.

Liquid penetration inspection sensitivity is highly dependent on defect nature. Defect detectability depends on defect volume, the flaw must be of sufficient volume so that enough penetrant will bleed back out to a size that is detectable by the eye or that will satisfy the dimensional thresholds of fluorescence.

2.1.3. Low frequency techniques

It consists of techniques based on the measurement of the structural natural frequencies and/or vibration damping. These quantities are very sensitive to whole structure state. Their main advantage is the fact that coupling is not required, resulting in more convenient testing. However, it is time-consuming, and is subject to inspector error, limited by noisy environments, and provides no quantitative data [11]. They are less sensitive than ultrasonic inspections because operating in low frequency.

The coin-tap test, is one of these techniques which is used by Boeing [11] to detect defects such as debonds in adhesive joints, delamination and voids in laminated and defectives honeycombs structures. However, the method is not suitable for detecting transverse cracking [12].

The sound produced when the structure is tapped is mainly at the frequencies of the major structural modes of vibration. These modes are independent of the position of the excitation. On the other hand, the response of a damage area or good area won't be similar. The impact of defective area won't excite the higher structural modes [12] as strongly as the one of a good zone.

An alternative version of the coin-tap test uses an instrumented hammer that measures the input force and provides a digital read-out of the tap duration. These measurements have the advantage to be insensitive to background noise. In damaged region, such as delamination, the structure flexibility in the direction normal to the surface is increased [12]. Thus the impactor stays a longer time in contact with the surface. The instrumented hammer compares automatically either the time history or frequency spectrum of the measured pulse and permits to know directly the structure state.

2.1.4. Thermal imaging

Thermal non-destructive methods are based on the monitoring of local thermal properties changes associated with the presence of inhomogeneities, e.g. holes, cracks, laminar flaws, variations in fibre alignment. By visualizing heat flows in the material it is possible to, rapidly and in an extremely versatile way, visualize the defect sites

The thermographic non-destructive evaluation are classified according to the heating process, namely active or passive heating [13]. In active heating, heat is stress-generated in damaged region under cyclic loading. The technique is, however, limitative as it requires a loading setting and the loading may extend the damaged area.

Nowadays the passive heating is the most used [13]. This method involves an external heat source, e.g. halogen lamps, photographic flashes, a laser, a beam of heated air, ultrasonic pulse. Mainly two different procedures of active thermography are being actually used: pulse and lock-in thermography [14].

With pulse thermography the examined material is warmed up with a short energy pulse. The heat response is recorded after a certain time by infrared camera, which maps the cooling or heating profiles and rapidly indicates the presence of flaws. Observations are sensitive to surface defects, interior flaws such as interlaminar debonds can also be rendered visible [13].

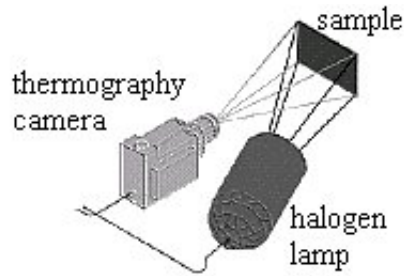


Figure 2.1 - Thermography set-up [14]

In lock-in thermography a sinusoidal heat (or ultrasonic) wave is provided to the surface of the specimen. The wave then propagates into the specimen and is reflected by the internal defects. The reflected wave interferes with the incoming waves. The phase delays can be measured with the thermographic camera system. The phase image permits then to reveal the defect presence.

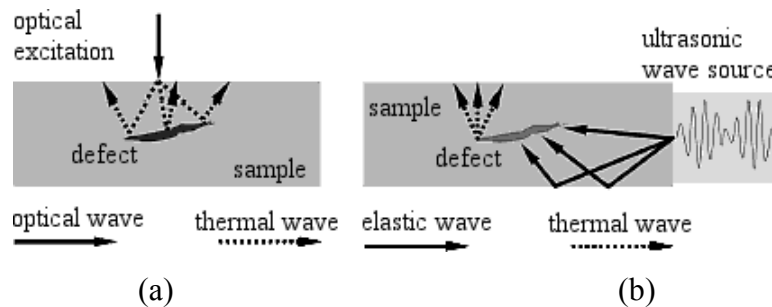


Figure 2.2 - (a) Principle of optical (b) ultrasound lock-in thermography [14]

In aircraft composite structures infrared thermography is successfully used to detect certain voids, inclusions, debonds, liquid ingress or contamination, foreign objects and delamination or broken structural assemblies [15]. It has been chosen in comparison to X-ray method for its fast operationality and reliability to detect liquid contamination in the composite sandwich [15]. All thermal methods are inferior to C-scan ultrasound which requires considerably greater testing time and is not a remote procedure [16]. However, for near surface defects and for testing thin materials, the lock-in thermography is approaching ultrasound's sensitivity and has the advantage to be a remote faster technique and is also able to test specimens with some slight contours, as in aircraft structures, more effectively [16].

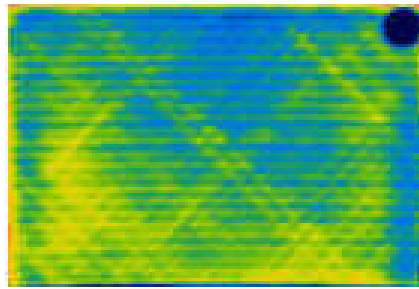


Figure 2.3 - Optical lock-in thermography phase image at 0.03 Hz of impact damage in carbon fibre reinforced plastic plate [17]

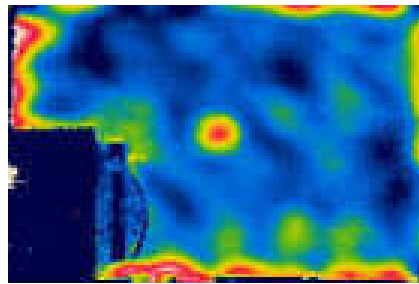


Figure 2.4 - Ultrasound lock-in thermography phase image at 0.03 Hz of the same impact damage in carbon fibre reinforced plastic plate, 300 W of ultrasound power [17]

2.1.5. Radiography

2.1.5.1. X-rays

The inspected object is exposed to X-rays radiations. The difference in radiations after their passage through the object provides informations about the presence of damage. To produce an X-ray radiography, the differences in radiations are recorded on a special type of photographic film sensitive to X-rays. The differences in intensity are caused by the differences in thickness and density of the object. In general, the absorption, by the object, of X-rays increases with increasing of atomic number of the material under inspection.

Using fluoroscopic screen, an image in real-time can be obtained, allowing the examination of moving objects. X-rays results can be improved substituting the radiographic film by a digital image processing [18] which allows image interpretation to

be automated, e.g. using neural networks [18,19], avoiding intervention of human operators making the inspection more reliable, reproducible and faster. The digital image is obtained by conversion of the X-ray to visible light by a scintillator crystal and successive recording by means of a digital charge-coupled device camera detector. There are cases where the conventional absorption radiography cannot be applied for non-destructive testing (e.g. light, weakly absorbing materials or very thin objects, materials consisting of multiple components with nearly the same absorption coefficients and in the case of high X-ray energies).

The most effective way to detect internal damage consists of using X-ray opaque penetrating fluids such as hydrogenated hydrocarbons, which improve the contrasts. The material to be inspected must be immersed some time in fluid before exposure to X-ray radiations to give time to penetrate into the damaged regions. The penetrant enhances X-ray's information on the nature and planar distribution of damage in fibre-reinforced composites. The technique demonstrated to be capable to detect fibre fractures, matrix cracking and delaminations [20].

However, it has some defects, as it can only detect damage in regions where the fluid can penetrate, thus defects originating from free edges or notches will be readily observed whereas delamination will not. This problem can be overcome by performing little holes to the delamination interface by a laser beam, and inject the opaque fluid by a hypodermic needle.

An alternative use of X-ray, that doesn't apply its penetrating ability, consists of the application of the diffraction of X-ray at the material's atomic planes. Using this technique, it is possible to measure the inter-atomic spacing variation when the structure is loaded, and to relate the values to stress measures. This technique is very useful for measurement of residual stresses in the composite.

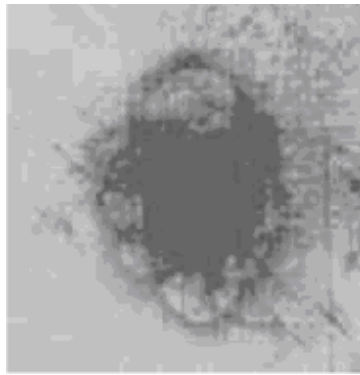


Figure 2.5 - X-radiography of damage impact (impact energy of 8.2 J) [21]

2.1.5.2. γ -rays

The gamma rays are similar, in nature, to X-rays, but they have completely different sources. One of the advantages of gamma rays is its independence from electrical power, what implies a simpler apparatus, more easily portable than for X-rays. The shortest wavelength in the X-ray spectrum is about equal in penetrating power to the gamma ray, but the rest of the wavelengths will be far less penetrating [20]. One disadvantage with using gamma rays sources is that the activity or intensity cannot be adjusted, but is given by the source and the elapsed time.

2.1.5.3. Neutron radiography

Neutron radiography uses a flux of neutrons, which is absorbed by the object to be inspected. The possible neutrons sources are nuclear reactors, electronic sources or isotope sources such as californium 252. Neutron radiation is generally more absorbed in the case of materials containing hydrogen like polymer matrices and least absorbed by materials with high atomic number. According to the fact that neutrons do not affect X-ray films, a screen must be placed before the film. When exposed to the neutron flux, the screen is excited and emits radiation to which the film is sensitive.

In the inspection of bonded composite to metal joints or of adhesively bonded honeycomb structure, the X-ray attenuation coefficients of the different materials vary in such a way that it provides very little information, for such structures a neutron

radiographic technique provides a clearer image of the bond or of the composite itself [20].

2.1.5.4. Computed tomography

Computed tomography is a radiographic non-destructive method entirely based on the computer reconstruction technique that offers a very detailed two-dimension and three-dimension graphic images of the tested object. It has a good spatial resolution and very good density resolution.

The technique is based on successive attenuation measurements of a narrow X-ray, γ -ray or neutron beam after it passes through a tested object in several directions. The attenuation coefficients depend on the material numerical atomic number, its density and beam radiation. A computed tomography-scanner generates the beam attenuation measurements to produce computed reconstructed images of any desired part of an object (tomogram also sometimes called the “density map”). The 2D image corresponds to a two-dimensional cross-sectional image of the material.

The tomogram contains information about the local, material related distribution of the attenuation coefficient. Therefore structural differences in the material cross-section will only get visible if materials of various attenuating characteristics are available.

Some companies use medical computed tomography-scanner like Eurocopter Deutschland in order to guaranty fibre composites main rotor blades quality and for maintenance [22]. They are able to detect delaminations of 0.20 to 0.30 mm with short examining times, fibre cracks, debondings, air pockets, pores, foam fractures and deformation. [22]. Defect sizes less than 0.2 mm are detectable only by an industrial scanner which use a microfocus tube and is able to use various radiation sources [22]. Higher resolution is not essential because all strength relevant manufacturing defects and damages like delaminations are larger than 0.2 mm.

There have been cases where the conventional computed tomography could not be applied for non-destructive testing, e.g. for object with low absorption contrast, for very thin objects or for materials consisted of multiple components with nearly the same absorption coefficients [23].

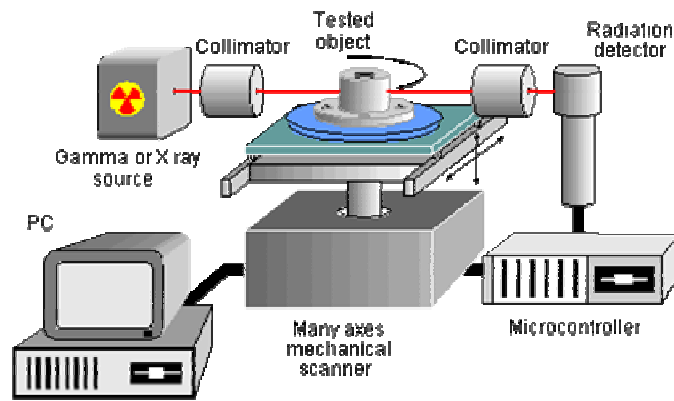


Figure 2.6 - Industrial computed tomography [24]

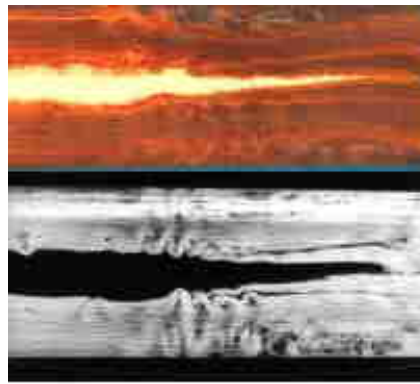


Figure 2.7 – Image of wavy glass fibre reinforced plastic laminate [22]

2.1.6. Eddy current

Eddy current testing is another important method, widely used within the broad field of materials non-destructive evaluations. Eddy current inspection can be performed with a minimum of preparation and a high degree of sensitivity. This technique is exclusively applicable to conductive composite materials, e.g. metal-matrix, carbon fibre composites. It is well suited for the detection of service induced cracks usually caused either by fatigue, stress corrosion [15] or low energy impact damage [25].

Eddy current testing is based on the principle of electromagnetic induction. A magnetic field is induced within the material by the mean of a coil carrying an alternating current to the proximity of the material to be tested. This magnetic field generates currents known as Eddy currents. Eddy currents are circular and oriented perpendicular to the direction of the applied magnetic field. They are affected by the electrical conductivity,

magnetic permeability; geometry and homogeneity of the test object [15]. A variation in the material structural integrity due to flaws or defects affects both the Eddy current and the electromagnetic field.

The probe geometry as well as the excitation frequency are two important controllable parameters on which depends the quality of the Eddy current [15]. Eddy current needs a small sensor for the detection and determination of the exact position of the defect [26]. Conventional Eddy current uses single frequency sinusoidal excitation and measures flaw responses as impedance or voltage changes on an impedance plane display. Flaws are detected by changes in the magnitude and phase [10].

For surface defects, high frequency are used whereas for sub-surface defects low frequency [15]. By combining multiple frequency measurements, a more accurate assessment of the structure integrity can be obtained by reducing signal anomalies that may otherwise mask the flaws [10]. Unfortunately, conventional multiple frequency methods are difficult to use for flaw visualisation in an intuitive manner.

An alternative consists of pulsed eddy current which excites the probe's driving coil with a repetitive broadband pulse, such as a square wave. The resulting transient current through the coil induces transient Eddy current in the test material, associated with highly attenuated magnetic pulses propagating through the material. The reflected signal contains flaw depth information. The pulse is broadened and delayed as it travels deeper into the highly dispersive material. Therefore, flaws or other anomalies close to the surface will affect the eddy current response earlier in time than deep flaws.

Similar to ultrasonic methods, the modes of presentation of pulsed Eddy current data can include A-, B- and C-scans [10]. Interpretation, therefore, may be considered more intuitive than conventional eddy current data. To better dissociate noised signals from defects signals artificial neural networks can be used [27]. The use of scanning methods with special probes allows the depiction of defects up to a size of 100 μm on the specimen surface in metal-matrix composites [26]. The threshold of device sensibility for defectoscopy and defectometry has been constantly decreasing. Nowadays, it is on the level of 0.1-0.2 mm in surface crack's depth [27].

2.1.7. Optic methods

Optical methods generate pictorial results easily understood at least from a qualitative point of view. Illuminating the material, information about its state are contained in the intensity and phase of the reflected light. Here are briefly presented the principles of the most used optical inspection methods. Their developments in the last year essentially rely on the apparition of new light sources, detectors and electronics systems.

2.1.7.1. Holographic interferometry

Holographic interferometry has been used for years in non-destructive testing. It is a global technique with high sensitivity, well suited for the analysis of material behaviour under mechanical or vibration loading [28]. The technique allows in principle to derive the surface displacement, strains and stresses, to detect and quantify cracks, to diagnose sub-surface phenomena by virtue of their effect at the surface [28].

Conventional holography technique consists of illuminating a photographic plate or thermoplastic camera with a reference light beam simultaneously with the light scattered from the inspected object. The two beams are mutually coherent. Interference effects between object and reference beams produce a hologram.

By reconstructing the hologram with a similar geometrical reference beam, an ensemble of light rays indistinguishable from the original ensemble scattered by the object emerges from the hologram, due to diffraction effects [28]. By superimposing this reconstructed ensemble corresponding to the object in some condition onto a beam corresponding to the object in some other condition, are created, due to mutual interference, light and dark fringes which can be mathematically related to the change in the material.

In summary, holographic interferometry uses two or more interferometric registry to obtain information about the material surface state. The correlation of interferometer patterns can be done through different techniques, e.g. double exposure, real-time and time-averaging, which differ on time exposure and reconstruction principle. Classical holographic interferometry must be carried out in a very stable environment [28].

2.1.7.2. Electronic speckle pattern interferometry

The recording medium used in the conventional holographic interferometry doesn't provide direct quantitative information. This has been partly resolved with the use of charge-coupled device cameras and the technique of electronic speckle pattern interferometry [29].

Speckles are statistical interference patterns [30]. In the case of diffusely reflecting surface, the interference of all the scattered light arriving at given points in whole space results in points with different brightness. The whole space appears to be filled with little alternate light and dark volumes [28]. Using a lens, speckle pattern can be observed in an image plane, allowing the image to be recorded by a charge-coupled device camera (figure 2.8). The speckle pattern is dependent upon the material scattering properties and the lens-aperture [28]. Any change occurring at the material surface can be observed in object's speckle pattern alteration.

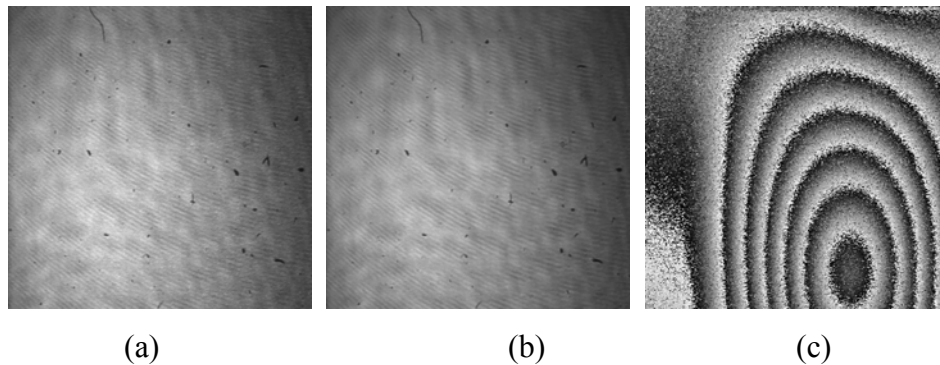


Figure 2.8 - Speckle pattern (a) before and (b) after deformation; (c) subtraction of the two [31]

In electronic speckle pattern interferometry, the speckle pattern results from the coherent addition, or subtraction, of the object's speckle pattern and that of a reference beam. By mean of double exposure, real-time or time-average methods interference fringes can be produced that displays lines of equal deformation of the surface. The distance between two fringes is correlated to the laser wavelength.

This technique is more adapted to industrial environments. The use of pulsed laser enables to work in a noisy environment and to catch transitory events [29]. The major

feature of electronic speckle pattern interferometry in comparison to holographic interferometry is in the recording process holography requiring long exposure time. Electronic speckle pattern interferometry provides relatively fast inspection whose results can be underlined using image processing techniques. It allows sensitive and non-contact detection of defects [32].

Electronic speckle pattern interferometry is very noisy, and may require stabilization systems. Another disadvantage is its vulnerability to dust. It is however well suited to the measurement of very small movements, as well as to delamination or debonding detection [29], for quantitative in-plane and out-of-plane strain measurement, in the range of few micrometers. Material's stiffness constants in a plate can also be obtained measuring the eigenfrequencies by the electronic speckle pattern interferometry technique and using the plate vibrations theory [33].

The basic electronic speckle pattern interferometry principle is illustrated in figure 2.9. A coherent laser beam is divided into two arms by the mean of beam splitter, the reference and object beam, respectively. Each beam is expanded through microscopic lens. The reference beam is filtered. The light reflected in the surface is captured by the charge-coupled device system and combined with the reference beam. The opening of the zoom determines the size of the speckle in the objective of the charge-coupled device. The signal processing is facilitated by controlling the phase of the beam. It is done by mounting a mirror in a phase modulator, e.g. a piezoelectric transducer, applied to the reference beam.

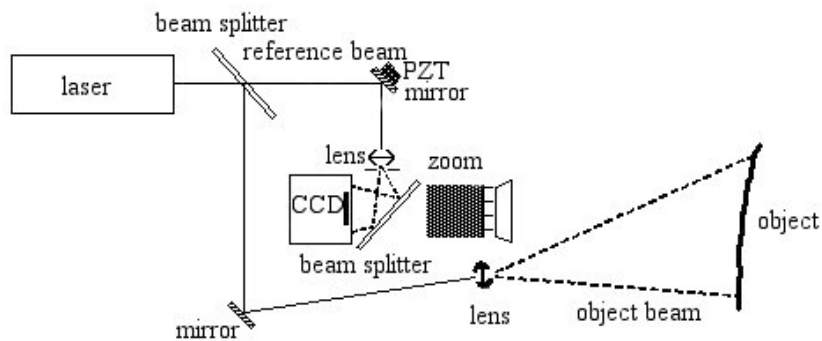


Figure 2.9 - Electronic speckle pattern interferometry principle [31]

In the figure 2.10 is represented the image of a composite plate with delamination.



Figure 2.10 - Defect in a composite plate [31]

2.1.7.3. Shearography

Shearography is a particular form of speckle-shearing interferometry. It consists of creating simultaneously two coherent images of the object surface one shifted with respect to the other. After some deformation has occurred, a second recording is made in the same way, in the double-exposure manner. By optical processing, fringes are observed being contours of the derivative of displacement, i.e. the slope of the deformation, rather than displacement itself [28].

Shearography requires less mechanical stability than electronic speckle pattern interferometry as it reacts only to differential movements within the body. Differential movements cause the fringes to change their positions and not the fringe spacing. It changes differently within the different speckles, and by suitable post-processing the derivative of displacement contours can be produced. Compared to holographic interferometry and electronic speckle pattern interferometry, its interpretation is facilitated by the lack of any fringe due to whole-body motion [28].

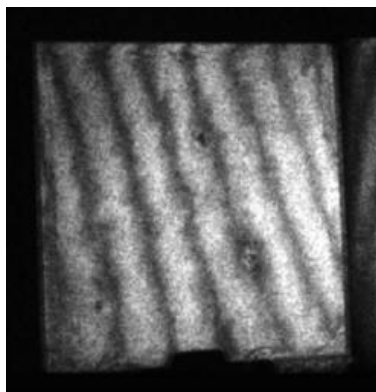


Figure 2.11 - Image of impacted sandwich panel [31]

2.1.7.4. Moiré fringe methods

In general, the term Moiré denotes the use of a regular pattern in the form of a series of parallel or crossed lines. These patterns may be material and visible or patterns of lights and dark projected in space. The technique is applied to in-plane strain measurement and surface form analysis [28]. The shadow moiré, the fringe projection and the moiré interferometry technique are based on the same principle. The shadow moiré technique is presented here.

It is considered as an aided visual inspection tool based on moiré interferometry. Its main objective is to locate, in more precise way than naked-eye visual inspection, a series of small zones in a large structure to be investigated deeply using conventional non-destructive techniques [34]. The expected benefit is a consequent reduction of in-service inspection times, then the related costs, keeping a high level of reliability.

In this method a grating is held close to the surface and illuminated obliquely. The lines of the grating combine with the line projected on the surface to create a series of surface contours [28]. The presence of a defect on the surface distorts the fringe patterns enhancing its visibility. A digital camera is then used for image acquisition.

The technique is not adapted to curved surfaces [34]. Besides the material surface must be free of dust or bubble inclusions that may produce a surface deviation.

2.2. Acoustic methods

Ultrasonic methods are among the most versatile and informative non-destructive evaluation methods. They can be divided into two cases depending on whether the waves are coupled into the inspected material from a transmitting transducer (ultrasonic inspection) or whether elastic waves are generated by damage occurring inside the material (acoustic emission).

2.2.1. Ultrasonic inspections

When the ultrasonic waves propagate through the material, they are modified during the propagation by the boundaries encountered, by the material itself and the presence of

defects. A defect in the material will result in a local change of the acoustic impedance, i.e. product of density and acoustic velocity, from the surrounding material. If the defect dimensions are large compared to the ultrasound wavelength it will cause waves reflections. Contrarily, if they are of the same order of magnitude, it will cause scattering of the interrogating beam due to diffraction. The sound scattering will be dependent on the size-to-wavelength ratio, the defect orientation, the direction of incident sound propagation and the wave mode type. If the defect is very small compared to the wavelength, little energy will be reflected but some energy scattered in all directions causing attenuation of the wave [35].

Traditionally ultrasonic transmitters are poled ferroelectric ceramics [36]. Due to the mismatch between the composite structure and the transducer acoustic impedance very little acoustic energy is transmitted to the material. To improve the transmission, the transducers can be immersed in a tank or if the transducers are in direct contact with the material, they can be coupled to the material by a thin grease or gel film, which are used for acoustical impedance matching.

The immersion of the composite structure may be problematic as some material, like porous materials or honeycomb, may be contaminated by water. Besides, it requires very large tanks complicating its application to field inspection. In order to withstand these difficulties, alternative non-contact transmitters and detectors are available or in development, namely ultrasonic capacitive pick-ups, electromagnetic acoustic transducers, laser beam optical generators and detectors, and more recently air-coupled ultrasonic systems [37]. Among them laser and air/gas-coupled acoustic systems have demonstrated great potentiality [37,38], notably to curved shaped structures [39].

Due to its reliability and sensitivity, ultrasonic inspection is the most applied technique on the detection and evaluation of defect in composite materials [40]. It is also used for the determination of the anisotropic constants of composite specimen from bulk ultrasonic wave velocities [41,42], the damage accumulation can thus be derived from the stiffness reduction [43].

The information about the specimen state can be visualized in different ways. The most widely used are the A-scan, B-scan, and C-scan.

2.2.1.1. Ultrasonic A-scan

This configuration involves, generally, only an ultrasonic system and a single transducer. Classically, it consists of generating a longitudinal wave at one of the surfaces of the material by a transmitter. The propagating wave is transmitted through the thickness of the material and is reflected back at the other side of the material. Two kinds of inspections can be made, the pulse-echo (figure 2.12) and the through-transmission inspections. In the first one, the reflected energy detected by the same transducer is analysed, whereas for the second the transmitted energy is detected by a separate transducer located on the other side of the specimen. This method has advantages compared to the pulse-echo technique, because the sound has to travel only once along the thickness. For composite materials this is important because the ultrasonic waves suffer high attenuation due to the material inhomogeneity and anisotropy. However, through transmission technique is not practicable for field inspections, where only one side of the components is accessible.

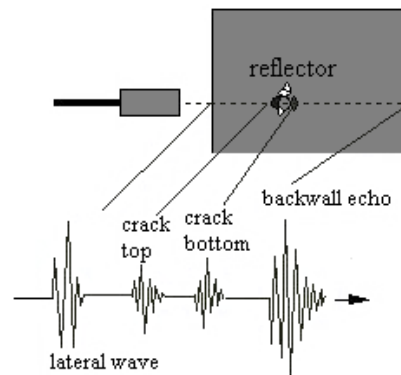


Figure 2.12 - A-scan set-up [44]

In figure 2.12 is represented an A-scan display observed at an oscilloscope. The incident wave is reflected at the defect before being back reflected at specimen surface. This configuration is often used to measure the specimen width, which is deduced from the velocity of propagation of the wave and the time of propagation. It permits to detect the defect presence through the material thickness, and to determine its position.

The amplitude of each echo gives some indication of the size and nature of the reflector, which might be a defect or a specimen boundary. The resolution for the

through-thickness position determination depends upon the ultrasonic wavelength and the duration of the sound pulse emitted by the transmitter. The spatial resolution depends on the wave divergence, the relation between the material volume size and the ultrasonic wavelength, and the distance between the sample and the transducer.

For multilayer composites, A-scan displays may be complicated due to wave conversion at boundaries. This technique can also be blind to defects present behind large defect such as delamination which create a shadow region behind them.

2.2.1.2. Ultrasonic B-scan

When moving linearly the transducer used for A-scan, manually or by a motor device, in a plane parallel to that of specimen surface, a number of A-scan can be performed at different positions across the specimen. The A-scans can be combined to display a two-dimensional graphical presentation, in which the travel time of an ultrasonic pulse is represented as a displacement along one axis, and the probe movement is represented as a displacement along the other axis (figure 2.13) [44].

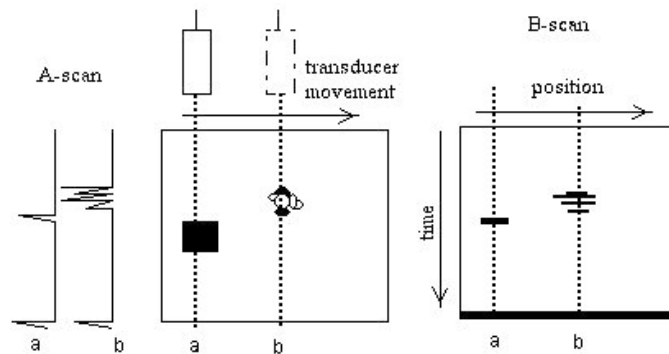


Figure 2.13 - B-scan [44]

B-scan permits to estimate the depth of the reflectors and their lateral extent along the axis of transducer movement. The depth resolution depends on the same factors as above discussed for A-scans, whereas the lateral resolution depends upon the transducer beam profile and the step size used for lateral movement. Besides, as for A-scans a shadow region behind large defects exists. A 3-D visualization of defects can be obtained performing projections of B-scan results. They are performed in top view of the test

piece, to any side view of the test piece. The obtained image is called a P-scan. It is mainly used in weld inspection.

2.2.1.3. Ultrasonic C-scan

C-scan image result of a more complex transducer scanning, that is performed along a plane parallel to the sample. Scanning can be performed manually but is generally automated. The ultrasonic system monitors the transducer position and stores it with the ultrasonic data. Time windows or gates are used to select particular parts of the received ultrasonic waveform. They measure the amplitude of the largest reflection within the selected time interval, and convert it into a digital output. C-scan image gives a good estimate of the lateral extent of a defect in a plan view [45]. The final result is represented by a coloured map that enhances the defects (figure 2.14). The resolution depends on the same parameters as for B-scan. Information about defect depth position can be inferred from the position and width of the time gate employed. According to the gates widths and the frequency, it is possible to investigate individual ply layers in composites.

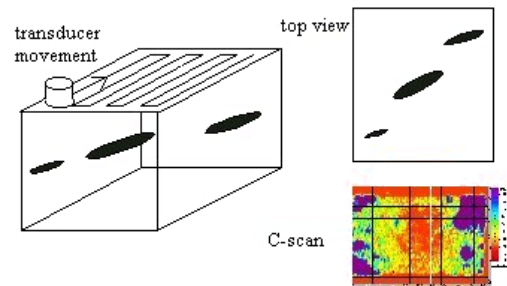


Figure 2.14 - C-scan [44]

Modified versions of the C-scan are sometimes proposed. They are the D- and F-scan. The D-scan represents the time-of-flight values. This permits to obtain indication of depth contrarily to C-scan. The F-scan represents the values of certain feature, e.g. centre frequency, instead of amplitudes [44].

2.2.2. Guided waves

Guided waves propagate in bounded media with dimensions of the same order as the wavelength. Rayleigh waves are sometimes used to detect subsurface flaws in thick plates, while Lamb waves are by far the most used in thin plates inspection [46].

2.2.2.1. Lamb waves

Lamb wave inspection is an alternative to the conventional ultrasonic scanning and opens the possibility of a one side testing, which is very useful for field inspections. It is potentially more attractive for large areas, as it involves guided waves which propagate along the structure being inspected.

Conventional ultrasonic inspections are very effective at detecting anomalies along the sound path. As they use ultrasonic bulk wave, longitudinal or shear waves, the inspection region is limited to the area immediately surrounding the transducer. Therefore, a large structure inspection is time consuming and, if done improperly, can miss areas.

Contrarily ultrasonic guided waves are excited at one location on the structure and propagate many metres. Guided waves propagation characteristics depend on structural boundaries such as those in plates, tubes, rods, and embedded layers.

The ultrasonic Lamb waves are guided between two parallel surfaces of the test object. They propagate in the plane of plate-like structures. Various wave modes exist with particular wave structure, i.e. particle motion through the thickness of the layer, and dispersion behaviour, their velocities being function of the product of the laminate thickness and frequency. The existence of many possible propagating modes may complicate the inspection. For simplification, it is possible to work in the frequency-thickness product range below 1 MHz.mm. In this case, there are only two possible Lamb modes, the antisymmetric A_0 and symmetric S_0 modes, which are referred as the fundamental flexural and extensional modes respectively [45]. The S_0 mode is almost dispersionless in this range. Consequently, it can propagate over a long distance without significant changes in the propagating waveform. The considered most promising use of Lamb waves for long range inspection consists of generating this mode at low-frequency-thickness products and to monitor reflections from defects in the wave path [47,48].

Since the Lamb wave velocity depends on the elastic properties of a structure, it is also possible to monitor damage in composites by measuring the velocity of these waves [49,50,51] as they are sensitive to the in-plane material elastic properties.

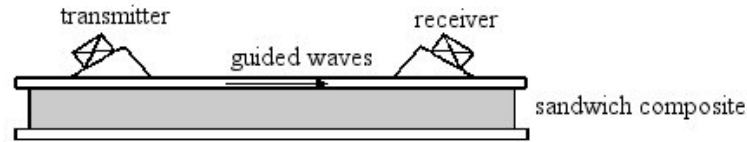


Figure 2.15 - Guided wave inspection setup [52]

2.2.2.2. Rayleigh waves

In the case of thick materials, an inspection method analogue to the previous one exists. Instead of Lamb waves, it involves surface waves (Rayleigh waves). The method can also be used in the case that only one surface is accessible and has also the advantage to inspect great distances. Ultrasonic surface waves are generated in materials if the incident angle approaches the critical angle [52]. Surface waves travel on and near the surface with a penetration depth of about one wavelength. They can be used for surface or sub-surface defects detection, whose presence is characterized from the measure of the variation of the Rayleigh wave velocity and the signal amplitude loss.

2.2.3. Acoustic emission

Acoustic emission testing is a non-destructive technique, where transient stress waves are generated from sudden stress release due to crack growth, dislocation movement, phase transformation, etc. Acoustic emission has been chosen in the present investigation, among the different non-destructive techniques, for its unique capability to monitor the dynamic of damage, to monitor continuously the structure throughout a test or throughout the service life of a component, to monitor in real-time the whole volume of structure with a limited number of transducers. The technique will be more deeply described in the next chapter.

2.2.4. Acousto-Ultrasonic

Acousto-Ultrasonic is a compromise between acoustic emission and ultrasonic methods. It is a non-destructive evaluation technique that leads to rapid inspection of whole material volume. It uses the same hardware as acoustic emission for acquisition, but, contrarily to this one, it doesn't require loading. An ultrasonic wave is induced into the material in a similar way to ultrasonic inspection. When propagating in the material, this wave will interact with the material on its path to the receiver. The wave is sensitive to any changes in the material's microstructure. The so-introduced variations on the signal carry information about the structure along the wave path. Typically, it involves frequency range of acoustic emission applications. The stress waves are detected by acoustic emission transducers, and treated as acoustic emission waves. The obtained information is very different to the one obtained by acoustic emission analysis. Traditionally, a stress wave factor is considered [53]. It is a measure of the efficiency of stress wave energy transfer [54] which usually decreases with increasing the flaw content and damage in composite materials [55]. Digital signal processing tools such as the Fast Fourier Transform or the wavelet transform can now be used to extract pertinent waveform discriminators, associated to pattern recognition algorithms the method can classify the inspected structure into an undamaged or damaged one.

2.3. Conclusion

The most widely used non-destructive techniques in the industry for composite materials inspection have been presented in this chapter. They are not equally sensitive to the different defects. As a consequence, they are applied in different contexts. Some techniques such as the optical and visual techniques are generally applied to surface inspection, whereas ultrasonic inspections are especially well adapted to delamination monitoring. Among all these techniques, acoustic emission has been chosen for being capable to detect damage at their occurrence. Moreover, contrarily to the other techniques, it is not necessary to interrupt the test temporarily, or in the case of real structure, they can be performed during service live

Chapter 3

Acoustic emission inspection

The American Society for Testing and Materials defines acoustic emission as “the class of phenomena whereby transient elastic waves are generated by the rapid release of energy from localised sources or sources within a material, or the transient elastic wave(s) so generated” [56]. In the literature, the acronym “AE” is generally used for acoustic emission (EN 1330-9) and “AT” for acoustic emission testing (prEN 473-2000).

Acoustic emission testing studies the propagating waves resulting of damage formation, permitting from only a few transducers to continuously monitor, in real-time, the whole structure volume. For acoustic emission inspection, the tested structure must be loaded inducing damage in its body. Therefore, it could not be considered as a completely non-destructive technique. But due to its ability to detect the evolutive defects in the structure, it guarantees the structure safety. It is, thus, considered as a passive, receptive non-destructive technique.

It is generally accepted that Kaiser’s researches at the Institute for Metallurgy at the Technical University Munich, in the 1950’s, represent the beginning of acoustic emission as it is known now [57]. Its practical use as a non destructive testing method for material studies only started in the early 1970’s with the work of Dunegan and his co-workers at the Lawrence Livermore laboratories [3]. Most of the early work concentrated on metals, but the more recent work has been much wider, covering composites, ceramics, plastics [58]. Its success on fibre-reinforced composites is essentially due to the fact that this class of materials emits high amplitude signals. Their brittleness, anisotropy and heterogeneity are major factors conducting to their high emissivity [59].

3.1. Acoustic emission

When loading a specimen, it starts to deform elastically. Elastic strain energy storage is associated with this deformation. Part of the elastic strain energy is rapidly released at

local stress redistribution such as that caused by growing cracks. This rapid release of elastic energy is called an acoustic emission event, which produces an elastic wave [60]. This wave propagates through the material. Classically, it is detected at the material surface by piezoelectric transducers (figure 3.1). The detected wave corresponds to the initial wave, but also to reflected components generated at the material edges and/or discontinuities and also mode-converted components generated at material surfaces. Classic sources of acoustic emission in materials are crack formation and growth, dislocation movement, phase transformation, and friction mechanisms.

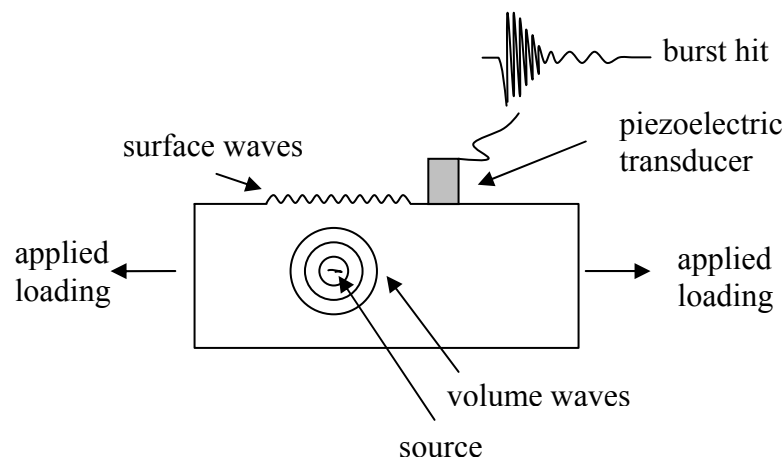


Figure 3.1 - Basic principle of acoustic emission method

There are two types of acoustic emission signals, the continuous and the transient. The continuous signals are observed when the acoustic emission activity overlaps and, generally, results from the combination of the electronic noise with the environmental acoustic noise in the acoustic emission bandwidth. They are usually analyzed using the root-mean-square techniques. In the case of composite materials, this activity reveals friction, leaks and plastic deformation. The transient signals also called burst signals correspond to discrete micromechanical events that occur within the material. Such bursts are random in time and have the aspect of damped sinusoid, with starting and end points deviating clearly from background noise.

In the case of composite material, acoustic emission has been, essentially, successfully applied in laboratory applications. Most of commercial acoustic emission testing concern

tanks and storage vessels proof tests [61,62]. Some standards exist, such as the one from the Committee on Acoustic Emission from Reinforced Plastics of the Society of the Plastics Industry or the American Society for Testing and Materials for pressure vessel testing [62].

The objectives of such tests are to locate problematic areas and to assess the quality of the vessel. They focus on measuring the amount of acoustic emission produced in a structure, and provide information about the initiation and evolution of damage.

The Felicity ratio is one of the tools being successfully used for periodical structural integrity testing of composite materials structures. It translates the irreversible nature of damage inside a structure. Considering a structure or material loaded at P_1 , when unloaded it won't emit any acoustic emission until the load applied in a second loading phase reaches a value P_2 . The ratio defined as $R=P_2/P_1$ is known as the Felicity ratio. For values of R inferior to 0.95 the structure is classed as unacceptable.

Such treatment of acoustic emission signals only provides qualitative information about the damage occurring in the structure. Different damage types may appear in the composite materials, when they are loaded: reinforcement/matrix debonding, matrix cracking, reinforcement failure and delamination in laminates. The distinction between the acoustic emission signals coming from these different damage types is not straightforward. This is one of the reasons why the acoustic emission technique is often used only to detect the onset of damage, its location and its severity. Other techniques, like ultrasonic inspection, X-rays, microscopy take then the relay to identify the damage type.

Using other non-destructive methods, it is possible to calibrate the acoustic emission signals in order to distinguish the different damage types directly from the acoustic emission signals and using data processing techniques, with the same material and acquisition configurations.

The diffusion of acoustic emission technique in the industry is still limited due to its interpretation which may be complicated and requires some experience. The existence of noise (electrical and mechanical) render more difficult the data interpretation, as they can be, sometimes, considered inauspiciously as acoustic emission signals. However, some techniques exist for noise reduction.

In table 3.1, the well known advantages and limitations of using acoustic emission compared to most other techniques are summarised.

Acoustic emission	Most other techniques
Detects movement of defects	Detect geometric form of defects
Required stress	Do not require stress
Each loading is unique	Inspection is directly repeatable
More material sensitive	Less material sensitive
Less geometry sensitive	More geometry sensitive
Requires access only at transducers	Requires access to all area of inspection
Tests whole structure at once with a limited number of transducers	Scan local regions in sequence
Permits a continuous in-service monitoring	Post service scanning
Main problem : noise related	Main problem : geometry related

Table 3.1 - Comparison to other methods

3.2. Theoretical aspects

The acoustic emission technique improved in the last decade in both experimental and theoretical domain. Thanks to the advancements in microelectronics and in computer-based analysis techniques, acoustic emission gains acceptance. Due to the high signal rates and their relatively high frequencies (from 20 kHz up to several MHz) the required analogue/digital-converters must have a high dynamic range and sampling rate. The development of user friendly software increased the data analysis efficiency and rendered their interpretation easier.

Another point, important for its development, is its interconnection with seismology, where the wave modes produced by earthquakes are used to determine the source of the earthquake. The contemporary theory of acoustic emission is mostly based on seismological wave concepts, bringing some ideas on how to explain the observed acoustic emission phenomena. Theoretical studies have been dedicated to the elastic

waves propagation modelling by numerical simulations [63] (finite elements), and to the physical modelling of the acoustic emission sources from the theoretical prediction of acoustic emission signals for a given data type [64,65,66].

3.2.1. Theoretical source characterization

The generalized theory of acoustic emission and acoustic emission source representation has been formulated on the basis of elastodynamics [67].

Acoustic emission waves are elastic waves due to dynamic dislocation in a solid. The microfracture, source of acoustic emission, occurring into the material has been modelled as an internal displacement discontinuity. The source is considered as punctual compared to wavelength. The body-force-equivalence theory permitted to change the source into an equivalent force distribution [68], which gives rise to the same radiation field [69]. The equivalent source system can be given in terms of a seismic moment tensor M_{pq} [70]. Such moment tensor characterizes the cracks kinematics [71]. It is defined from the product of the crack motion vector, b_k , and n_l the normal vector to the crack surface with the elastic constants, C_{ijkl} (equation 3.1).

$$M_{ij} = C_{ijkl} b_k n_l \quad (3.1)$$

Quantitative information of the acoustic emission source is obtained by the determination of all moment components, which induce equivalent displacement field as the real source. The moment tensor provides information about the source location, the crack orientation, the crack motion direction and the crack type

The moment tensor analysis has been, essentially, applied with success to thick composites and especially to concrete [72,73,74], where size is larger than the propagating wavelengths. Such material is considered, by approximation, as homogeneous, the effect of heterogeneity inclusion being inconsequent compared to wavelength. The moment tensor components are obtained experimentally from the waveforms obtained at six independent channels.

Direct information about the source may be distorted by elastic wave propagation through the material. Theoretical studies of transient wave propagation have been made in order to extract information from the acoustic emission waveform in the far field. The acoustic emission source characteristics may be deduced through knowledge of the propagation medium and the measurement system characteristics. This approach may be written as:

$$V(t) = T(t) * [G(t) * M(t)] \quad (3.2)$$

where $V(t)$ is the measured voltage transient, $T(t)$ is the response function of the acoustic emission system, $G(t)$ is the elastodynamic Green's function for the material, $M(t)$ is the function representing the acoustic emission source, '*' is the convolution operator. The Green's function $G_{ij}(x; x', t - t')$ represents the complex transfer function of a structure between the source and a signal detector, i.e. the displacement response in i -direction at point (x, t) to an unity pulse in j -direction at point (x', t') .

The acoustic emission waveform $u_i(x, t)$ observed at point x due to crack vector $b(y, t)$ on crack surface F is an inverse problem solution to the equation 3.2. Such deconvolution has been successfully performed on simulated data, but finds many problems in real situations. The time-dependent displacement at (x, t) is given by [74].

$$u_i(x, t) = \int_F G_{ij,k}(x; x', t - t') M_{jk} * S(t') dF \quad (3.3)$$

where $G_{ij,k}$ is the spatial derivative of Green's function, $S(t)$ represents the source-time function, '*' means the convolution integral.

Once the dynamic Green's function known, it is possible to simulate the acoustic emission signal. Guo [64] used the equivalent body forces to calculate the surface response of a composite plate to a given microfacture (fibre breakage, delamination and matrix cracking).

3.2.2. Acoustic emission waves propagation

Acoustic emission waves are mechanical waves. Mechanical waves propagate through the material in different modes having different characteristic (e.g. polarization). The propagating waves depend on the material geometry (e.g. rod, shell, plate).

In the case of thick composites, the elastic waves propagating through the materials are bulk waves. In anisotropic materials, three independent wave modes propagate: the quasi-longitudinal (QL), the quasi-shear vertical (QSV) and the shear horizontal (SH). These wave modes propagate at different velocities. During the propagation the waves are reflected at the material surface, generating surface waves (e.g. Raleigh, Stoneley) depending on the interface nature, the material thickness, and the material lay-up. The wave propagation in anisotropic material of arbitrary geometry is expressed from the three-dimensional elasticity theory. The propagation of bulk waves into elastic solids obey to the Christoffel equation that can be found in literature [75].

Propagating waves are attenuated during the propagation. The mechanisms responsible of this attenuation are the geometric spreading of the wave, the internal friction, the absorption, the dissipation of the waves into adjacent media and the losses related to velocity dispersion [76]. Propagating mode conversions are also observed at material interfaces.

In this dissertation, acoustic emission in composite plates, for which the wavelength λ is much larger than the thickness, is studied. For this geometry, three wave types propagate: the extensional and flexural mode and the shear horizontal mode.

To formulate the wave propagation problem in plates, simplifications to the three-dimensional elasticity theory are proposed [77,78]. Lamb wave theory assumes that propagating waves affect the structure as a whole [4]. Lamb waves are referred as guided waves. These waves are divided into two modes which contain components of different order. For symmetric modes, the particle displacement is symmetric about the specimen midplane. The different components are indicated as $S_0, S_1, \dots, S_n$. For antisymmetric modes, the particle displacement is asymmetric about the midplane of the specimen. The different components are indicated as $A_0, A_1, \dots, A_n$ [4].

Another simplification is the classical plate wave theory. It assumes a plane strain state and neglects the influence of shear deformations and rotary inertia. It considers only the lowest order symmetric mode, S_0 , called the extensional mode, and the lowest order antisymmetric mode, A_0 , called the flexural mode. The extensional mode is characterized by a large in-plane displacement component, whereas the flexural mode is characterized by a large out-of-plane displacement [4].

The classical plate theory has been successfully applied to composite materials by various authors [3,78]. The equation of motion can be found in the literature [3]. The classical plate theory predicts a dispersionless extensional mode, i.e. all frequency components travel at the same velocity. More detailed analysis of the extensional mode showed that it does exhibit a dispersive behaviour, i.e. the velocity increases as the frequency increases [3]. Concerning the flexural mode, the plate wave theory predicts a dispersion behaviour.

A higher order plate wave theory, which takes into account the effect of shear deformations and rotary inertia has been developed by Tang et al. [79] for composite materials based on the work by Mindlin [80] on isotropic plates. The results of velocity and dispersion at low frequency for the flexural mode fitted better [3].

During the propagation in composite plate, the wave modes are differently attenuated. Besides, due to the anisotropic nature of the composite materials, the wave mode velocity of propagation also varies in function of the direction of propagation.

3.3. The acoustic emission chain

The acoustic emission waves detection is a crucial part of the inspection. The waves are detected by a transducer, amplified and then digitalised. The acoustic emission chain is briefly described.

3.3.1. Coupling

The transmission of the elastic wave into the transducer is improved by the use of a coupling agent, e.g. silicone grease (high vacuum grease), oil, or glue. It is necessary due to the acoustic impedance mismatch between the piezoelectric disc and the composite

material. For best coupling results, a thin couplant layer is required, and a pressing may be required (using tapes or holders) to guarantee its good coupling to object's surface. After attaching the sensor, the quality of the coupling must be verified (pencil lead break, automatic coupling test). If required, the coupling procedure must be repeated

3.3.2. The transducer

The transducer is the fundamental and most important element for the efficiency of the waves acquisition. It converts the mechanical waves into electrical signals. The ideal transducer should be small, highly sensitive, with nearly flat response over a wide frequency range, dependent of a single parameter such as displacement normal to the surface or velocity, easy to couple to the structure to be inspected, cheap, robust and easy to construct. But unfortunately such transducer doesn't exist. However, many progresses have been realized in this area, leading to more sensitive and reliable transducers. Acoustic emission sensors based on piezoelectric transducers are commonly used for being relatively cheap, robust, easy to use and having adequate sensitivity. Traditionally the sensing part consist of a single disc of lead zirconium titanate (PZT) poled in the thickness direction (figure 3.2). Normally, it possesses a well-defined natural resonant frequency, dependent largely on its thickness. The transducer is highly sensitive around this frequency and much less sensitive at other frequencies. In consequence, the obtained signal is highly "coloured" by its transfer function.

Another transducer type commercially available, the broadband transducer, is becoming more and more popular. It ideally has a flat frequency spectrum, treating all frequency components equally, but shows some fluctuations.

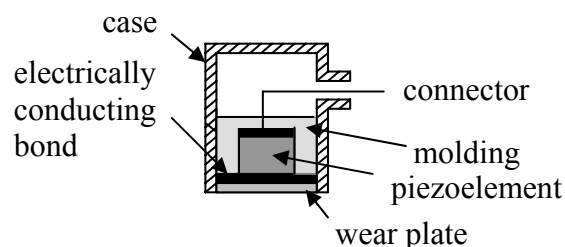


Figure 3.2 - Acoustic emission transducer

The development of new piezoelectric materials, as lead metaniobate, polyvinylidene fluoride (PVDF), 1-3 piezo-composites, associated to theoretical modelling permits the conception of different sensor types with well defined directional and sensitivity properties. Hence new transducers sensitive to selected wave modes appeared [81,82].

The transducer aperture, i.e. size of the area of contact with the specimen surface, is another important factor. A conical transducer [83] with a PZT element in the form of a truncated cone, with the smallest diameter being about 1mm, was conceived to avoid the strong directionality effects observed in classical one. It appears to be sensitive to normal displacement of the surface on which it is placed [57].

Non contact laser interferometers with frequency bandwidth about 10 MHz, and sensitivity approaching 0.1 nm have been successfully used [84,85,86]. Their high fidelity transduction of acoustic emission signals allows direct comparison of detected acoustic emission signals with numerical simulation results, and support better understanding to acoustic emission phenomena [87]. Another non-contact transducer based on magnetic fields (the electromagnetic-acoustic transducer) has also been used [88]. It is made of a coil and a magnet. It has a narrow-band and requires strong magnetic fields. It may work at elevated temperature and in remote locations. It is not very applied due to its low sensitivity and large dimensions.

Other alternative transducers that have also been successfully used are the capacitive transducer [85,89], which is broadband with few identifiable resonances, but is relatively insensitive [57], and the optical fibre sensors.

For better correlation of the observed acoustic emission signals to the acoustic emission source, a calibration of the transducers is required. It consists of observing the transducer's answer to waves simulated by a standard reproducible source. Different procedures exist with different source types. The most commonly used by the transducers manufacturers is the face-to-face calibration which results in the familiar sensitivity versus frequency curves (figure 3.3). It consists to put face-to-face a transducer with well known response and the transducer to be calibrated. Helium jet is also often used [90].

Absolute sensitivity calibrations permit to know in which way the transducer responds to a surface vertical displacement at any point of its frequency range. They are proposed by some institutions (e.g. National Institute for Science and Technology [91,92], Nippon Steel Corporation [93,94]). They require elaborate equipment. This calibration approach

assumes that an acoustic emission transducer responds to the out-of-plane waves only, but the piezoelectric element is sensitive both to the in-plane and out-of-plane stimuli, especially when a high viscosity or solid couplant is used to mount the transducer. For real structures applications multiple wave modes exist simultaneously due to mode conversions and reflections within the structure. A calibration should thus be performed before each test.

The normal acoustic emission user doesn't have all these equipment for calibration. The pencil lead break test also called Hsu-Nielsen test is used for determining the reproducibility of the transducer response [95]. However, it doesn't produce absolute calibration. Presently, there are no standard methods for in-situ calibration of acoustic emission transducers [96]. Various investigators are focusing their attention to develop potential procedures [96,97,98,99].

In this work, a resonant (150 kHz) piezoelectric transducer, Micro 30 of Physical Acoustics Corporation and a broadband B1025 piezoelectric transducer of DigitalWave Corporation, with a near flat frequency response from 150 kHz to 2 MHz, were used. The B1025 acoustic emission sensor is a high fidelity, piezoelectric transducer. It is specially designed for modal acoustic emission measurements. According to the manufacturer, a flat response proportional to out of plane displacement is possible from about 150 KHz to about 2 MHz depending on the type of wave and material. From 17 KHz to about 100 KHz the B1025 transducer is proportional to velocity. The broadband transducer was used for transient signals acquisition, whereas the resonant was used to trigger the acquisition and for localization of acoustic emission sources. The transducers were mounted on the specimen using a tape. Silicone grease was used as coupling agent between the sensor and the composite surface.

In figure 3.3 is represented the calibration curve of the resonant transducer provided by Physical Acoustics Corporation. The calibration methodology was the face-to-face technique based on the ASTM E 976 standard [95].

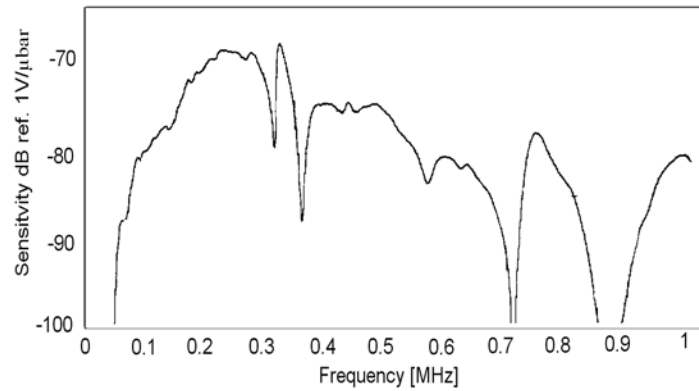


Figure 3.3 - Frequency response of resonant transducer

In figure 3.4 is represented the curve of calibration of the broadband transducer provided by Digital Wave Corporation. The calibration methodology was the transient surface wave calibration technique based on the ASTM E 1106 standard [91].

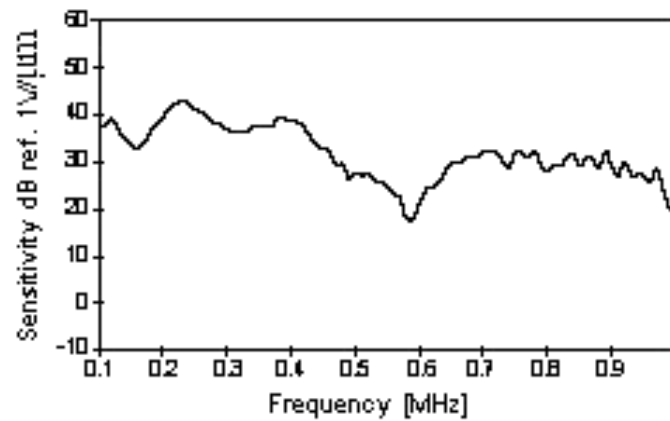


Figure 3.4 - Frequency response of broadband transducer

3.3.3. The preamplifier

The transducer is connected to a preamplifier by a short cable, when it is not integrated into the transducer. It is placed closed to the transducer to minimize pickup of electromagnetic interference.

The preamplifier amplifies the acoustic emission signal to more usable voltage. Then, it drives the signal over a long length of cable permitting the acoustic emission system to be distant from the tested structure. The preamplifier must satisfy some requirements. It

must have a low input noise to distinguish smallest signals from electronic noise, a large dynamic range to process high amplitudes without saturation, a large range of operating temperature for applications in the neighbourhood of low temperature vessels as well as above the transition temperature from brittle to ductile behaviour [100]. The preamplifier typically provides a gain of 100 (40 dB) and has plug-in frequency filters to eliminate the mechanical noise and background noise that prevails at low frequency. In this work two preamplifiers 1220A from Physical Acoustics Corporation with a 40 dB gain and a high pass 100 kHz plug-in filter were used.

Preamplifiers inevitably generate electronic noise. The improving of signal-to-noise ratio of acoustic emission measurement requires the optimization of acoustic emission transducer/preamplifier connection and the minimization of the preamplifier noise [101].

The preamplifier is connected to the acoustic emission system via a coaxial cable, with 50 Ω BNC connectors at both ends, which transmits the signals.

3.3.4. The acoustic emission system

The acoustic emission equipments highly improved with the apparition of digital systems. They permit an easier acquisition, storage and presentation of acoustic emission data. The first digital systems digitized the signal picked up by the sensor before extracting acoustic emission signal characteristics like amplitude, energy, duration, and counts. The new systems still perform this task but, simultaneously, record the transient signals.

A two-channels AMSY-5 acoustic emission system developed by Vallen-System GmbH was used in the present investigation. Each channel had a plug-in high-pass (17 kHz) and low-pass (960 kHz) filter. After filtering, the signal is digitalized by an analogue/digital converter having a dynamic range of 16 bit using a sampling rate of 10 MHz. The system, then, performs a feature extraction. The data are, thus, transferred by a PCI-interface board (ASyC) to an external computer, running under Windows XP. This ASyC has a 32 MB memory for intermediate data storage prior to data transfer to the computer, to compensate the fact that Windows XP doesn't operate in real-time. The features data and the transient signals are then saved into two separated files. User friendly softwares permit the visualisation and treatment of those data.



Figure 3.5 - AMSY-5 Acoustic emission system

3.4. Damage discrimination

The relationship between acoustic emission signals and the damage mechanisms sources of acoustic emission is not straightforward. Three analysis techniques are used for damage discrimination: the parameter, frequency and modal analysis.

3.4.1. Parameter analysis

In the classic acoustic emission testing, signal parameters are studied. The acoustic emission signals are characterized by different parameters (e.g. counts, amplitude, energy, duration, rise time). They are defined from a predefined threshold determined in function of the background noise (figure 3.6).

In many cases a single parameter is used for damage discrimination (e.g. [1,2,102,103,104,105,106]). The most commonly used parameter is the amplitude. Investigations could relate the acoustic emission signal amplitudes to the damage mechanisms sources associating the signal amplitude to microscopic observations. Specific amplitude ranges were attributed to the different damage mechanisms. For example, Benzeggagh et al. [102] observed signals with amplitude from 40 to 55 dB, when the damage mechanism was matrix cracking or 60 to 65 dB when debonding was observed, 65 to 85 dB for fibre pull-out, 75 to 85 dB for delamination and 85 to 95 dB for fibre break. However, the values of amplitude limits vary from study to study, because

they are material, material geometry and acquisition hardware dependent. Consequently, no consistent general conclusions have been proposed.

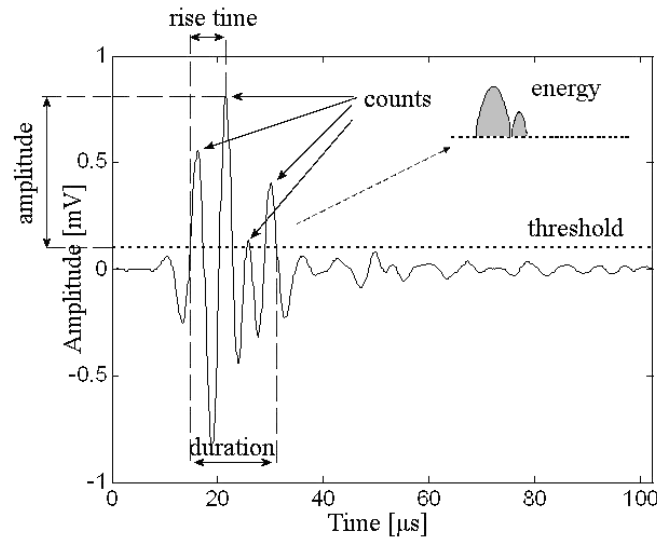


Figure 3.6 - Signal decomposition into parameters

The parameter analysis has been essentially used for laboratory specimens with well defined geometry. In real structures, the wave propagation paths are more complex. A signal generated by the same damage phenomenon, but at different locations may produce completely different parameters, depending on the wave propagation to the sensors. This will make more difficult a discrimination based on single parameter.

A multiparameter analysis, studying various parameters simultaneously, permits to partially overcome those problems. The extraction of information from multivariable data has been highly improved using mathematical tools permitting statistical multivariate analysis.

3.4.2. Frequency analysis

The frequency content of the acoustic emission signals is studied for damage discrimination. The frequency spectrum is usually obtained by the fast Fourier transform [107,108,109,110,111], but the wavelet transform has also been used for that purpose

[112,113,114]. From the results in literature, a relation between micro mechanical events and specific frequencies exists.

De Groot et al. [108] correlated the mean frequency of acoustic emission signals to the damage occurring in carbon/epoxy laminate. Four different frequency bandwidths were associated to different damage mechanisms, 90 to 180 kHz to matrix cracking, 240 to 310 kHz to decohesion, 180 to 240 kHz to fibre pull-out and > 300 kHz to fibre rupture, respectively.

Calabro et al. [109,110] observed frequencies around 400 kHz, when fibre ruptures occurred in unidirectional and cross-ply carbon/epoxy laminates submitted to tension.

From the literature review, no general theory exists to attribute specific frequency ranges to a given damage mechanism. The limits depend on the material and test. However, the same trends were observed, i.e. the highest frequencies correspond to fibre rupture and lowest to matrix cracking [108]. The frequency analysis has been essentially applied, in the case of composite materials, to laboratory tests, but no practical applications have emerged so far.

3.4.3. Modal acoustic emission

In recent years, an alternative treatment has been proposed with specific objective to obtain more quantitative information about the damage and a deeper physical understanding of the acoustic emission phenomenon. It consists of studying the mechanical nature of the propagating waves resulting of the process of damage formation. The mechanical waves propagate through solid materials in a number of modes as previously referred. The distinction between these wave modes is used as a discriminating parameter for different damage types.

Although the first investigations paying attention to the complete acoustic emission signal waveforms dated of early 70's (e.g. Stephens et al. [115]) practical implications appeared only in the 90's, when Gorman et al. used wave propagation theory and modal analysis for acoustic emission testing [5,116,117,118,119,120,121]. Most of their pioneer work was dedicated to the study of graphite/epoxy thin-plates behaviour. Using the classical plate theory for modal acoustic emission analysis they could determine the

orientation of cracking [5], they observed that in thin-plates transverse matrix cracking produces essentially the extensional Lamb wave mode [116].

Modal acoustic emission analysis has known an increasing success. Significant work was done for example by Surgeon [4], Morscher [122], Johnson [65,66], and Dunegan [123,124,125], who apply modal acoustic analysis to thicker structures such as a honeycomb panel to which two graphite/epoxy panels were bonded [124].

Its application in practical testing situation is not yet very common. Downs et al. [126] were the first to use plate wave modes discrimination during proof testing of a graphite/epoxy pressure vessel. Their work underlined the limitation of analysing a single parameter like amplitude, energy and duration which can be seriously affected by the propagation distances typically encountered in practical structures.

3.5. Source localisation

Acoustic emission source spatial location is derived from the arrival time difference at various transducers positioned at different locations in a structure. Numerous location algorithms covering a wide range of applications are available in traditional acoustic emission softwares (e.g. linear, zonal, planar, and spherical). Each algorithm uses a different method for specific structures. In this study, two acoustic emission transducers are available. It is thus possible to calculate the source location along a line between them, if the distance between them and the velocity of waves propagation are known.

The arrival time at a transducer is traditionally determined by the first crossing of the threshold. Ziola et al. [127] pointed out that accurate linear location can only be performed if the modal nature of acoustic emission signals is taken into account and the arrival times are determined on the same wave mode at both transducers. The benefits of modal acoustic emission location are significant in larger and more complex structure geometries. In the case of plate-like specimens, Ziola et al. [127] determined that the extensional wave is the most suitable for location. The authors proposed a methodology based on cross-correlation of the signal with a Gaussian cosine-wave of fixed frequency to isolate a particular frequency component to guarantee that arrival times are based on the same frequency component.

Authors proposed an alternative arrival-time estimation using wavelet transform [128,129,130,131,132,133,134] or neural networks [135,136,137]. Others proposed linear location using the arrival-time difference of two different propagating modes at a single transducer [134,138,139]. Some work is also being done to propose more accurate location in more complex structures (e.g. [140,141,142]).

3.6. Noise discrimination

During acoustic emission testing noise is unavoidable (e.g. electromagnetic interference, hydraulic, vibration, fretting noise). Thus, one of the major difficulties of data analysis remains the separation of signals due to noise and damage, especially because signals due to damage are in the same frequency range. Special care must be devoted to develop methodologies for the elimination of noise sources (e.g. acoustic isolators, vibration damper, specimen end tabs) and avoiding noise acquisition (e.g. frequency filters, data acquisition only near maximum load during a fatigue test based on the doubtful assumption that damage only occur then).

Most of signals due to noise can be removed from data in a pre-processing phase. Different techniques have been successfully used for that purpose. For example, grips noise is generated at tabs, by retaining only the signals originated between the transducers it will be possible to reject it. Electronic noise hits all transducers at the same time and can thus be removed.

In classical treatment, the differences on parameters are studied for noise removal. It is considered that bursts with less than 3 threshold crossings and durations less than 3 ms can be regarded as noise [100]. Most of the bursts with low amplitudes and long duration are friction noise, whereas very short signals may indicate electrical noise peaks, especially, if they arrive at all channels at the same time [100]. Acoustic emission hits due to damage are highly correlated as far as duration, counts and amplitude are concerned [59]. The study of these correlations also permits noise dissociation.

Modal acoustic emission analysis improved the noise dissociation which is obtained from the wave mode discrimination (e.g. grip noise produce low frequency flexural signals). Ziola [143] proposed a noise rejection using both the amplitude and the

frequency characteristics of the detected signals because noise signals tend to be of larger amplitude and lower frequency content than damage signal.

Chapter 4

Single fibre specimen

Single-fibre specimens consist of a single fibre embedded in resin. They are, essentially, involved in studies where the reinforcement/matrix interface properties are investigated (single fibre fragmentation tests). The single fibre fragmentation test is one of the rare methods allowing the correlation of each discrete burst with the acoustic emission sources. Published results have shown that there is a one-to-one correlation of acoustic emission to fibre breaks in the single fibre fragmentation test for most fibre/matrix systems including glass/epoxy and carbon fibre/epoxy [144]. The acoustic emission can, thus, be correlated to the specific fibre break that generated it [145].

This configuration is chosen to relate the acoustic emission waveforms to the damage occurring during a tensile test. For this simple configuration, the damage process is believed to be reproducible. By altering some parameters such as the fibre diameter, the fibre/matrix interface adhesion, it is possible to control the damage process. The acoustic emission activity occurring during the tests, in the different configurations, has been acquired in order to establish relationships with the specimen configuration.

4.1. Damage mechanisms

The fibre/matrix interface is the place of complex mechanical phenomena. Among the different micromechanical tests commonly used to characterize the interfacial properties (the single fibre fragmentation test, the pull-out test, the microindentation test, and the microbond test) the single fibre fragmentation test is the most popular, because it is easier to implement and provides more information about the damage process.

For such test, a resin with an elongation at rupture at least three times higher than the fibre is required in order to guarantee multiple fibre ruptures [146]. Fragmentation process is well known and widely described in the literature [8,146,147,148].

When a specimen containing a single continuous fibre is loaded the matrix and the fibre deform in the same way. The stress is transferred from the matrix to the fibre through interfacial shear stress. When increasing the tensile load, a point is reached at which a fibre fracture occurs, at the weakest point along the fibre. An increase of the specimen elongation, during the test, leads to successive fibre fragmentations. As the number of fibre breaks increases, the original continuous fibre becomes a succession of fibre fragments. At each fibre rupture, a fibre fragment splits into two smaller fragments. The fibre continues to break into smaller fragments until the fragments lengths become so short that it is not possible to break further. This final fragments length is called the critical length, and the state where the fibre no longer fractures is defined the saturation state.

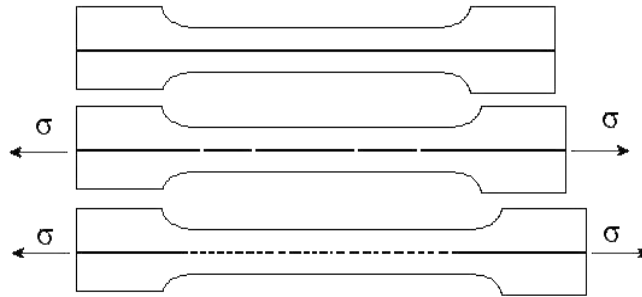


Figure 4.1 - Fragmentation process

Acoustic emission has demonstrated to be a powerful tool to monitor damage process during the fragmentation test [110,149]. Laser Raman Spectroscopy is also used to monitor the fibre fracture and interfacial damage [150,151]. This is done from the mapping of the Raman spectrum along the fibre, as some absorption bands are sensible to the strain state.

For transparent resins, the analysis of the photoelasticity effect is an efficient method that allows measuring the stress or straining profile around fragments ends [8,152]. The photoelastic analysis is based on the observation of the optical anisotropy, created in the optically isotropic polymers, due to the variations of the birefringence resulting from the strain. These photoelastic effects can be observed by an optical microscope using polarized light.

Kim et al. [8] monitored continuously the fragmentation process devoting a special care to the debonding at each fibre breaks. Their observation of the photoelastic birefringence patterns in the specimen during the tests give a clear idea of the damage process occurring at the interface.

They embedded carbon and glass fibre in epoxy resin. Fibre breaks were seen optically by photo microscopy, and by camera, at occurrence. During the fragmentation test, the stress state near the fibre breaks and the interface between the fibre and the matrix were observed using crossed polarizers. By controlling the angle of the two polarizers, shear stress could be viewed by microscopy.

During testing, once the fibre failed, stress birefringence was simultaneously observed near the breaks. Birefringence patterns showed the shear stress originated from the tensile loading. The shear stress was observed distributed near the fibre breaks. The birefringence usually showed symmetric features at both sides of the fibre. Interfacial debonds usually occurred simultaneously between the fibre and the matrix when the fibre broke. Birefringence did not appear at fibre breaks because there was no shear stress there.

Once the fibre fractured, the fibre ends slipped leaving empty space at the position of the fibre break called the fibre gaps. They could be seen using the microscope or, in the case of carbon fibre, could be deduced from the stress birefringence, as they were less apparent. At low strains, small gaps were observed, they widened at higher strains. As the loading increased, more stress was transferred to the fibre. The interface sustained shear stress until a limit, where interfacial debonding occurred. The weak debonding caused shear strength decreases. Small debonding zones were observed for strong interfacial bonding and larger for weak interfacial bonds. The debonding zone was usually symmetric on both sides of the fibre break site. The unidirectional lengths of debond zones were measured from the photoelastic birefringence. The debond zone became longer as the strain increased. When strain increased, new fibre failure and new instantaneous debonding occurred. The new created debond zones were larger than the one occurring at lower strain, until a certain strain level, from which the new debond zone were shorter as the strain increased. This decrease was attributed to the lower energy being reduced by fibre breaks as the fragments got shorter [8]. Meanwhile all debond zones continued to increase continuously.

Concerning the fragments ends, Nordstrom [85] observed, under polarized light, two different patterns for both glass and carbon fibre fragments ends, when embedded in epoxy resin. He described these patterns as having the shape of a “V” or an “X”, according to how the surfaces were oriented with respect to the plane of vision.

4.2. Stress transfer at the interface

The fibre reloading is initially perfectly elastic and after the shear stress reaches a certain limit, decohesion occurs at the interface, thus the debonded part is reloaded by friction of the Coulomb type [146].

Different models (3- [153], 2- [154] and 1-dimensional [155,156,157] models) were proposed for the evaluation of the full stress field. The most used to estimate the interfacial shear strength are the two 1-dimensional models: the shear lag theory formulated by Cox [155] and the Kelly-Tyson model [156].

The Kelly-Tyson model is the most commonly used in the literature considering its simplicity of application, despite the involved approximations. It is considered in this dissertation. It is briefly presented. More information about the different models can be found in the literature [147,148].

4.2.1. Kelly-Tyson model

This approach considers that the interface withstand a maximum shear strength value, τ_m , above which there is decohesion, at the fibre/matrix interface. This value is supposed to be characteristic of the particular interface. To each τ_m value correspond a critical fibre length, l_c , or more precisely, a fibre length distribution ranging from $l_c/2$ to l_c , since any fibre with length just above l_c will break. Considering a distribution of fibre fragments approximately symmetric, the fragment average length, $\bar{l}$, is equal to:

$$\bar{l} = \frac{3}{4}l_c \quad (4.1)$$

This model considers that, at the interface, there is no relation between the fibre and matrix elastic displacement, that the fibre is ideally elastic, that the forces are uniformly distributed, and that the shear strength is constant at the fibre extremities and falls to zero away from the extremities. Based on the above assumptions the average shear strength, $\bar{\tau}$, can be expressed as

$$\bar{\tau} = \frac{d}{2l_c} \sigma(l_c) \quad (4.2)$$

where $\sigma(l_c)$ is the fibre tensile strength at critical length.

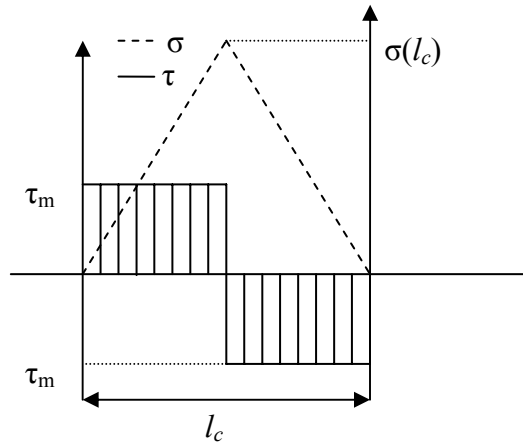


Figure 4.2 - Stress state in the fragment at critical length

4.3. Acoustic emission applied to the fragmentation test

The advantages of using acoustic emission for fragmentation test monitoring has been demonstrated in a wide variety of studies involving different fibre/matrix combinations, some of them are reviewed in literature [85]. It is a useful tool for determination of the fibre fractures location and the fragment lengths. It can be used in complement to the classic techniques for breaks counting using a polarizer during the test [158,159,160], a microscope [160] or by resin burning after test. In the case of non-transparent matrices for which optical breaks verification by microscope is not possible. For such material acoustic emission is crucial.

Acoustic emission has enhanced the fragmentation test, allowing the determination of the stress of occurrence of successive fibre breaks [161,162,163]. Their linear location is obtained from the arrival time difference at two transducers. The location precision is highly dependent on the wave arrival time determination.

Sachse et al. [161] recommended the use of point-like broadband acoustic emission transducers and a good signal processing technique to determine the arrival time of the correct wave mode, the different wave modes propagating at different velocities.

Netravali et al. [164] defined a correlation algorithm to apply to the front of the incoming waveform to avoid the threshold dependence arrival time determination. The same authors [165] considered the evolution of the velocity in function of the strain during testing. A velocity value corresponding to the average of the measured velocity during testing was used for location calculation.

Manor et al. [163] introduced a correction in the distance between the two transducers, corresponding to the displacement during the tensile test. Doing so, they locate the fibre rupture with a location precision of about 0.15 mm.

In earliest papers, Narisawa et al. [144] established a “one-to-one correlation” between common fibres breaks (glass and carbon) and acoustic emission events. This connects the break and the acoustic emission event to the same single cause. This result was observed using a piezoelectric transducer resonant at about 150 kHz and covering the range of 100-300 kHz. This one-to-one correlation of acoustic emission signals to visible fibre breaks holds for most fibre/matrix, but there are exceptions, e.g. in certain non-isotropic fibres such as Kevlar secondary fibre breakage events occur at sites of primary breakage [85]. The secondary fibre breaks are the fibre splitting along the fibre axis, which produce lower amplitude acoustic emission and can then be differentiated using a threshold [164].

The frequency content has been investigated in some studies [85,158,166,167,168,169,170] to extract the information contained on the acoustic emission signals about the failure source. It is pertinent considering that compared to the amplitude, the acoustic emission frequencies remains almost unchanged whereas amplitude suffers significant attenuation [170]

Bohse [167] used the single fibre specimen to identify acoustic emission source mechanisms. Specimens were made of epoxy and single glass or carbon fibre, with respective diameter 20 and 7 μm . Acoustic emissions were classified into matrix

cracking, fibre breakage and fibre/matrix debonding from their frequency content. The spectral power density was used for that purpose. It was assumed that matrix cracks had at least 70% of the signal power in the 100 to 350 kHz frequency interval and fibre breaks in the range of 350 to 700 kHz. Signals in between were attributed to fibre/matrix debonding. Those results were then applied for assignment of acoustic emission waves to single failure mechanisms in tensile tests of multi-fibre specimens. The authors recognized that the application of such criteria may not be possible in large structures due to the wave's attenuation during propagation.

Ni et al. [169] embedded a single carbon fibre with a diameter of 6.9 μm in epoxy resin. The frequency content of acoustic emission signals obtained by the fast Fourier transform revealed several frequency peaks, which were related to the damage mechanisms. Frequency peaks inferior to 100 kHz were associated to matrix cracking, in the 200-300 kHz range to debonding and 400-450 kHz to fibre break. For glass and carbon fibre breakage acoustic emission signals with 100-200 μV amplitude were observed. Ni and Iwamoto [170] proposed to use the continuous wavelet transform for frequency content calculation in complement to the Fourier transform. Two frequency peaks were observed at 20 and 400 kHz from the Fourier transform. The wavelet transform gave a complementary information about the damage sequence and duration. The peak frequency for fibre break had a duration of about 18 μs , while the peak frequency of matrix cracking was about 35 μs . This indicates that the matrix cracking continues for a while even after the fibre break occurred.

Single fibre specimen were used by some authors [110,159,171] to isolate a single damage mechanism, i.e. the fibre break, and to identify typical acoustic emission signals corresponding to this damage mechanism.

Calabro et al. [110,159] submitted to tensile loading a single carbon fibre embedded in a polyester matrix. Fibre fractures were observed during loading by a polarized light microscope and simultaneously detected by a wideband acoustic emission transducer, a resonant one being used for acquisition triggering. The acoustic emission signals from the wideband transducer were analysed by the fast Fourier transform. The authors suggested the use of the same methodology to investigate the fibre/matrix debonding and matrix cracking.

Huguet [171] adopted the same methodology when trying to identify a typical acoustic emission waveform due to fibre breakage to use it for further classification, by neural networks, of acoustic emission signals detected during a tensile test of unidirectional glass-fibre/epoxy and glass-fibre/polyester composites. The same fibre/matrix configurations were used for the single fibre specimens. A typical waveform was attributed to fibre breakage. The author recognized that the resulting signal may be affected by the presence of decohesion.

In other studies, the single fibre specimen constituents were varied to observe their influence on the interface characteristics.

Haselbach et al. [166] devoted a special attention to the fibre/matrix decohesion. Instead of using the classical dogbone specimen, they used a necked sample with an embedded single fibre. Before the embedding of the glass fibre, of diameter 70 μm , into epoxy resin, the glass surface was treated in order to produce weak areas of adhesion. A mixture of fatty alcohol sulphates and amphoteric surfactants in aqueous solution was used. The authors used the frequency at the centre of gravity of the area below the envelope to describe the frequency spectra of the waveforms. Debonding was accompanied by signals showing amplitudes smaller than 45 dB and a frequency at the centre of gravity in the 270-330 kHz range. Matrix cracking was accompanied by signals showing amplitudes smaller than 60 dB and a frequency at the centre of gravity at 170 kHz. Whereas, fibre breaks were accompanied by signals showing amplitudes smaller than 90 dB and a frequency at the centre of gravity in the 90-180 kHz range.

Mäder et al. [168] studied the interface in glass-fibre/polypropylene single fibre specimens. The fibres had different sizing (silane, either polyurethane or polypropylene dispersion film formers) in order to vary the interfacial characteristics. The frequency content of acoustic emission signals was studied as well as the signal amplitudes. The frequency analysis permitted to put in evidence that the different observed mechanical behaviours were related to the interface. An evolution of the frequency content was observed for the lower amplitude signals, which were attributed to matrix cracking, suggesting a dependence of matrix cracking on fibre surface treatment. Frequency variations were also observed for the signal attributed to decohesion whereas no variation was observed for acoustic emission due to fibre breakage.

Park and co-workers [172,173,174,175,176] have, during the past years, investigated the interface characteristics of many different reinforcement/matrix (carbon, steel, SiC and glass-fibres/BMI/epoxy) configurations. The interface quality was varied by different surface treatments (e.g. silane, electrodeposition). Acoustic emission has been used as a complement to the fragmentation test. The acoustic emission analysis was based on amplitude and waveform analysis. Waveforms due to fibre fracture are reported. The waveforms revealed to be function of the interface.

Nordstrom [85] applied different coupling agent thicknesses at carbon fibre surface to reduce the fibre reload length. A laser interferometer was used for acoustic emission wave sensing. Two different patterns were observed. The author attributed the existence of different patterns to the orientation of glass fibre breaks (the “X” and “V” shape) underlined by polarized light.

4.3.1. Conclusions

Considering the one-to-one correlation of the acoustic emission signals with the observed fibre breaks, verified by many authors [85,144,158, 169,171], it is possible to conclude that an acoustic emission event corresponds to one fibre breakage and that all failure mode occur simultaneously, i.e. fibre break, fibre/matrix decohesion and matrix cracking. Thus, the single fibre specimen permits the correlation of each discrete burst with the acoustic emission sources. From the literature review, the frequency analysis of the acoustic emission detected during fragment test seems to be pertinent.

Some authors supposed that a typical waveform due to fibre fracture in composite material could be isolated from fibre fracture in single fibre specimen. Such statement can be subjected to critics, as the single fibre specimen does not reflect the behaviour of a full-scale composite which must have a reasonable volume fraction of fibres.

4.4. Tensile strength determination

According to the Kelly-Tyson model, the interfacial shear strength depends on the fibre tensile strength at critical length (equation 4.2). The critical fibre lengths must be determined. The tensile strength for lengths around the critical length can not be

measured directly. The values are obtained by extrapolation from the results obtained for longer fibre lengths.

Fibre strength depends on the gauge length. A higher scatter is observed for longer lengths, due to a higher flaws population on the fibre surface leading to fibre break. In order to estimate the fibre strength, a statistical model must be used taking into account the “flaw-induced” nature of the tensile strength [177,178]. For longer fibre lengths, a larger number of flaws is present. There is a higher probability that a severe flaw may occur. Therefore, the average tensile strength decreases as the gauge length increases. By analyzing the fracture surfaces of filaments broken in tension with electronic microscopy, some authors have shown, that the strength is greatly dependent on the severity of the flaws rather than the flaw type, e.g. particle inclusions, surface damage [147].

There are three main methodologies to determine the fibre strength [85]: the single fibre static tensile test, the fibre bundle tension test or the fibre surface examination. In this study, the first one was chosen, for being the most straightforward characterization method. The advantage with respect to the bundle is that the fibre failure is completely isolated. However, large number of single fibres must be tested. This is time consuming. Tensile tests of the single fibre were performed following the ASTM D3379-89 [179] recommendations.

4.4.1. Mathematical strength distribution model

To describe the tensile strength data, several statistical distributions are used, e.g. the normal distribution, the Weibull distribution. Those models are not related to the physical nature of the fracture process. Implicit in the models is the assumption that the failure is due to sudden catastrophic growth of pre-existing defects, each defect corresponding to a certain local failure stress. Failure at the most serious defect leads to the immediate failure of the entire sample. The fracture process is, therefore, of a perfect brittle nature, hence independent of time and environment. It is assumed that the defects are homogeneously distributed along the filament.

In most cases, where the failure of brittle materials is described, the simplified 2-parameters Weibull distribution [180] is used. It is typically used to describe life data, mostly when there is little information about the population under study. It is an

asymmetric function described by two parameters, the shape parameter, m , which is the measurement of distribution breadth, and the scale parameter, σ_0 , which is near the mean of failure stresses. Its success is particularly due to its shape flexibility. For example, when m is unity, it reduces to the exponential distribution, while for values of m between 3 and 4, it approximates the normal distribution.

Alternative and more sophisticated models based on the Weibull distribution were proposed by Stoner [181] and Padgett [182]. The “end-effect model” by Stoner [181] considers the end-effects in the clamps, where the fibres tend to fail due to experimental factors rather than due to the random flaws in the fibres themselves. While Padgett [182] tried to propose a broader statistical approach based on an application of the “accelerated life test” concept used for electronics, where an acceleration variable is introduced, decreasing the life time of the item under test.

The easiest way to estimate the tensile strength is to use a normal distribution, which gives an average value and a standard deviation for each gauge length. The tensile strength at average fragment length can be estimated by a linear extrapolation using the least squares method. This method is sometimes used because the Weibull distribution, seems to lead to an overestimation of the tensile strength for small fibre lengths [183]. Considering its easiness, the method has demonstrated to be very useful [184] to provide qualitative result about the interface shear strength.

Most studies in literature agree in the good fitting of tensile strength data over different gauge lengths by using a Weibull distribution and its modifications. In this dissertation the simplified 2-parameters Weibull distribution and normal distribution are considered.

When considering the filament as a single chain consisted of n links of length, l_0 , once the failure probability, $P_i(\sigma)$, at any stress, σ , applied to “a single” link is known (through experimental measurements) the probability of failure, P_n , of the whole chain, is derived considering that the chain fails if one of the links fails. Then, the probability of survival of one unit is $1-P_i(\sigma)$, whereas for the entire serial chain of n units the cumulative failure distribution is

$$P_n(\sigma) = 1 - e^{(-nP_i(\sigma))} \quad (4.3)$$

The exponent is assumed to be a monotonically increasing function that leads to the Weibull cumulative distribution. n is proportional to the length, L , of the filament.

$$P_n(\sigma) = 1 - e^{\left(-L\left(\frac{\sigma}{\sigma_0}\right)^m\right)} \quad (4.4)$$

The cumulative distribution function considers the fraction of units or samples that fail at or below a stress σ . The parameter m is dimensionless and is called the Weibull modulus. In reverse to the normal standard deviation a high value for m corresponds to a narrow fracture stress distribution function. The mean strength is therefore given by

$$\bar{\sigma} = \sigma_0 L^{\frac{1}{m}} \Gamma\left(1 + \frac{1}{m}\right) \quad (4.5)$$

where Γ is the Gamma function.

The traditional method for determining the Weibull parameters from a measured fibre break population is to take two successive logarithms of the Weibull equation 4.4 resulting in

$$\ln\left(\frac{1}{\ln(1-P)}\right) - \ln(L) = m(\ln(\sigma) - \ln(\sigma_0)) \quad (4.6)$$

Considering $\ln(L)$ as a constant, the equation 4.6 expresses a linear dependence between $\ln(-\ln(1-P))$ and $\ln(\sigma)$ with slope m . The shape of the fracture stress distribution is only determined by the magnitude of m and is independent of σ_0 [185]. σ_0 is estimated from the strength at

$$\ln\left(\frac{1}{\ln(1-P)}\right) = 0 \quad (4.7)$$

The Weibull distribution only depends on the flaw population. The parameters are characteristic for a given strength distribution and should be constant for all L [186]. In reality it is a common situation to obtain a good description of tensile strength for the individual gauge lengths, but quite different Weibull parameters. So, in many cases it is not possible to obtain a consistent representation of fibre strength over a range of gauge lengths described by two parameters only.

To assign the failure probability to a particular stress σ different formulas are used [147]. The stress values have to be organised in ascending order of magnitude and the probability used in the Weibull plots can be approximated by using the following equation

$$P_i \approx \frac{n_i - 0.5}{n} \quad (4.8)$$

To obtain the tensile strength values for different gauge lengths, it is usual to test at least twenty-five fibres for each gauge length. The extrapolation from the tested length, L , to other gauge lengths, l' , can then be made using the equation 4.5. However, the effectiveness of this equation is limited by the fact that the simple Weibull distribution usually gives a good description of the experimental data obtained only for a particular gauge length [147].

4.5. Single fibre testing

In this dissertation different fibres were tested: carbon fibre, two E glass fibres and an optical fibre. The carbon fibres (HS 3K, sizing: 1% epoxy) had an average diameter of 6.9 μm . Two E glass fibres were studied, with different average diameters 10.8 (PPG 3313, sizing: polyvinyl acetate/silane) and 21.4 μm (VEX300, sizing appropriate to have a particularly good adhesion to epoxy resins). Optical fibres, made of silica, with an average diameter of 128.6 μm were used for their high diameter compared to the traditional fibres.

In order to change the adhesion fibre/matrix, some of the higher diameter glass fibres were submitted to two different surface treatments. To improve the adhesion, they were

bathed into silane, diluted at 2% in water. After some hours, at ambient temperature, the evaporation process of water was accelerated in an oven at 60° C during 10 hours. The silane guaranteed the reinforcement of the chemical link between the resin and the fibre. Another group of these fibres were impregnated by a silicone mould release spray from Wacker Germany in an attempt to weaken the fibre/matrix adherence.

Mechanical characteristics of fibres were determined from tensile tests performed following the ASTM D3379-89 standard [179]. The fibre was glued to a rectangular cardboard (figure 4.3), without central part. This cardboard guaranteed the reference length to be reproducible. It also prevented the fibre to break when mounting in the testing device, and decreased stress concentration at the grips. The cardboard was mounted on a Tira® universal testing machine model 2705, with the fibre oriented along the loading direction. A 20 N load cell was used. Special pneumatic grips designed for textile fibre testing with rubber ends (figure 4.4), were used to minimise the damage induced on the fibre at clamping.

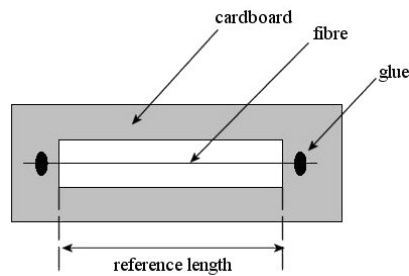


Figure 4.3 - Sample for testing

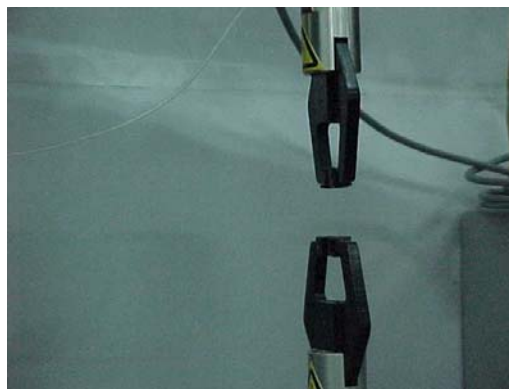


Figure 4.4 - Pneumatic grips

Once mounted, the free cardboard edges parallel to the fibre were burned to guarantee that only the fibre sustained the applied load. To guarantee at least 25 fibres to be correctly tested, 30 fibres of each were tested.

The ASTM standard [179] for single fibre testing recommends that only gauge lengths at least 2000 times longer than the average filament diameter should be tested. Three fibre lengths were tested (5, 15 and 30 mm) for carbon and E glass fibres, whereas only the longer for optic fibre. All fibre diameters were previously measured using an optical microscope. The diameter distributions for the different configurations are represented in figure 4.5 to figure 4.10. The average diameter, standard deviation and variance are summarised in table 4.1

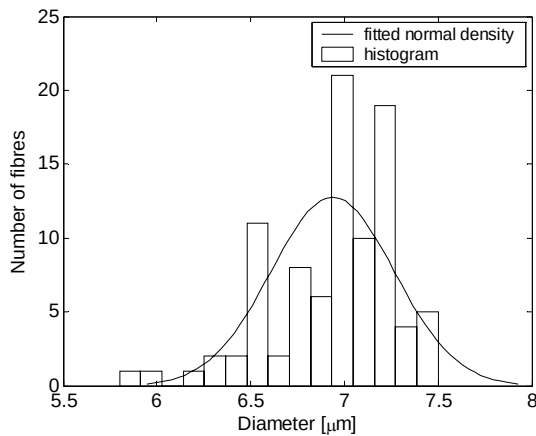


Figure 4.5 - Carbon fibre diameter distribution

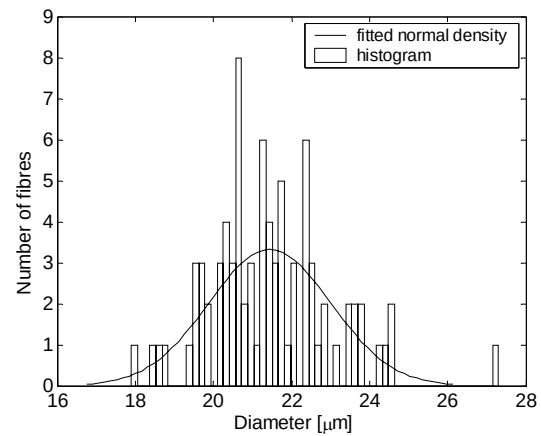


Figure 4.7 - E glass fibre (VEX300) diameter distribution

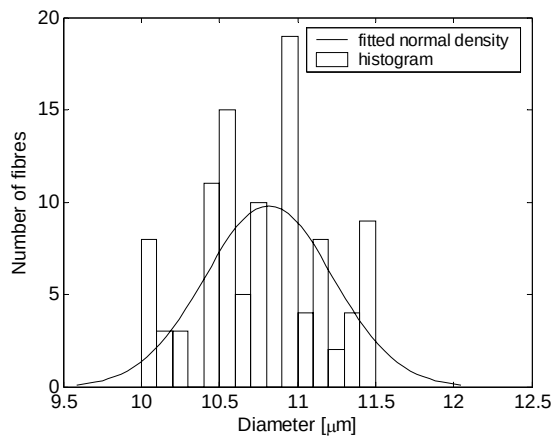


Figure 4.6 - E glass fibre diameter distribution

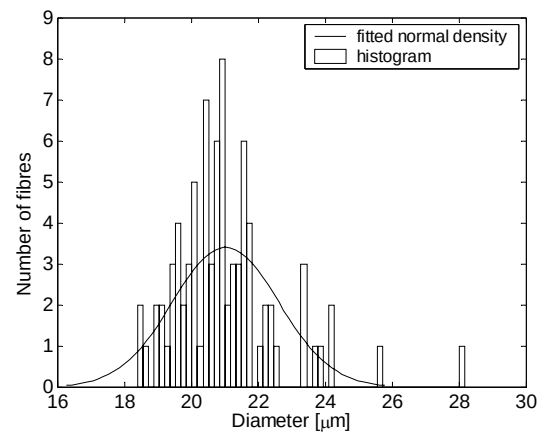


Figure 4.8 - Distribution of E glass fibre (VEX300) diameter after silicone treatment

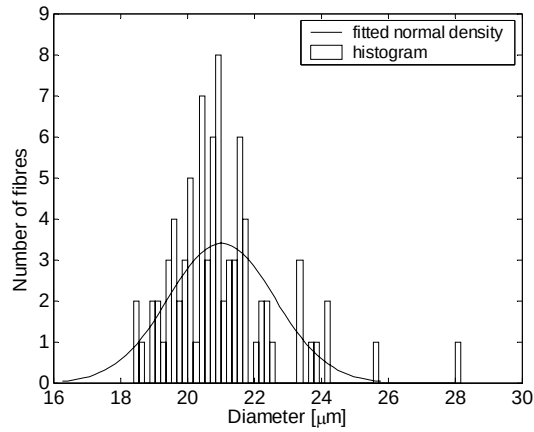


Figure 4.9 - Distribution of E glass fibre (VEX300) diameter after silane treatment

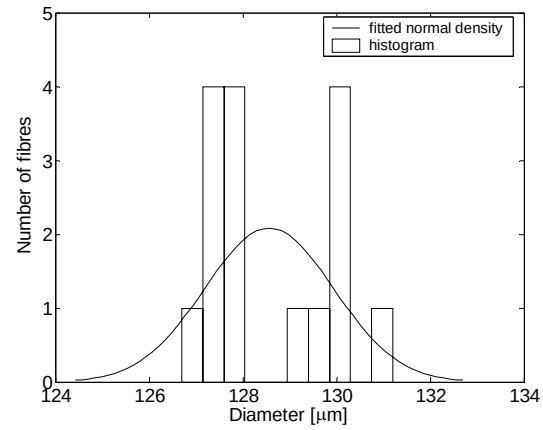


Figure 4.10 - Distribution of optic fibre diameter

Fibre	Average diameter	Standard deviation	Young's Modulus
	[μm]	[μm]	[GPa]
Carbon	6.9	0.3	232.2
E Glass	10.8	0.4	74
E Glass (VEX300)	21.4	1.4	73.5
E Glass (VEX300) + Silicone	21.0	1.6	67.0
E Glass (VEX300) + Silane	22.0	1.8	46.7
Optic fibre	128.5	1.9	36.5

Table 4.1 - Fibre diameter

Single fibre tensile tests were conducted with a controlled displacement rate of 0.5 mm.min^{-1} . A typical curve stress vs. displacement is represented in the figure 4.11. At the initial part of the test, the load doesn't vary linearly with the displacement, due to fibre misalignment and slipping in the grips.

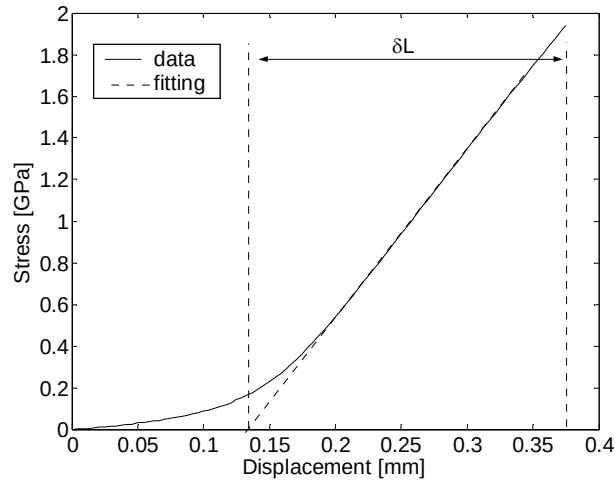


Figure 4.11 - Stress vs. displacement from the fibre tensile test

A procedure for the fibre Young's modulus determination is proposed in the ASTM standard [179], the specimen fragility preventing the use of normal strain sensing devices. The testing machine strain must be known as well as the total displacement, δL , determined graphically [147]. The so-obtained Young's modulus values are summarised in the table 4.1.

Tensile tests results are represented in Weibull plots in the figure 4.12 to figure 4.27. The Weibull parameters values graphically determined are summarised in the table 4.2. As previously discussed, different Weibull parameters values were obtained for the different lengths, contrarily to what observed Van der Zwaag [186]. A reason for this may lie on the variations of the dominant flaw population with varying gauge length, or other factors that were not accounted for, with influence over fibre failure [147]. Classically in those cases, it is then recommended to use the measured strength at a length as close to the critical fibre length as possible for strength extrapolation at the critical fibre length [147].

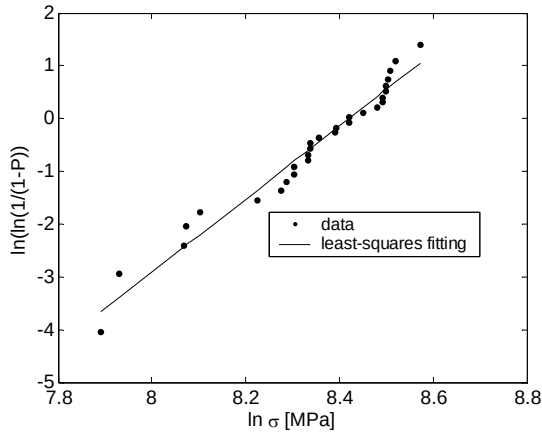


Figure 4.12 - Weibull plot, carbon fibre, gauge length of 5 mm

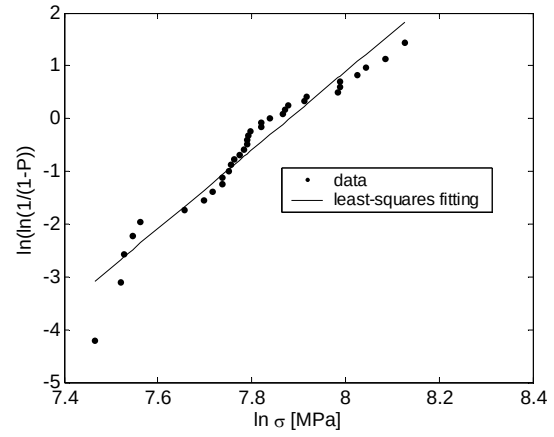
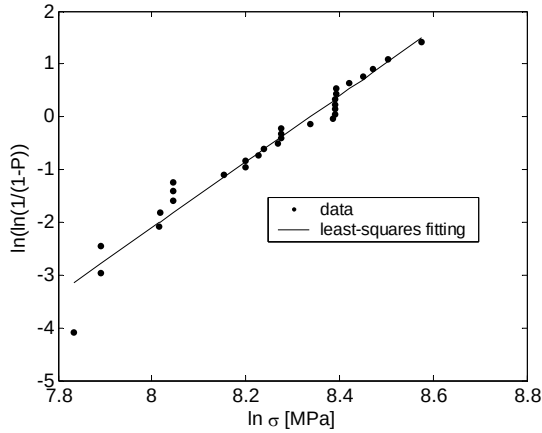
Figure 4.15 - Weibull plot, E glass fibre ($d=10.8 \mu\text{m}$), gauge length of 5 mm

Figure 4.13 - Weibull plot, carbon fibre, gauge length of 15 mm

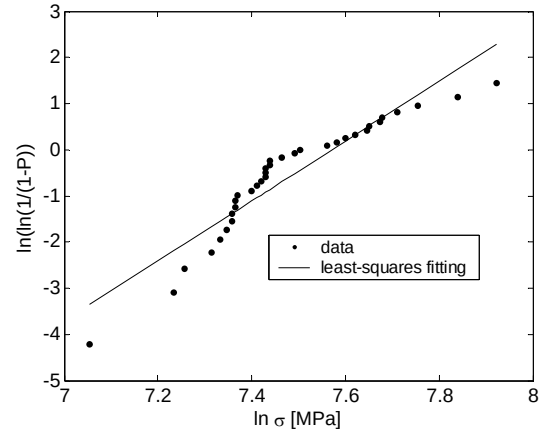
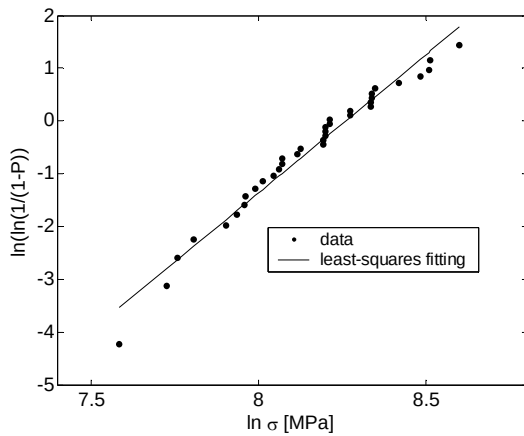
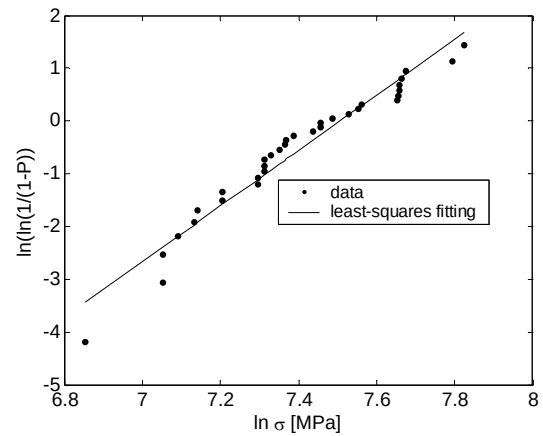
Figure 4.16 - Weibull plot, E glass fibre ($d=10.8 \mu\text{m}$), gauge length of 15 mm

Figure 4.14 - Weibull plot, carbon fibre, gauge length of 30 mm

Figure 4.17 - Weibull plot, E glass fibre ($d=10.8 \mu\text{m}$), gauge length of 30 mm

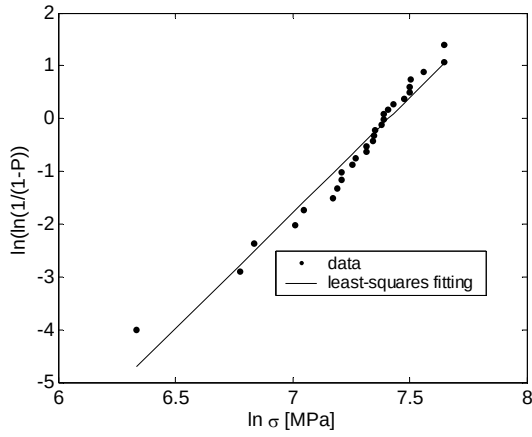


Figure 4.18 - Weibull plot, E glass fibre ($d=21.4 \mu\text{m}$) for a gauge length of 5 mm

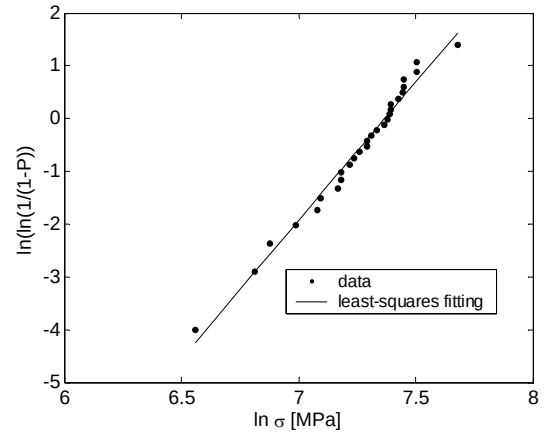


Figure 4.21 - Weibull plot, silicone treated E glass fibre ($d=21.4 \mu\text{m}$), gauge length 5 mm

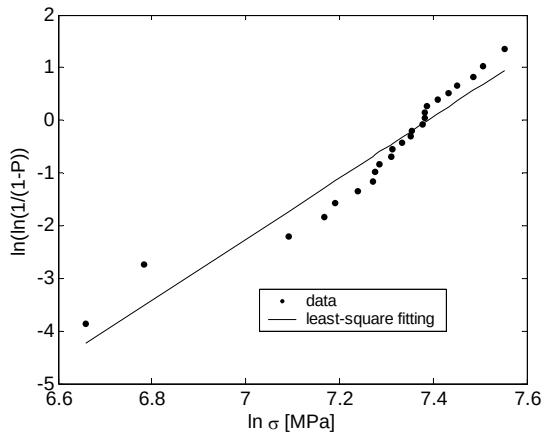


Figure 4.19 - Weibull plot, E glass fibre ($d=21.4 \mu\text{m}$), gauge length of 15 mm

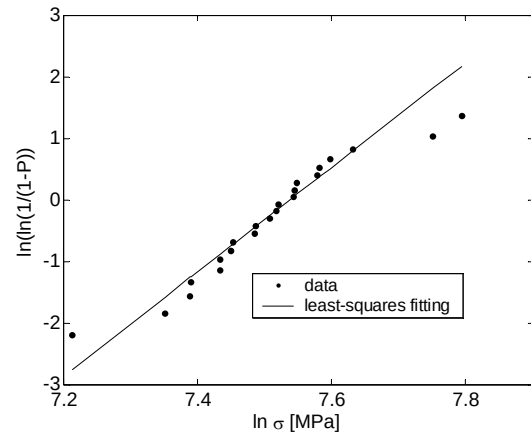


Figure 4.22 - Weibull plot, silicone treated E glass fibre ($d=21.4 \mu\text{m}$), gauge length 15 mm

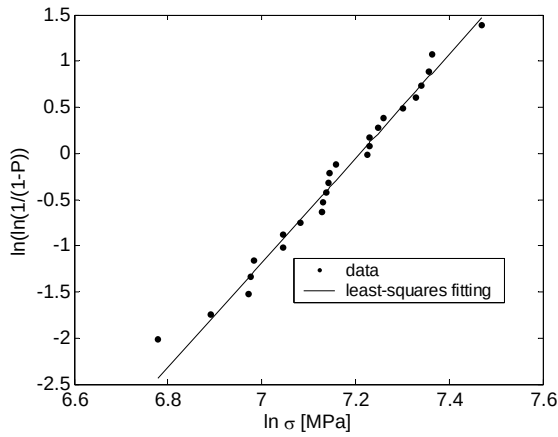


Figure 4.20 - Weibull plot, E glass fibre ($d=21.4 \mu\text{m}$), gauge length of 30 mm

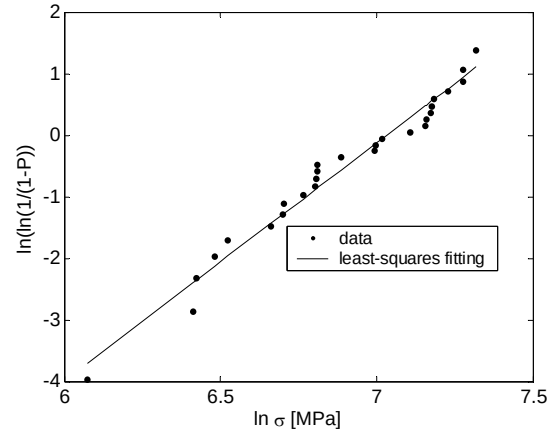


Figure 4.23 - Weibull plot, silicone treated E glass fibre ($d=21.4 \mu\text{m}$), length of 30 m

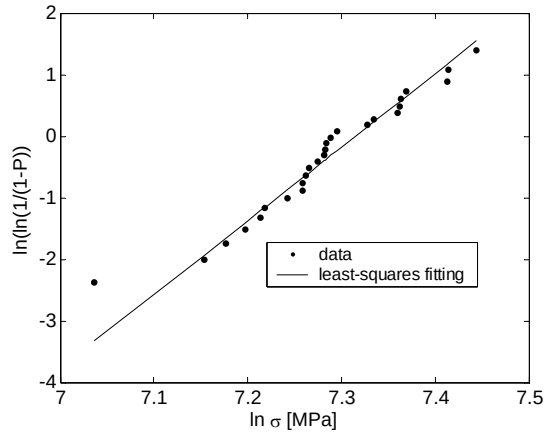


Figure 4.24 - Weibull plot, silane treated E glass fibre ($d=21.4 \mu\text{m}$), length 5 mm

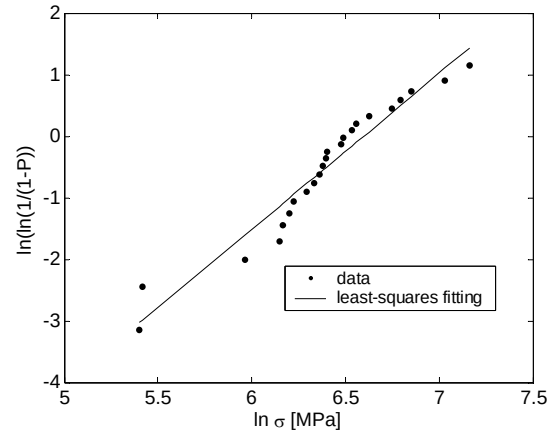


Figure 4.26 - Weibull plot, silane treated E glass fibre ($d=21.4 \mu\text{m}$), gauge length 30 m.

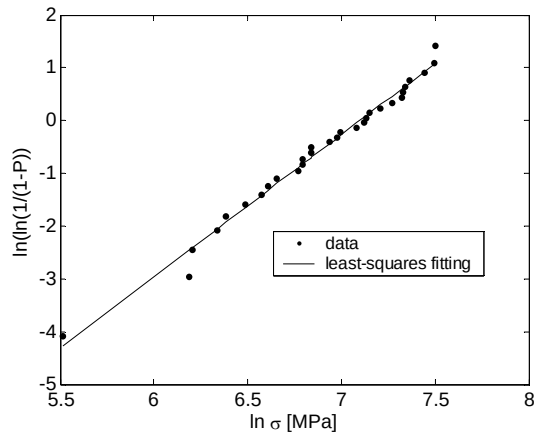


Figure 4.25 - Weibull plot, silane treated E glass fibre ($d=21.4 \mu\text{m}$), gauge length 15 mm

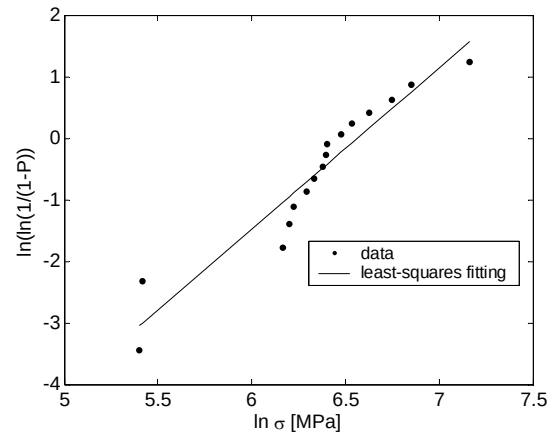
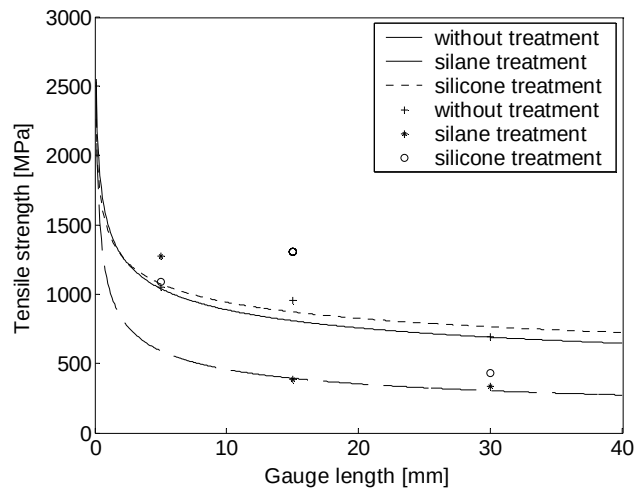


Figure 4.27 - Weibull plot for optic fibre of length 30 mm

The tensile strength resulting of the extrapolation from the Weibull distribution, for the E glass fibre ($d=21.4 \mu\text{m}$) without any treatment and after silane and silicone treatment, are presented on the figure 4.28, in order to observe the effects of surface treatment on fibre mechanical properties. Extrapolation is performed from the equation 4.5 using the Weibull parameters obtained for the tested lengths for which the experimental data were best fitted by the Weibull distribution.

Figure 4.28 - Tensile strength extrapolation to smaller gauge lengths for E glass fibre ($d=21.4 \mu\text{m}$)



In table 4.2 are reported the values obtained from Weibull distribution analysis.

Fibre	5 mm		15 mm		30 mm	
	m	σ_0	m	σ_0	m	σ_0
		[MPa]		[MPa]		[MPa]
Carbon	6.92	4538.1	6.24	4178.1	5.24	3861.9
E Glass ($d=10.8 \mu\text{m}$)	7.44	2645.6	6.49	1941.8	5.27	1818.8
E Glass ($d=21.4 \mu\text{m}$)	4.36	1651.7	5.80	1618.3	5.63	1352.8
E Glass ($d=21.4 \mu\text{m}$)+ Silicone	5.26	1584.4	8.46	1877.1	3.87	1133.6
E Glass ($d=21.4 \mu\text{m}$)+ Silane	11.95	1503.1	2.69	1210.6	3.21	1074.5
Optic fibre					2.62	709.1

Table 4.2 - Weibull parameters obtained by the simple Weibull distribution

Waseem et al. [184] showed that the normal distribution can be useful for the determination of the tensile strength for critical length of fragments, as it does not require any extrapolation. The normal distribution is also used for data fitting. The fitted curves are presented on the figure 4.29.

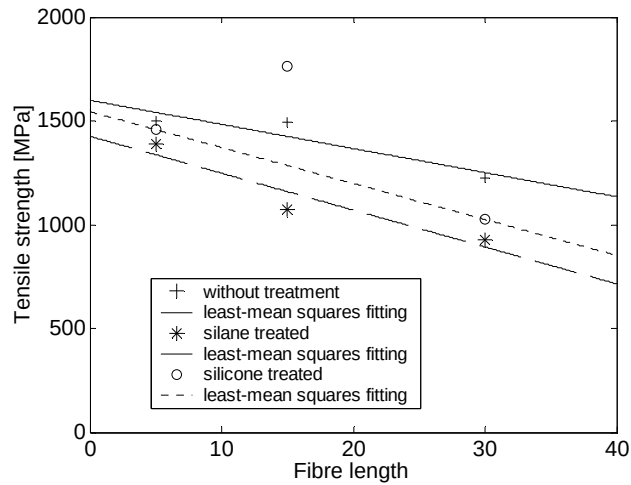


Figure 4.29 - Tensile strength from the normal distribution

For normal distribution fitting, in the case of the 15 mm gauge length silicone treated E glass fibre ($d=21.4 \mu\text{m}$), too high tensile strength values were obtained when comparing to those obtained for 5 mm gauge length. These tests were made from the same lot of fibre, but were not performed in the same day. These results are not taken into account for the data fitting, because the resulting values would be overestimated, and higher values would be obtained than for the untreated fibre.

Fibre	5 mm		15 mm		30 mm	
	Standard Deviation [MPa]	$\bar{\sigma}$ [MPa]	Standard Deviation [MPa]	$\bar{\sigma}$ [MPa]	Standard Deviation [MPa]	$\bar{\sigma}$ [MPa]
Carbon	690.6	4241.4	726.3	3884.0	817.8	3557.6
E Glass ($d=10.8 \mu\text{m}$)	342.1	2482.0	341.5	1808.4	383.6	1675.6
E Glass ($d=21.4 \mu\text{m}$)	352.6	1499.5	262.7	1495.0	309.6	1222.9
E Glass ($d=21.4 \mu\text{m}$) + Silicone	309.1	1458.1	338.8	1765.0	299.0	1025.0
E Glass ($d=21.4 \mu\text{m}$) + Silane	297.7	1388.5	421.8	1073.4	358.1	927.0
Optic fibre					259.1	624.8

Table 4.3 - Normal distribution parameters

In table 4.3 are reported the values obtained from normal distribution analysis of the tensile strengths for the different gauge lengths.

The tensile strength values obtained by extrapolation by the Weibull distribution are higher than the normal distribution results. From the normal distribution results, a slightly lower tensile strength values was obtained for the silicone treated fibres than the untreated fibres, whereas the silane treatment affected more the fibre tensile strength.

The same tendency was observed for the values extrapolated by the Weibull distribution for low fragment lengths. For fragment lengths longer than 5 mm, the extrapolation didn't fit well the data of silicone treated fibres. This suggests that the analysis of the data by the simple Weibull distribution is not the most appropriate.

One of the methods previously described, e.g. including the end-effect [181], should be more adequate. Besides, the number of single fibres tested may not have been sufficiently statistically significant and more single fibre could have been tested. Considering that it is only intended to obtain qualitative information about the fibre tensile strength, the results obtained from the normal distribution can be considered sufficient, as it seems to require fewer fibres to be tested.

Some attention has also been paid to the fibre behaviour after successive loadings. A fibre breaks in two fragments. These fragments were reloaded. It was observed that these fragments have lower tensile strength than fibres with the same gauge length that were not loaded previously. This effect was not quantified due to the not sufficiently statistically significant number of performed tests.

4.6. Fragmentation test

In order to obtain a resin with elongation three time higher than fibre's, an epoxy system constituted of two different epoxy resins with different elongation was chosen. It is constituted of the Wood RX-8 resin, from REApox, and a very flexible and viscous resin, SR 8150 from Sicomin France, with an elongation at rupture around 80%. The resulting resin had an elongation at rupture around 20%. Its hardness was lower than a traditional epoxy resin (Barcol hardness of 20 instead of 30) [187]. However, that is not critical considering the objective of this work. The resin mechanical properties are summarised in the table 4.4.

Resin	Wood RX-8	SR 8150	Mixture
Modulus [MPa]	2950	149	1028.29
Tensile strength [MPa]	62	23	20.73
Stress at break [MPa]	49	23	18.65
Elongation at break [%]	6	83	20

Table 4.4 - Resin tensile properties

The mixture consisted of 50% in mass of each resin system composed of the resin and its respective hardener. To avoid oxygen bubbles formation, the resins were degasified in vacuum and pre-heated, before mixing, to decrease the viscosity of the second resin. The fibre was previously mounted in a silicone mould with the dogbone shape (figure 4.30). The fibre was maintained at the middle of the specimen. It was also prestressed at its extremities, by two little mass of 1.5 g, to guarantee the alignment. Once cautiously filled with the resin, the mould was covered by a glass plate, to guarantee the surface planarity. The resin cured at room temperature during 24 hours, then a post-cured was made, at 40°C during 6 hours and at 60°C during 6 hours. The obtained dogbone tensile specimen's dimensions were 132×10×2.5 mm.

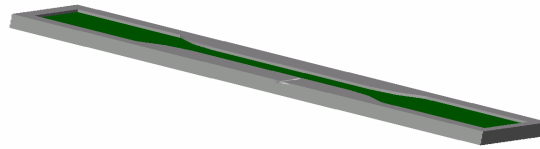


Figure 4.30 - Single fibre specimen mould

The two piezoelectric transducers, described in the previous chapter, were mounted in the central part of the specimen, distant of 50 mm. The monotonic tensile tests were conducted on an Instron® 4208 universal testing machine armed with a 1 kN load cell, according to the ISO 527 standard [188], with a controlled displacement rate of 0.1 mm.min⁻¹. For part of the tests, an extensometer from Instron® was used, to measure the strain suffered by the specimen during testing (figure 4.31). Ten specimens were tested for each configuration until fragmentation saturation (at an elongation around 10%). The

fragmentation saturation was confirmed by acoustic emission monitoring. Microscopic observations were made after testing in an Olympus TH3 optical microscope. When using polarized light, fibre fractures were enhanced. Fragments lengths could be thus measured. Measurements were made for at least five specimens per configuration.

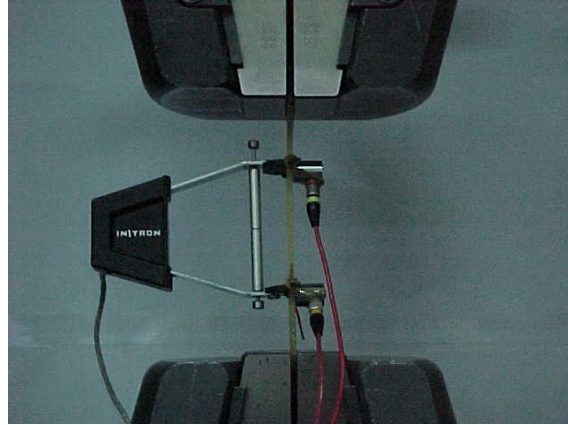


Figure 4.31 - Experimental set-up

4.7. Experimental results

4.7.1. Mechanical test

Typical stress-strain curves derived from the tensile tests are reported in the figure 4.32. Tests were interrupted around 10 % strain.

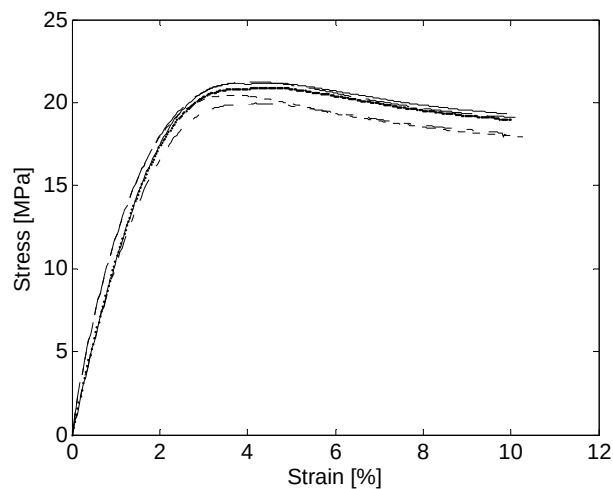


Figure 4.32 - Tensile test curve for the resulting epoxy resin

From the average fragments lengths, reported on figure 4.33 to figure 4.37, it can be noticed that the silane and silicone surface treatment successfully altered the interface characteristics. The silane treatment decreased the reload distance whereas the silicone treatment increased it. Fragment lengths measurements were not performed for the specimen with the optical fibre reinforcement, as saturation was not reached.

The obtained fibre fragment length distributions can be considered as symmetrical, the best fitted normal density function are represented. The critical fragment length can thus be calculated from the equation 4.1. The obtained values are summarised in table 4.5, as well as the extrapolated tensile strength at critical lengths from the normal distribution.

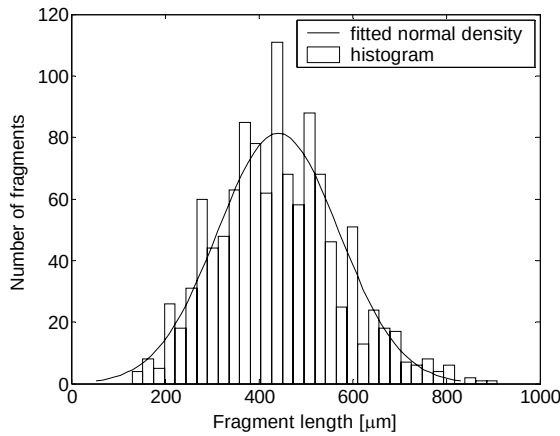


Figure 4.33 - Carbon fibre fragment length distribution

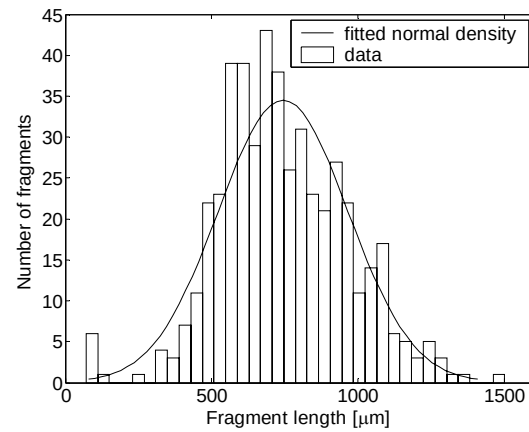


Figure 4.35 - E glass ($d=21.4 \mu\text{m}$) fibre fragment length distribution

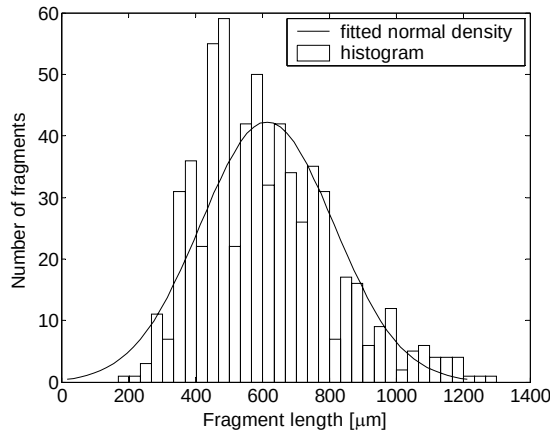


Figure 4.34 - E glass ($d=10.8 \mu\text{m}$) fibre fragment length distribution

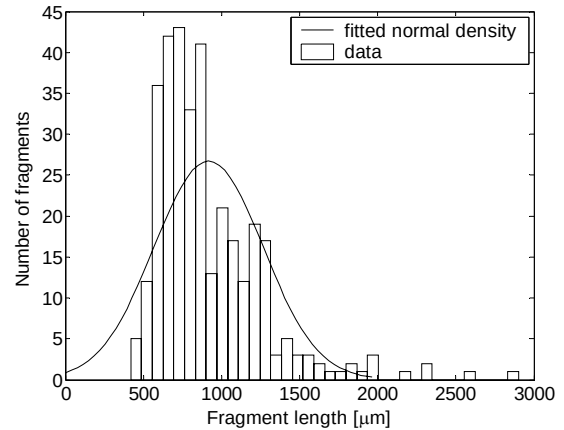
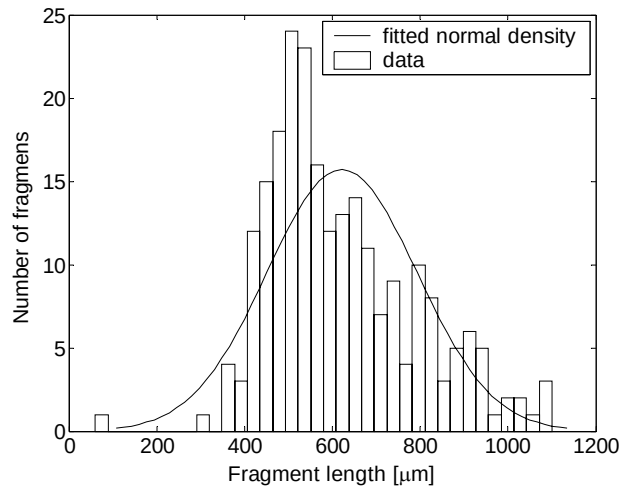


Figure 4.36 - Silicone treated E glass ($d=21.4 \mu\text{m}$) fibre fragment length distribution

Figure 4.37 - Silane treated E glass ($d=21.4 \mu\text{m}$) fibre fragment length distribution

Fibre	$\bar{l}$	l_c	Normal distribution
	$[\mu\text{m}]$	$[\mu\text{m}]$	$\sigma(l_c) [\text{MPa}]$
Carbon	441.8	589.1	4326.9
E Glass ($d=10.8 \mu\text{m}$)	615.0	820	2471.1
E Glass ($d=21.4 \mu\text{m}$)	743.7	991.5	1588.0
E Glass ($d=21.4 \mu\text{m}$)+ Silicone	917.5	1223.3	1523.5
E Glass ($d=21.4 \mu\text{m}$)+ Silane	621.8	829.1	1411.1

Table 4.5 - Experimental results

4.7.2. Optical microscopy

The differences on the mechanical behaviour of the fibre/matrix interface for the various configurations were underlined by the mechanical test results. Optical microscopy inspections were also performed on specimens after testing to verify if these alterations reverberate on the damage process observed at the interface.

The observed damage was quite reproducible for the different configurations. For carbon fibre specimens cracking of the matrix was observed with no significant decohesion (figure 4.38). On the contrary, for glass fibre specimens, for both diameters, no matrix cracking was observed, whereas decohesion was noticed. Along the fibre, debond zones with different size could be observed, as well as different gap lengths

conforming the observation made by Kim et al. [8]. In figure 4.39 to figure 4.41 are presented different debond zone aspects observed in the case of silicone treated glass fibre.

In the case of silicone treated fibre high debonding zones were observed. For the untreated fibre decohesion was also observed but it was less significant. In many cases no decohesion was observed. In those cases, despite the absence of decohesion a fibre gap could be seen. No significant difference was observed for silane treated glass fibre compared to the untreated fibre case. For all cases, different fibre ends were observed (e.g. figure 4.39, figure 4.41), conform previously described by Nordstrom [85].

For optic fibre, huge decohesion was observed at fibre break (figure 4.42).

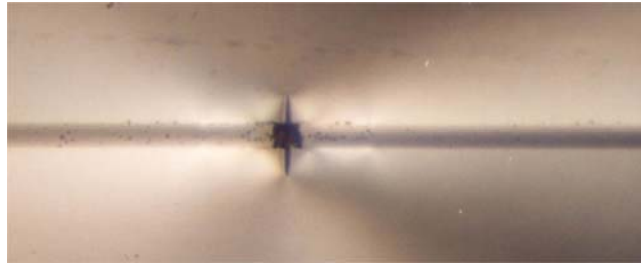


Figure 4.38 - Fibre break on carbon fibre specimen ($\times 400$)

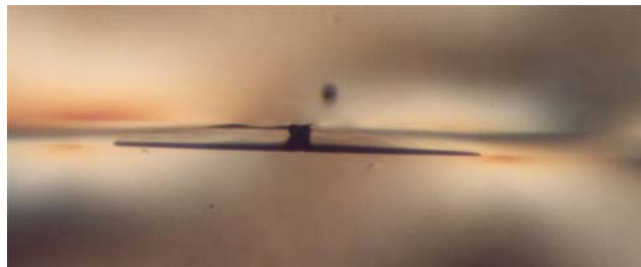


Figure 4.39 - Fibre break in silicone treated glass fibre ($d=21.4\ \mu\text{m}$) specimen ($\times 200$)

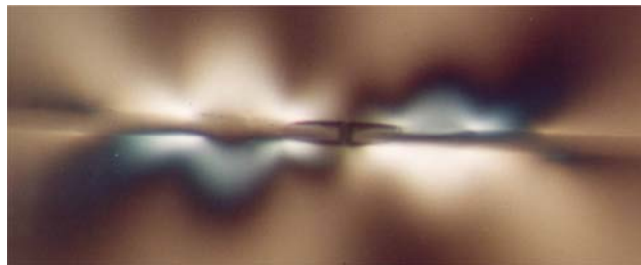


Figure 4.40 - Fibre break on silicone treated glass fibre ($d=21.4\ \mu\text{m}$) specimen ($\times 200$)

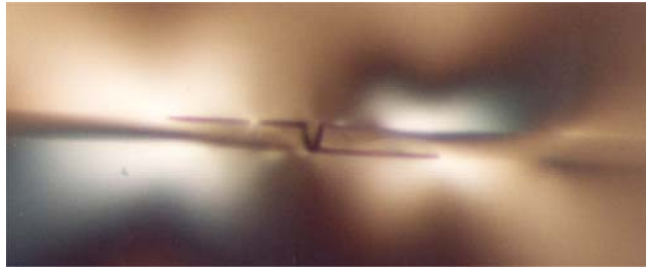


Figure 4.41 - Fibre break on silicone treated glass fibre ($d=21.4\ \mu\text{m}$) specimen ($\times 200$)

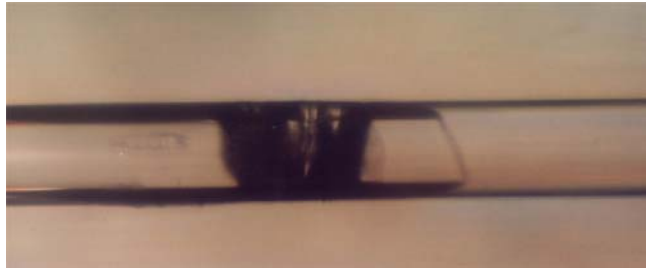


Figure 4.42 - Fibre break on optic fibre specimen ($\times 200$)

Some specimens were maintained under loading for microscopy observation. Doing so, the shear stress state near the fibre breaks could be observed using polarized light. The specimens exhibited birefringence near the fibre breaks and the interface due to shear stress. The photoelastic stress birefringence in glass fibre ($d=21.4\ \mu\text{m}$) is shown in figure 4.43. The birefringence showed symmetric features at both sides of the fibre ends. Such photoelastic birefringence of shear stress was observed around a fibre break with debonding.

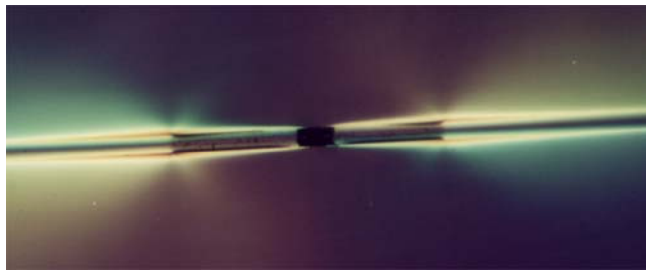


Figure 4.43 - Stress field at fibre break on glass fibre ($d=21.4\ \mu\text{m}$) specimen ($\times 200$)

4.7.3. Acoustic emission analysis

4.7.3.1. Acoustic emission activity

In figure 4.44 and figure 4.45 is represented the acoustic emission activity observed during the tensile test of an E glass single fibre specimen ($d=21.4\ \mu\text{m}$). During this tensile test, acoustic emission, due to cracking, initiated at the remaining air bubbles and noise is observed at both transducers from 1.5% of strain. Higher amplitudes signals are observed at transducer 2. This is due to its resonant nature. The transducer 2 is devoted to data acquisition triggering and location, derived from the arrival-time difference at the two transducers, Δt .

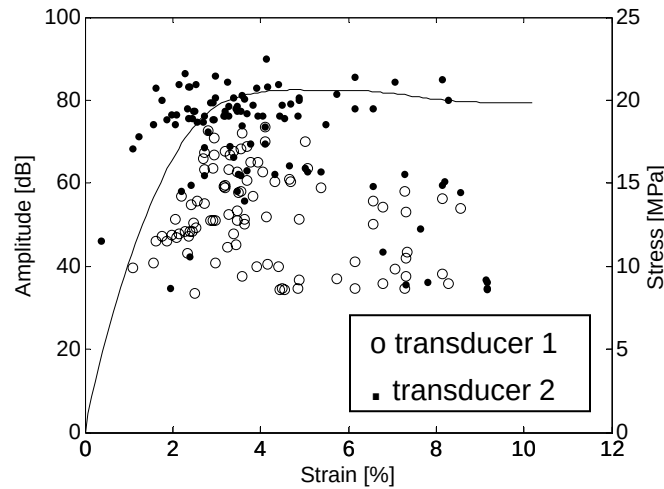


Figure 4.44 - Acoustic emission activity

The arrival-time at each transducer was first determined from the waveform. It is independent of the time the signal amplitude first exceeds the threshold, like in classical location. The so-obtained results are less dependent on the transducers sensitivity. The difference on location results compared to results obtained with the conventional threshold-crossing arrival time determination was not significant, due to the short distance between transducers. Considering that the arrival-time determination from the waveform was computational time consuming, the conventional threshold method was adopted.

The acoustic emission source location precision would be improved using transducers with smaller diameter and two identical broadband transducers what would facilitate the wave propagation modes recognition.

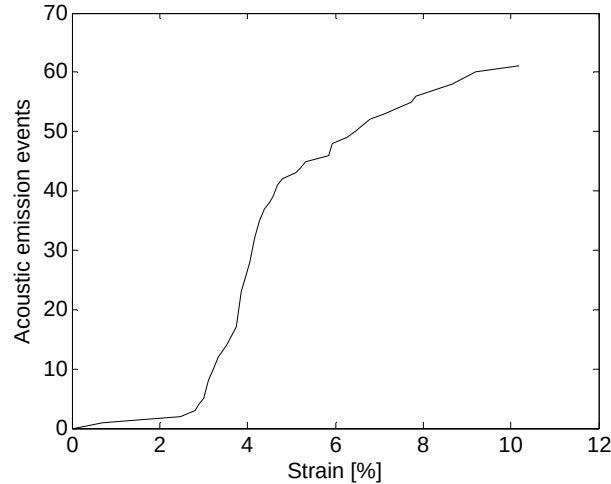


Figure 4.45 - History of acoustic emission events

The evolution of the number of fibre breaks as function of the strain can be observed at figure 4.45, where the cumulative number of acoustic emission events is represented as function of the strain. At 2.5 % of strain the fibre starts to break, the number of breaks strongly increases until 4.5 % of strain. Then new fibre fractures occur but are more spaced in the time, until the saturation.

4.7.3.2. Source location

The transducers were mounted on the central part of the dogbone specimens. They were separated by a distance, D_0 , of 50 mm. In order to perform the source location, the velocity of propagation, C , of the acoustic emission waves was calculated.

Acoustic emission waves were simulated according to the Hsu-Nielsen method, which consists of breaking a pencil lead causing a monopolar event which takes place as the load on the material surface is released according to the ASTM E976 standard [95].

A pencil lead 2H of 5mm diameter was used. At breakage, the pencil leads of 3 mm lengths were oriented at 30° of the material edge. To guarantee the repeatability of the process, a simple jig was mounted at the pencil extremity according to the ASTM E976

standard. Pencil lead breaks at specimen's edge simulated in-plane acoustic emission sources. The measured value corresponds to the extensional wave mode velocity. The average value is reported in the table 4.6.

Pencil lead break location	C [m.ms ⁻¹]	Standard deviation [m.ms ⁻¹]
Specimen surface	1.80	.16

Table 4.6 - Wave velocity

In this study, only the acoustic emission signals located between the two transducers were considered. An individual location algorithm was developed, which takes into account the elongation of the gauge length, $\Delta D(t)$, measured during the tensile test, introducing a correction factor.

The source location, $x(t)$, was determined from the middle of the transducers from the equation 4.9.

$$x(t) = \frac{1}{2} (D_0 + \Delta D(t) - C\Delta t) \quad (4.9)$$

For the source location some assumptions were made, which are not critical considering that the major source of error for location lies in the transducers.

The fact that the acoustic emission waves propagation velocity fluctuates due to the variation of the material stiffness in the propagating direction as the strain increases was neglected. The wave velocity variation as function of the strain is represented in the figure 4.46. It is measured from simulated waves by pencil lead breaks performed on the specimen surface at different strain level. The velocity of propagation tends to decrease with the strain increase, but the decrease is not significant compared to the deviation between each measure. The error bars represent the range of values from the maximum and minimum velocity.

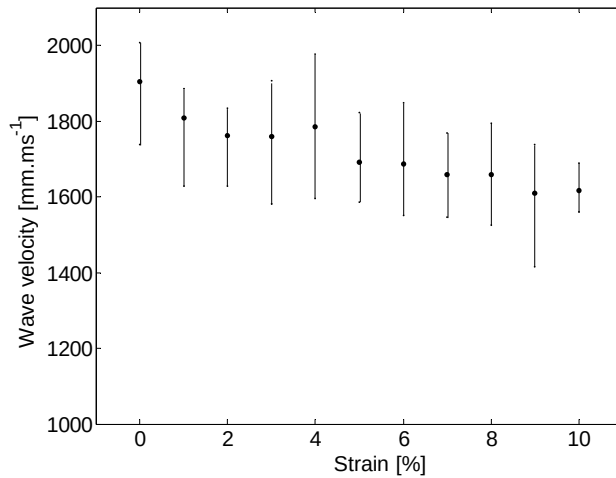


Figure 4.46 - Wave velocity versus strain.

The average velocity value for the unstressed specimen was then considered for the location. An average location error of 0.32 mm is achieved, for simulated source location, what is good considering the pencil lead diameter (5 mm). In figure 4.47 is represented the acoustic emission determined location versus the pencil lead break position.

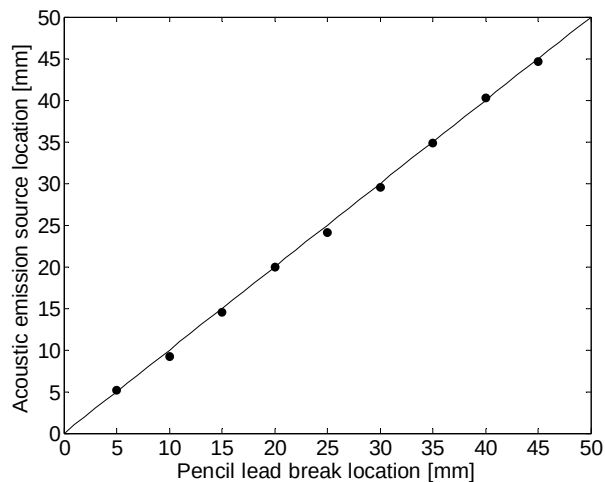


Figure 4.47 - Acoustic emission determined location versus the pencil lead break position

Acoustic emission waves are highly attenuated during the propagation. The different frequencies suffer different attenuation. The amplitude attenuation is noticeable in the figure 4.48, where the amplitude of simulated waves, detected by the broadband

transducer, is represented as function of the pencil lead breaks distance to the transducer. The error bars represent the range of values from the maximum to the minimum velocity.

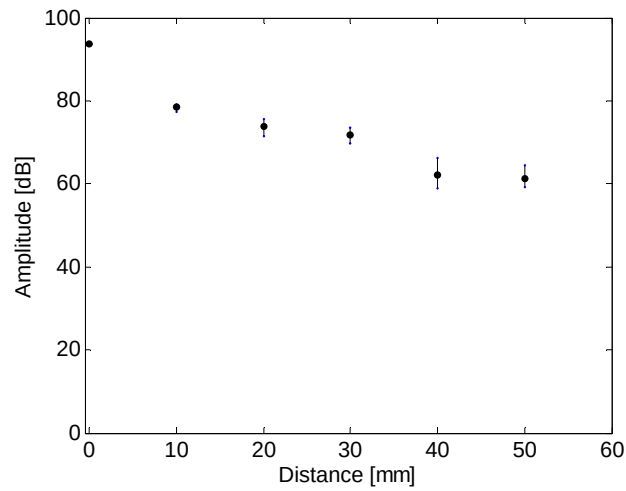


Figure 4.48 - Amplitude versus propagation distances.

Fibre ruptures are uniformly distributed along the specimen length as it can be seen in figure 4.49. Are only considered the events located between the two transducers

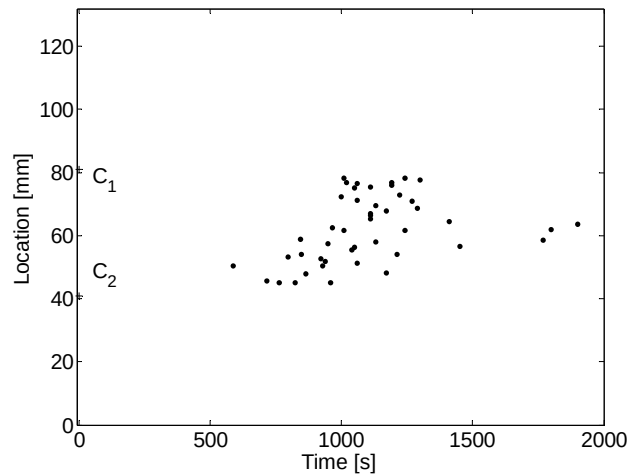


Figure 4.49 - Acoustic emission events location along time

The acoustic emission wave's amplitude varies as function of the fibre break distance to the transducer, in a similar way to the simulated waves (figure 4.50). An important attenuation is observed considering the short distance between the two transducers. The

propagation effects are visible on the acoustic emission waveforms, as well as the difference of attenuation for the different frequencies (figure 4.51).

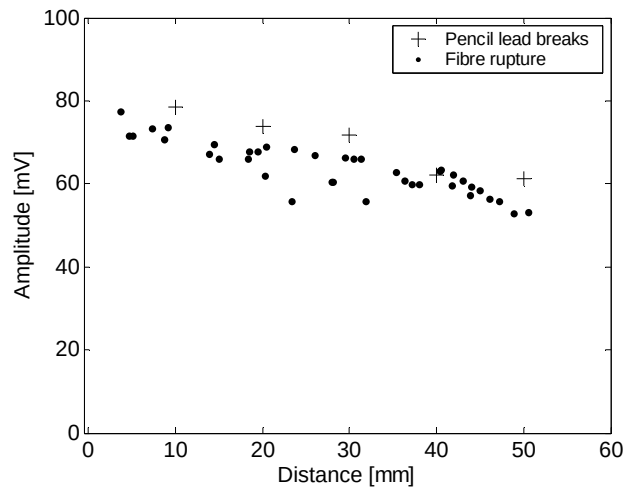


Figure 4.50 - Amplitude of acoustic emission signal generated by the fibre fracture detected by the transducer 1 versus the distance

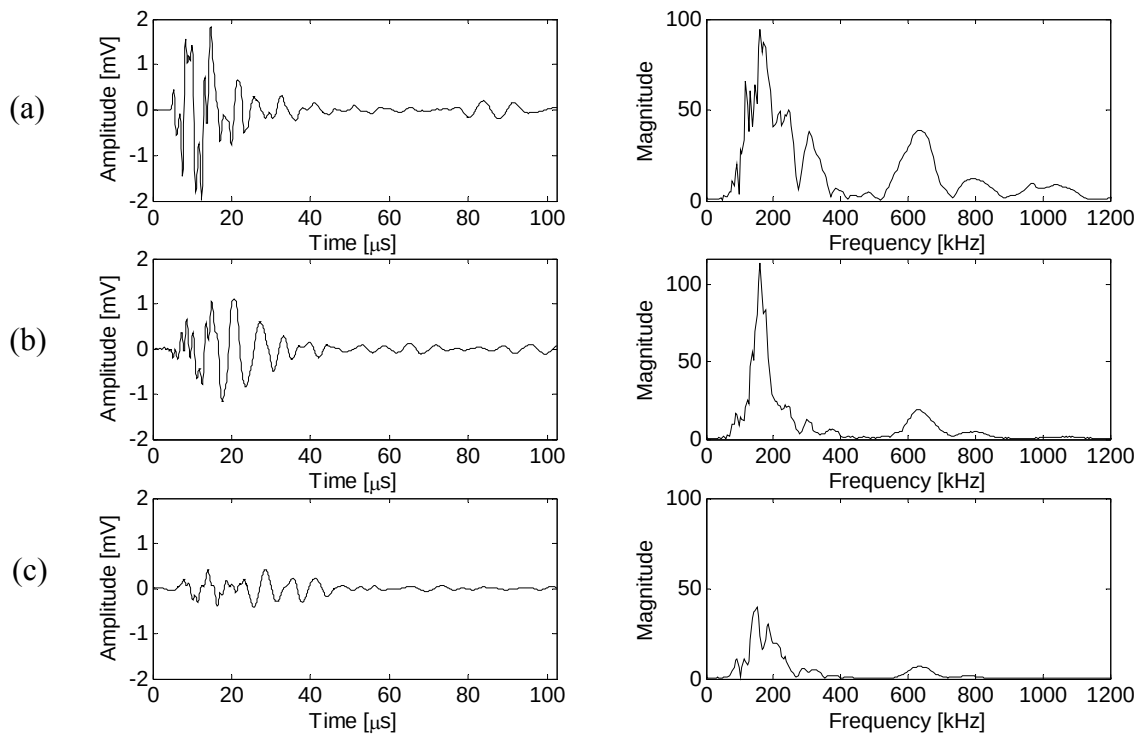


Figure 4.51 - Acoustic emission waveforms and frequency content corresponding to fibre breaks at (a) 0 mm, (b) 20 mm and (c) 40 mm

4.7.3.3. Correlating signals to fibre fracture

The correlation between the cumulative number of acoustic emission events and the number of microscopic fibre fracture observed by optical microscopy was verified (table 4.7). Five different specimens were considered. The specimens were maintained under tension, while fibre fractures were quantified by optical microscopy. The values are quite close. The signals can thus be attributed to the fibres fractures.

The difference may be due to error on microscopy fracture counting, to acoustic emission events overlapping, matrix cracking initiated at remaining air bubbles in the matrix or to the fact that events may occur during the pre-defined time intervals the acquisition is interrupted to avoid acquisition of wave reflections at specimen edges.

Strain level [%]	Fibre fractures	Acoustic emission events
3.9	25	25
3.8	24	27
3.7	44	40
9.9	85	85
10.1	81	84

Table 4.7 - Correlation between acoustic emission events and fibre fractures

The fragments length can be determined from the fibre fracture location. The results obtained by acoustic emission, for the tests performed with extensometer, were compared to the values measured by optical microscopy. The results are summarised in table 4.8.

They are satisfying considering the approximations made for the location and the high transducer diameters. Besides, values obtained by acoustic emission measurement include the gap lengths, which are not considered in the measurements by microscopy. The smaller difference is observed for the silane treated case for which more fibre breaks occurred but smaller fibre gaps were noticed. Low modulus matrix may also generate higher position error due to a higher attenuation that decreases the location precision.

Specimen	Microscopy [μm]	Acoustic emission [μm]
E Glass ($d=21.4 \mu\text{m}$)	730.7	852
E Glass ($d=21.4 \mu\text{m}$)+ Silicone	928.7	1054
E Glass ($d=21.4 \mu\text{m}$)+ Silane	636.6	679

Table 4.8 - Comparison of mean fragment lengths measured by optical microscopy and acoustic emission

4.7.3.4. Energy released at fibre fracture

Fibre fracture process can be modelled by a spring/mass system [1] (figure 4.52). The fibre can be decomposed into m spring/mass elements. Before fracture of one element, it is represented by a spring/mass system of mass $2m$ and stiffness $k = ES/l_t$, where E is the Young modulus of the element, S the surface of rupture created, and $2l_t$ is the transfer length (decohesion length). Fracture is represented by the separation of the mass $2m$ into two masses m . At fracture, the force imposed to the element is $F = \sigma_u S$, where σ_u is the fibre stress at rupture. The fracture creates a discontinuity $\Delta F(t)$, of the force in this element, of amplitude $\sigma_u S - R_t$. The force R_t takes into account the interaction after fracture of the damage area and the neighbourhood zone.

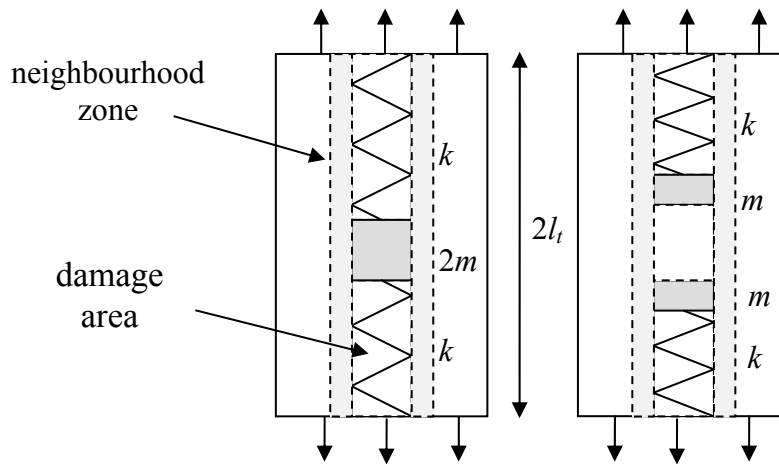


Figure 4.52 - One-dimensional model of rupture [1]

The energy released at each side of the fissure is given by the relation:

$$\Delta W_u = \frac{1}{2} \frac{\sigma_u^2}{E} S l_t \left[1 - \frac{R_t}{\sigma_u S} \right]^2 \quad (4.10)$$

This relation shows that the released energy at fracture depends on:

- the nature of the damage mechanism
- the surface of damage
- the decohesion length
- the interaction of the fissured and the neighbourhood area (adhesion)

4.7.3.5. Relating acoustic emission waves to specimen configuration

The signals characteristics were studied to establish relationships between the acoustic emission signals and their sources. Signals were visually classified. The signal spectrum was calculated from the fast Fourier transform using MATLAB. It has been previously observed that the acoustic emission waveforms are highly influenced by the propagation. For this purpose, only the signals located under the broadband transducer and in its vicinity were considered.

For location, the transducers are considered as points. Their diameter is thus neglected. In consequence the location uncertainty is higher in their vicinity. It is then difficult to precisely associate given signals to an observed fibre rupture, without in-service visual observations. However, the reproducibility of the signal waveforms and fracture aspects, meticulously observed by optical microscopy, permitted to underline certain patterns with significant statistical meaning.

4.7.3.5.1. Interface influence on acoustic emission

In figure 4.53 is represented the typical waveform and its frequency content detected, at fibre break when the untreated E glass fibre ($d=21.4 \mu\text{m}$) was used as reinforcement. The observed fibre fractures didn't exhibit decohesion. Typically, fibre gap length was $10 \mu\text{m}$.

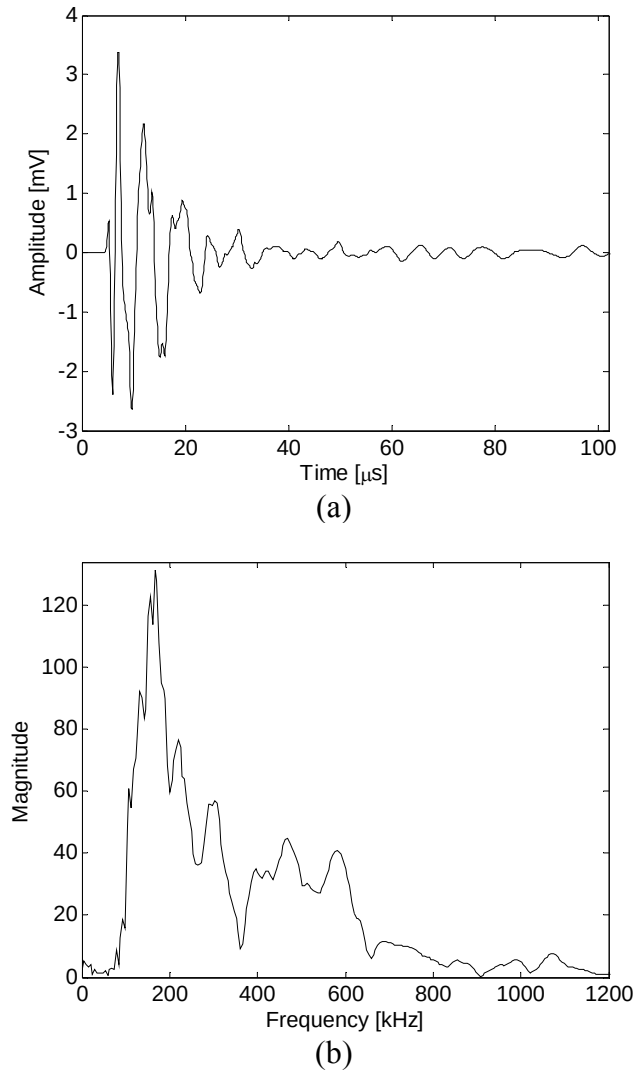
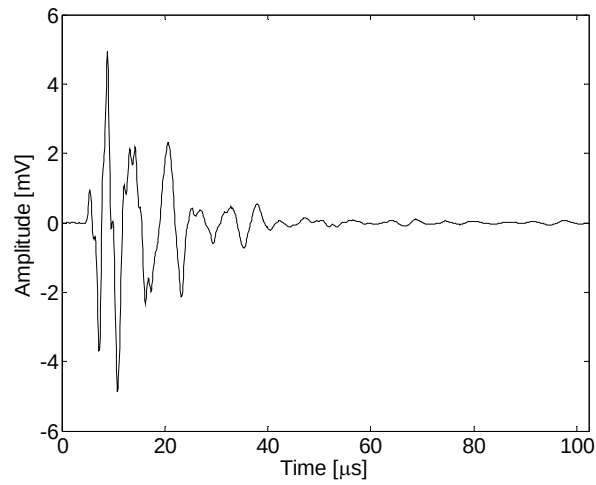
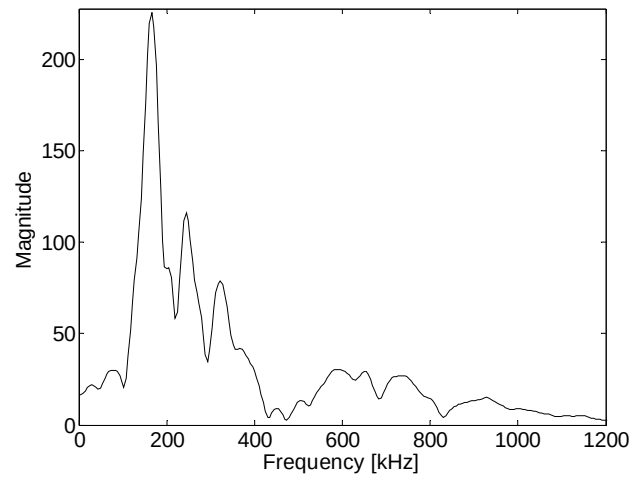


Figure 4.53 - (a) Typical waveform and (b) its spectrum corresponding to the E glass ($d=21.4 \mu\text{m}$) fibre break without debonding

The signal detected at fibre break without debonding has a frequency peak around 180 kHz. This frequency is closed to the frequency of resonance of the second transducer (250 kHz). It is important to confirm that the second transducer which is in contact with the surface of the material doesn't modify the propagating ultrasonic wave or load this surface. To guarantee it, some tests were performed with only the broadband transducer mounted in the middle of the specimen. Signals with the same characteristics were observed (figure 4.54). This permits to confirm that the signal detected by the broadband transducer is not influenced by the transducer 2.



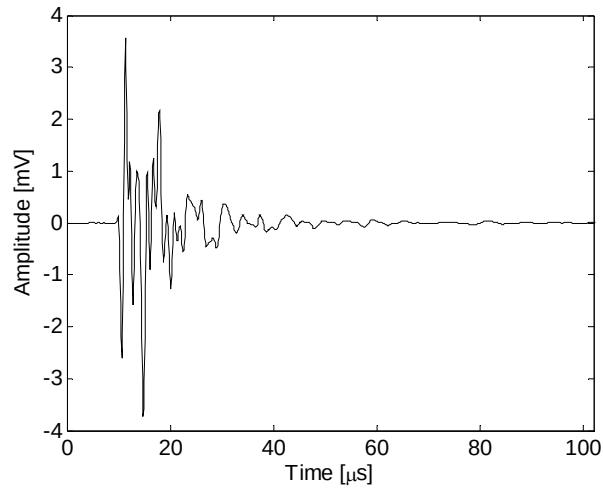
(a)



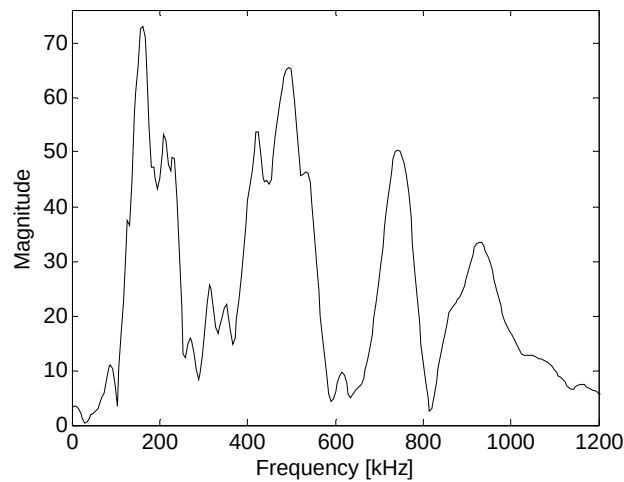
(b)

Figure 4.54 - (a) Typical waveform and (b) its spectrum at fibre break without debonding (untreated E glass ($d=21.4 \mu\text{m}$) specimen)

When debonding was observed different acoustic emission waveforms were detected (figure 4.55). Comparing the frequency content of this signal to the previous, two peaks appear on the frequency range 400-600 kHz and 600-800 kHz that were not apparent when no debonding occurred. This must be related to the higher freedom of the fibre ends that may oscillate at fibre break when there is decohesion. In figure 4.56, is represented a waveform detected when a long fibre gap is observed but no decohesion. The spectrum presents a peak in the 600-800 kHz frequency range.



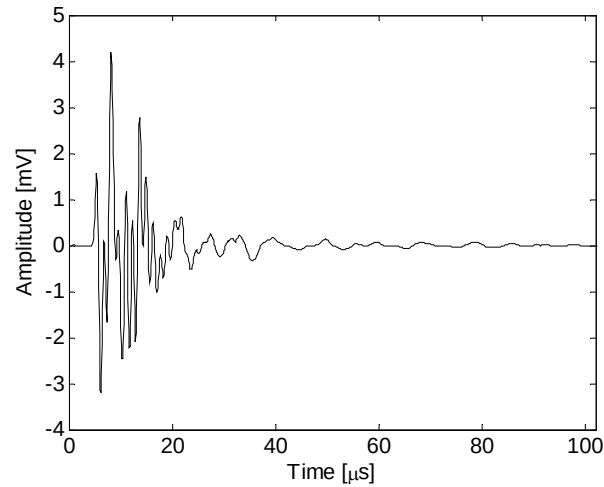
(a)



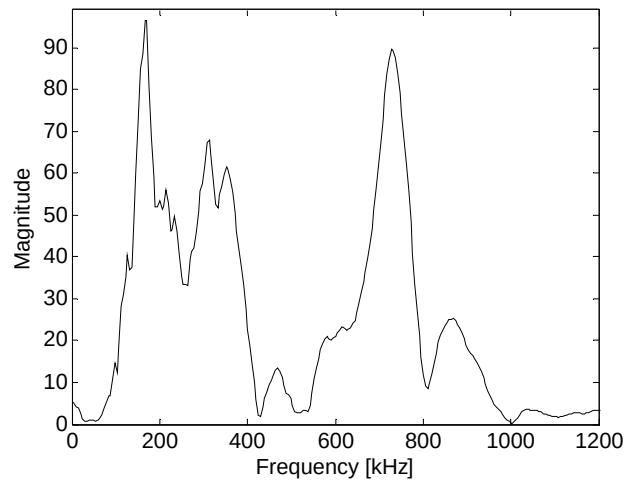
(b)

Figure 4.55 - (a) Typical waveform and (b) its spectrum observed at fibre break with decohesion (silicone treated E glass ($d=21.4 \mu\text{m}$) specimen)

When decohesion occurred, the detected acoustic emission waveforms were less reproducible. A reason can be given by the microscopy observations, which permitted to see that decohesion zones (e.g. figure 4.39 to figure 4.41) showed various aspects. Kim et al. [8] observed that decohesion zone size created at fibre break varies as function of the strain. The fibre oscillation at fibre break will depend on the decohesion size.



(a)



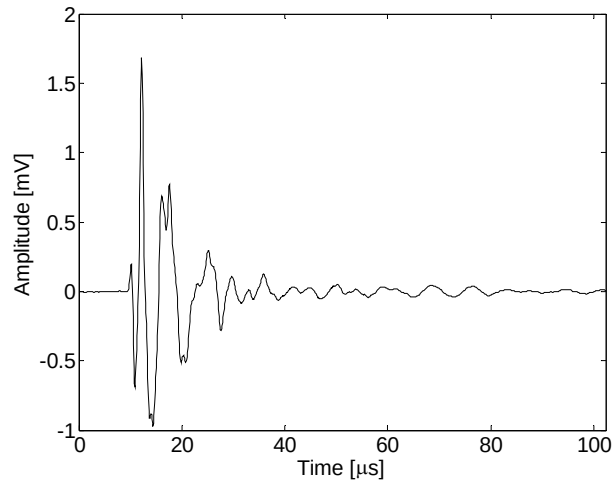
(b)

Figure 4.56 - (a) Typical waveform and (b) its spectrum observed at fibre break with long gaps (untreated E glass ($d=21.4 \mu\text{m}$) specimen)

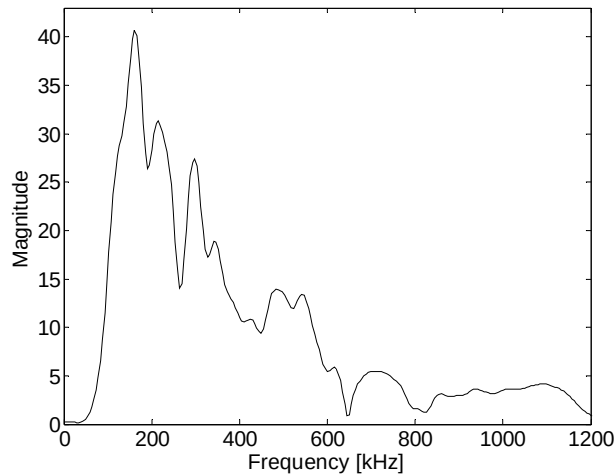
As showed previously, the released energy at fracture is proportional to the crack area and, in this case, to decohesion area. The acoustic emission energy could be used to monitor decohesion area and observe the evolution of decohesion area. However, due to the high attenuation observed with this matrix, it was not possible to find any correlation between the energy and the time of occurrence of the damage.

4.7.3.5.2. Fibre influence on the acoustic emission signals

In the case of E-glass ($d=10.8\ \mu\text{m}$) specimens no decohesion was observed and in many case any fibre gap neither. The detected acoustic emission waveforms have the same trend than the waveform detected for the E glass fibre with higher diameter. However, lower amplitude signals were detected.



(a)

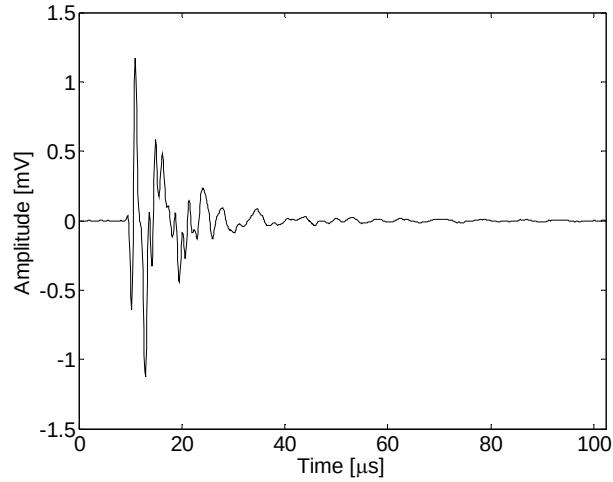


(b)

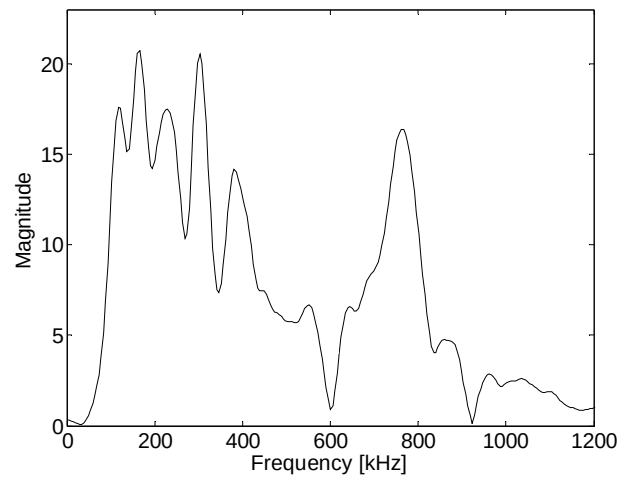
Figure 4.57 - (a) Typical waveform and (b) its spectrum observed at fibre break without decohesion (E glass ($d=10.8\ \mu\text{m}$) specimen)

In figure 4.58 is represented a typical signal detected when carbon fibre specimens were loaded under tension. The observed fibre breaks (figure 4.38) showed significant

fibre gaps and a matrix cracking that must have occurred simultaneously with fibre fracture. Higher frequency components are observed in the signal that must be related to the existence of this longer fibre gap and to the matrix cracking.



(a)



(b)

Figure 4.58 - (a) Typical waveform and (b) its spectrum observed at carbon fibre break

A typical acoustic emission signal detected when optical fibre fractured is represented in figure 4.59. The detected waves saturated the acoustic emission acquisition system.

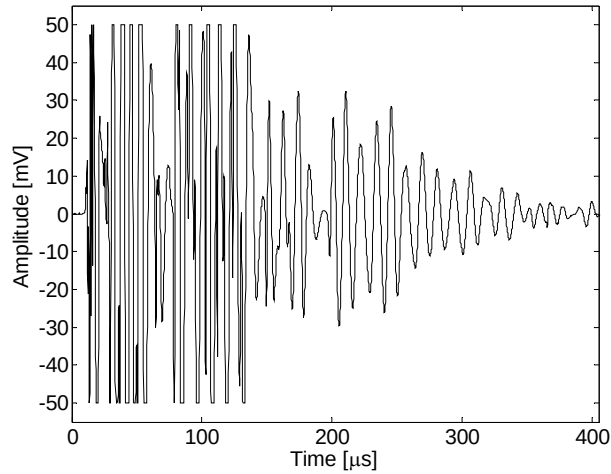


Figure 4.59 - Waveform observed at optical fibre break

4.8. Discussion

The main objective of this chapter was to get a better understanding of the acoustic emission event. For that purpose well defined events, whose characteristics could be changed, were generated. In the case of the single fibre specimen this was done changing the fibre diameter, its nature and the interface.

In table 4.9 are summarized the average values of the acoustic emission signals amplitude detected in the different configurations as well as the mechanical characteristics of the fibres. There is no apparent correlation between the fibre mechanical characteristics and the mean amplitude. For carbon fibre ($d=6.9 \mu\text{m}$) a slightly higher amplitude is observed than for the fibre glass ($d=10.8 \mu\text{m}$), but the difference is not relevant compared to the dispersion of the measured values. Acoustic emission amplitude depends clearly on the fibre diameter.

Concerning the frequency content, signals with higher frequency components were detected when decohesion occurred at fibre fracture and when long fibre gaps were observed. The higher frequency range is clearly related to the higher freedom of the fibre ends at fracture.

Specimen	Average Amplitude [dB]	Young's Modulus [GPa]	$\sigma(l_c)$ [MPa]
Carbon ($d=6.9 \mu\text{m}$)	59.9	232.2	4326.9
E Glass ($d=10.8 \mu\text{m}$)	57.6	74	2471.1
E Glass ($d=21.4 \mu\text{m}$)	73.7	73.5	1588.0
E Glass ($d=21.4 \mu\text{m}$) + Silicone	72.0	67.0	1523.5
E Glass ($d=21.4 \mu\text{m}$) + Silane	73.2	46.7	1411.1
Optic fibre	> 93.8	36.5	

Table 4.9 - Acoustic emission amplitude for different fibres

When comparing the different signal waveforms observed for the different configurations, similarities are obvious (e.g. figure 4.53 and figure 4.58). This suggests that it could be judicious to remove the dependence of the waveform on the piezoelectric transducer by a deconvolution of its transfer function.

The transfer function of the transducer is sometimes deduced from the answer of the transducer to a pencil lead break fracture directly on the transducer face or on the material. In this dissertation, such method was not adopted as the impulse due to pencil lead break has a rise time longer than $0.5 \mu\text{s}$ [189], hence the answer of the transducer to higher frequencies wouldn't be obtained. To get a significant knowledge of the transfer function of the transducer, it would be necessary to have two transducers with similar transfer function to perform calibrations such as the face-to-face test.

Chapter 5

Pattern clustering

During acoustic emission testing, a large amount of data is acquired. Their analysis is not straightforward. Advanced user-friendly pattern recognition softwares are proposed by acoustic emission system manufacturers [190,191] to enhance the data treatment. However, commercial softwares provide limited control to the user. In this work, the programming and visualisation capabilities of MATLAB are used to overcome this limitation. A clustering methodology was developed based on artificial neuronal networks and statistical methodologies. It is presented in this chapter.

5.1. Pattern recognition

Pattern recognition is a branch of artificial intelligence concerned with the classification and description of observations. A complete pattern recognition system involves transducers, pre-processing, feature extraction, classification and post processing.

The transducers detect the acoustic emission waves to be classified. The pre-processing increases the quality of data, performing data normalization, noise removal and/or other transformations.

The goal of feature extraction is to compute numeric or symbolic information from the signals. Features or descriptors whose values are very close for signals in the same classes and very different for signals in different classes are chosen to optimize the pattern recognition system efficiency. The features are regrouped into a feature vector whose components must be as independent as possible. The signals are thus represented by a multivariable vector.

The classifier assigns the feature vector to a certain pattern, determining its probability of belonging. The classifier is fitted to data in a process known as the training. They are different learning strategies for the training. In the case of the supervised classifier, the classes are known a priori. The classifier is trained from a group of signals with well-

known and wanted characteristics. Once trained, the classifier can classify the input signals as function of their similarities with the characteristics of the pattern signals. The unsupervised classifiers work differently, as the classes are not known a priori. The purpose of an unsupervised algorithm is to discover patterns among the input data without any “teacher”. The system forms clusters or natural grouping of the input sharing some common characteristics.

There are different clustering algorithms which will lead to different clusters. Optimal clustering is a partitioning that minimizes distances within and maximizes distances between clusters. The classification scheme may use statistical, structural, or neural approach [192]. Statistical pattern recognition is based on statistical characterisations of patterns, assuming that the patterns are generated by a probabilistic system. Structural pattern recognition is based on the structural interrelationships of features. Neural pattern recognition employs the neural computing paradigm that has emerged with neural networks.

The post-processor uses the output of the classifier to decide on the recommended action. A simple action is the validation or measurement of the classifier performance calculating the classification error rate, i.e. the percentage of wrong assignment of new signals. It is thus common to seek minimum-error-rate classification.

5.2. Literature review

In literature, successful applications of statistical and neural network algorithms to acoustic emission can be encountered. Some of the most significant are briefly presented.

5.2.1. Statistical analysis

The studies involving statistical pattern recognition are mostly dedicated to damage discrimination.

Ono et al. [193] used a supervised classifier (the k -nearest neighbour) to correlate the signals to the different failure modes observed during testing of unidirectional, cross-ply and mat carbon/epoxy composites as well as cross-ply glass/epoxy laminates. A previous visual classification of detected signals during preliminary tests was performed. Six and

three different signal types were so defined in the case of the carbon/epoxy and glass/epoxy, respectively. The classifier was then applied to data obtained during tensile tests. This method suffers of its high dependence on practitioner during the visual classification.

Anastassopoulos et al. [194] used the Maxmin distance (unsupervised method) [195] for a primary classification of data. The resulting cluster centres were used as initial conditions for the application of a modified version of k -means (the Forgy algorithm) for signal classification. Acoustic emission signals were detected during testing of glass/epoxy and carbon/carbon specimens. Signals were represented by a four component feature composed of signal parameters (rise time, amplitude, amplitude/decay time, rise time/duration). Six different classes were so identified. Their respective evolutions during the loading were studied along the test. So, the authors could establish a criterion of approach of rupture. Anastassopoulos and co-authors applied similar statistical pattern recognition methodology to the monitoring of more complex composite structures such as wind turbine blades [196,197,198,199].

Papas et al. [200,201] also used the k -means classifier for monitoring of centre-hole 2D carbon/carbon during quasi-static and dynamic-cyclic loading. Correlation between clusters and specific material failure modes was achieved. Five acoustic emission descriptors were used: amplitude, energy, duration, counts, and rise time.

Loutas and co-authors [202,203] investigate the failure mechanisms in a new type of oxide/oxide composite material. They used various unsupervised algorithms configuration (Maxmin Distance-Forgy, Maxmin Distance-Cluster Seeking, Main Distance-Isodata, k -means) proposed in a commercial software [190] and evaluate their performances. K -means was used alone, since it does not demand initial conditions. The obtained clusters were associated to damage visualised in scanning electronic microscopic observations of the fracture surfaces.

Johnson [204] studied the clustering ability of principal component analysis. Glass/epoxy laminates with different lays-up were studied under tensile testing. Damage mechanisms such as matrix cracking and delamination were observed. The entire acoustic emission waveform was used as input to the classifier. Once the clusters defined, the acoustic emission transients were classified using a supervised method (Soft Independent Modelling of Class Analogy). Proceeding so, the author could distinguish the signals due

to matrix cracking and local delamination. Furthermore, it was possible to separate different types of matrix cracking signals and different delamination signals (delamination initiation or prior to rupture).

Huguet [171] and Godin et al. [205] used a combination of an unsupervised pattern recognition scheme (k -means) with the supervised k -nearest neighbours to discriminate the damage mechanisms occurring during the loading of an unidirectional glass/polyester composite. The k -means method was used for data clustering and the k -nearest neighbours for classification. The k -nearest neighbours classifier was compared to the self-organizing map. They showed a good agreement but the former was easier to use.

5.2.2. Artificial neural networks

Neural networks have also been successfully applied for acoustic emission analysis in the case of composite and non-composite materials with different purpose. They have been extensively used for metal machining process monitoring and tool wear inspection [206,207,208,209,210,211,212,213,214,215,216,217,218].

In the case of composite material, the association of acoustic emission and neural networks was used for residual strength prediction [219,220], pressure vessel burst pressure prediction [221,222], leak monitoring [223,224], source location improvement [135,136,137,223,224], noise discrimination [225], waveform estimation [226] and damage discrimination. This last case is under the topic of this dissertation.

Artificial neural networks revealed to be a useful tool for acoustic emission signal clustering and classification. Most of the work involving acoustic emission and neural network was performed in laboratory, with the perspectives to propose real-time procedures for damage detection in complex fibre reinforced plastic structures. Different approaches were considered (e.g. different artificial neural network architecture, signal features).

Philippidis et al. [227] used a modified learning vector quantization algorithm for signals classification, for phenomenological correlation with failure modes occurring in woven carbon/carbon laminates. Acoustic emission signals were represented by a seven set feature vector (Amplitude, Rise time, Energy, Amplitude/Duration, Rise time/Duration, Counts to peak/Counts, Decay counts/Counts to peak). The authors could

determine a reliable criterion for structural integrity assessment from the signals classification.

Kouroussis et al. [196] applied an unsupervised pattern recognition procedure (k -means) to acoustic emission data obtained during the first static loading of a wind turbine blade. The criticality of the so-obtained classes was assessed. A supervised classification (multilayer perceptron neural network using backpropagation learning algorithm) was then performed to the acoustic emission events detected during fatigue testing of the same blade. The supervised classifier was trained from the results of the k -means classifier. The authors noted the higher need of pattern recognition techniques in the case of fatigue loading due to the acoustic emission analysis complexity increase.

Huguet et al. [171,205,228] applied the unsupervised self-organizing map of Kohonen to the classification of feature vectors constituted of six acoustic emission signal parameters (Amplitude, Rise time, energy, Counts, Duration, Counts to peak). Signals were detected in unidirectional glass fibre reinforced polymer composites. Three signal types were identified and attributed to matrix cracking, fibre/matrix decohesion and fibre ruptures.

Bhat et al. [229] developed a procedure for acoustic emission analysis in noisy conditions such as those encountered in monitoring of in-flight aircraft. A hybrid neural network was proposed. Clusters identified from a self-organizing map were used as a priori information for training of a multi-layer perceptron using back-propagation algorithm. Signals were characterised by four parameters: the amplitude, rise time, counts and energy. Fatigue tests were performed on carbon fibre reinforced plastic laminates. Six classes of signals were identified to be due to damage and attributed to matrix cracking, fibre/matrix cracking and fibre failure.

Bar et al. [230] adapted this methodology to the analysis of acoustic emission signals detected by polyvinylidene fluoride film sensors mounted on the surface of glass fibre reinforced plastic composites under static loading. Unidirectional, cross-ply and angle-ply laminates were tested. Three classes were identified corresponding to the three observed damage mechanisms (matrix cracking, fibre/matrix cracking and fibre failure).

5.2.3. Conclusion

From the literature review, it appears that the application of pattern recognition methodologies to acoustic emission signals provides more refined information about damage sources. It permits to classify the acoustic emission signals, whose parameters are highly overlapping.

Unsupervised learning revealed to be the most appropriate methodology for acoustic emission signal analysis due to the fact that the same damage may have different characteristics depending on where it occurs, how it evolves. It is then difficult to have a concrete a priori knowledge of acoustic emission signals.

Two unsupervised learning methods, the k -means statistical procedure and the self-organizing map neural network, were the most used in acoustic emission signal analysis.

In the table 5.1 are summarised the investigations reported in this literature review. The adopted methodologies are listed.

Authors	Features	Classifier
Ono et al. [193]		- Visual classification - k -nearest neighbours
Anastassopoulos et al. [194]	Amplitude, Rise time, Amplitude/Decay time, Rise time/Duration	- Combination of the max-min (initial segmentation) and Forgry (optimized segmentation) algorithms
Papas et al. [200]	Amplitude, Rise time, Counts, Duration, Energy	- k -means
Koustopoulos et al. [203]	(Selected features vary from classifier to classifier). - Amplitude, Rise time, Counts, Duration, Amplitude/ Duration, Counts to peak, Average frequency, Initiation frequency, Rise angle.	- Maxmin Distance/ Forgry, - Maxmin Distance/Cluster Seeking, - Main Distance/Isodata - k -means
Johnson [204]	Waveform	- Principal component analysis
Huguet [171]	Amplitude, Rise time, Counts, Duration, Counts to peak, Energy	- k -means - k -nearest neighbours - Self-organizing map
Philippidis et al. [227]	Amplitude, Rise time, Energy, Amplitude/Duration, Rise time/Duration, Counts to peak/Counts, Decay counts/Counts to peak	- Classifier: learning vector quantization algorithm
Philippidis et al. [231]	Amplitude, Rise time, Counts, Duration, Energy, Average frequency, Counts to peak	- Feature number reduction by principal component analysis - Classifier: learning vector quantization algorithm
Bhat et al. [229]	Amplitude, Rise time, Counts, Energy	- Self-organizing map - multi-layer perceptron using back-propagation algorithm
Bar et al. [230]	Amplitude, Rise time, Duration, Counts	- Self-organizing map - multi-layer perceptron using back-propagation algorithm
Kouroussis et al. [196]	Amplitude, Rise time, Duration, Energy, Average frequency, Counts to peak	- Clustering: k -means, learning vector quantization algorithm - Classification: multi-layer perceptron using back-propagation algorithm

Table 5.1 - Analysis review

5.3. Clustering methodology

In this study a two-level approach is considered for data clustering. Data set is first clustered using the self-organizing map, and then, the self-organizing map is clustered using k -means. This procedure permits a considerable computational load decrease, making possible the clustering of large data sets [232]. This approach facilitates the quantitative analysis of data improving the interpretation of the clustering made by the self-organizing map. Similar approach was used by Huguet [171] in the case of $[\pm 35/\pm 55]$ glass-fibre/polyester laminates.

The self-organizing map is used in exploratory phase of data analysis because of its prominent visualization properties. The self-organizing map projects high-dimensional inputs into a two-dimensional regular grid that can be effectively utilized to visualize and explore the properties of the data.

5.3.1. Artificial neuronal networks theory

The artificial neuronal networks are information-processing paradigms inspired by the way the human brain processes information. A neural network is a massively parallel distributed processor made up of simple processing units (the neurons), which has a natural propensity for storing experimental knowledge and making it available for use. Despite the simplicity of each processing unit, the use of a high number of neurons guarantees the execution of many tasks.

A neuron is an information-processing unit that is fundamental to the operation of an artificial neuronal network. The non-linear model of the neuron is represented in the figure 5.1. The neurons are connected by links or synapses, each of which is characterized by a weight. An input, x_j , of synapse, j , connected to a neuron, k , is multiplied by the synaptic weight, w_{kj} , which modulates the effect of the associated input. A pondered sum of the input signals weighted by the respective synapse of the neuron is performed. The neuron transmits an activity level. The final answer of the neuron is the result of the non-linear function of activation, that may be the Heaviside function, but the more used is the sigmoid function.

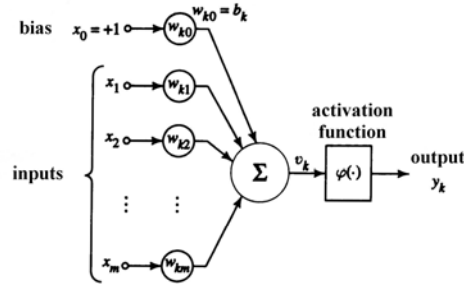


Figure 5.1 - Non-linear model of a neuron

The most important property of the neuronal network is its ability to learn from its environment, assuring an improvement of its performance. It results from an iterative process of adjustment of its weights (the training). The different artificial neuronal network architectures are defined as function of the connection types between the neurons. The most known are the multilayer perceptron, the radial basis function network, and the self-organizing map of Kohonen [233,234]. Those artificial neuronal networks have different learning algorithms. The multilayer perceptron and the radial basis function network are supervised classifiers, whereas the self-organizing map is an unsupervised classifier.

5.3.2. The self-organizing map

The self-organizing map [233] is the most popular artificial neural network algorithm in the unsupervised learning category. It solves difficult high-dimensional and nonlinear problems such as feature extraction and classification patterns. Besides, it is one of the most realistic models of the biological brain function. Self-organizing map is unique in the sense that it can be used at the same time both to reduce the amount of data by clustering, and to construct a nonlinear projection of the data onto a low-dimensional display, permitting a good visualization of clusters.

The self-organizing map transforms an input signal in a uni- or bi-dimensional discrete map, and executes an adaptive transformation into an ordered topology. The proposed network architecture consists of a two-dimensional array of $l=p \times q$ units.

Each unit j is represented by a b -dimensional prototype vector $w_j = [w_{j1}, w_{j2}, \dots, w_{jb}]$. The map adjusts to the data by adapting the prototype vectors. Together the set of prototype vectors form a two-dimensional representation of data.

An input pattern with n features, x_i , is represented by a pattern vector $x = [x_1, x_2, \dots, x_n]^T$. All inputs are connected to all output layer nodes. The output layer neurons are interconnected.

The network is trained by an iterative algorithm. Two algorithms are used: the sequential and the batch training which proceed as follows [235]:

5.3.2.1. Sequential algorithm

(1). Randomly initialise all the weights values between 0 and 1.

(2). Randomly select an input vector x ; present it to all neurons of the network and evaluate the corresponding quadratic distance, d_j , according to the relation:

$$d_j = \|x - w_j\|^2 = \sum_{i=1}^b (x_i - w_{ji})^2 \quad (5.1)$$

(3). Select the neuron with the minimum output, d_j , as the best matching unit, i.e. the nearest neuron to the input vector. The output of the winning neuron of index j^* is:

$$d_{j^*} = \min_{j^* \in [1 \dots I]} \|x - w_j\|^2 \quad (5.2)$$

(4). Update the neurons weights according to the expression:

$$w_j(k+1) = w_j(k) + \alpha(k) h_{jj^*}(k) [x - w_j(k)] \quad (5.3)$$

where k is the learning iteration count and $\alpha(k)$ is the learning rate. h_{jj^*} is the neighbourhood function centred on the winner unit. It is of high importance, as it

translates the map's topology forming. h_{jj}^* is symmetric and with monotonously decreasing amplitude with increasing distance to the best matching unit. The Gaussian function satisfies these requirements. Both the learning rate and the neighbourhood radius decrease during the training to improve the classification. The neighbourhood function used in this dissertation is

$$h_{j,j^*} = e^{-\frac{\|r_j - r_{j^*}\|^2}{2\sigma^2(t)}} \quad (5.4)$$

where r_j and r_{j^*} are position of neurons j and j^* .

(5). Repeat steps 2 to 4 until all the input vectors have been used at least one time, and no noticeable changes in the feature map are observed.

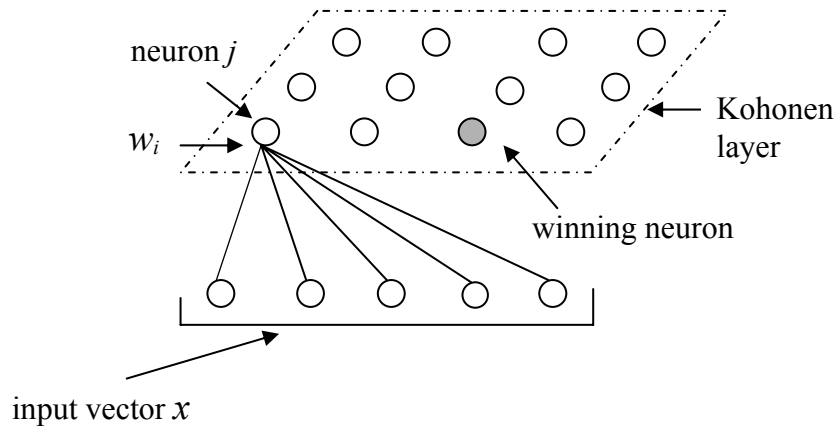


Figure 5.2 - Self-organizing map architecture

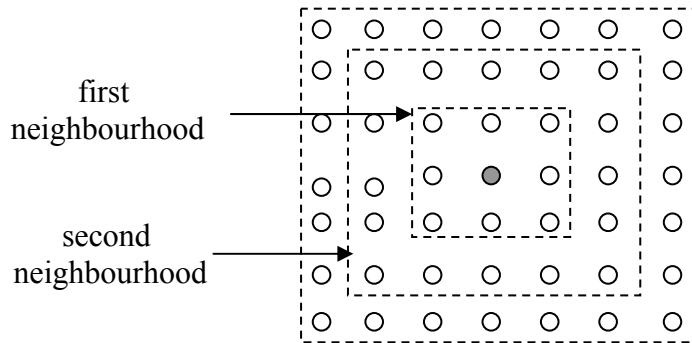


Figure 5.3 - Self-organizing map neighbourhood scheme

5.3.2.2. Batch algorithm

The batch version of the self-organizing map is computationally more efficient [233]. At each step of the algorithm, all the input data vectors are simultaneously used to update all the model vectors:

$$w_j(k) = \frac{\sum_{j=1}^l n_j h_{j,j^*}(k) \bar{x}_j}{\sum_{j=1}^l n_j h_{j,j^*}(k)} \quad (5.5)$$

where $\bar{x}_j$ is the mean of the data vectors in V_j , the Voronoi set of unit j , and n_j is the number of data vectors in V_j . $h_{j,j^*}(k)$ denotes the value of the neighbourhood function at unit j when the neighbourhood function is centred on the unit j^* . In the batch algorithm, the learning rate function $\alpha(k)$ used in the sequential algorithm is no longer needed, but the width of the neighbourhood is monotonically decreased during the learning like in the sequential algorithm.

5.3.2.3. Data clustering using self-organizing map

Visual inspection of the map after training permits to get an initial idea of the number of clusters in the self-organizing map, as well as their spatial relationships. The most widely used methods for visualizing the cluster structure of the self-organizing map are distance matrix techniques [236,237], especially the unified distance matrix (*U*-matrix). The *U*-matrix shows distances between prototype vectors of neighbouring map units.

Clusters can thus be visually selected. However, this is a tedious process and nothing guarantees that the manual selection is done consistently. Instead, automated methods can be used. In this dissertation this is done by the map unit clustering using *k*-means.

5.3.3. *K*-means

K-means [238] is a partitioning method. It divides a data set into k clusters, fixed a priori, by trying to minimize a criterion or error function. The k -means algorithm is a local search procedure. Its performance heavily depends on the initial conditions. The algorithm is composed of the following steps:

- (1) Determine the number of clusters.
- (2) Initialize randomly or manually the cluster centre locations.
- (3) Compute the distance of each vector to cluster centres.
- (4) Assign each input to the group with closest centre, in a way to minimize the error between a data point x and the cluster centres c_k .

$$E = \sum_{k=1}^C \sum_{x \in Q_k} \|x - c_k\|^2 \quad (5.6)$$

where C is the number of classes.

- (5) Recalculate the positions of the k centres
- (6) Repeat steps 3 to 5 until the centres no longer move.

The k -means algorithm does not necessarily find the global minimum. The algorithm is also significantly sensitive to the initial randomly selected cluster centres. The k -means algorithm must be run multiple times to reduce this effect. A validity index can then be used to select the best among the different partitioning. There are different methods for that purpose. In this study the Davies and Bouldin index [239], DB , is calculated for each

partitioning. The low values, indicate good clustering results. The Davies and Bouldin index is calculated as follow

$$DB = \frac{1}{C} \sum_{k=1}^C \max_{t \neq k} \left\{ \frac{S_C(Q_k) + S_C(Q_t)}{d_{ce}(Q_k, Q_t)} \right\} \quad (5.7)$$

where S_C is the within-cluster distance and d_{ce} the between clusters distance.

Chapter 6

Time-frequency analysis

Acoustic emission signals are transient, with spectral content changing as function of time. Fourier analysis describes signal in the frequency domain and consequently has no time resolution. In the case of non-stationary signals, such as acoustic emission signals, whose frequency content varies, it is convenient to describe them in time and frequency domains, to know when the different frequencies are present. Several solutions have been developed to overcome this problem. The idea behind these time-frequency joint representations is to cut the signal of interest into several parts and then analyze the parts separately. In this study the continuous wavelet transform was used for time-frequency representation of the classified acoustic emission signals. In this chapter, are reviewed the most significant investigations involving acoustic emission and time-frequency analysis, and are presented the basic theoretical aspects of time-frequency analysis.

6.1. Literature review

Most of the studies concerning time-frequency and acoustic emission waves involved the wavelet transform. However, other transforms were used such as the Wigner Spectrum [240], the Cohen's class of time-frequency distributions [241] or the pseudo Wigner-Ville distribution [242,243,244], and the short-Fourier transform [245,246,247].

Wavelets are mathematical functions that cut up data into different frequency components, and then study each component with a resolution matched to its scale [248]. Wavelet transform has been mainly used for signal denoising [249,250,251,252], source location [128,129,131,132,133,134,253,254,255] and damage discrimination [112,113, 114,170,256,257,258].

6.1.1. Noise removal

Acoustic emission signals are usually disturbed by noises of different frequency ranges. They contain high-frequency noise, mainly caused by the measurement equipment such as the preamplifier as well as the surrounding. On the other hand, a low-frequency noise is superimposed by the testing device itself (testing machine). This complicates the damage onset detection [252]. The wavelet transform is a fast and efficient way of filtering signal. It can be used for acoustic emission signals denoising. The acoustic emission signal is decomposed into different wavelet levels. The levels that do not contain significant energy are considered as noise and are removed to enhance the signal to noise ratio. Such procedure was adopted by Qi et al. [246], who observed better results with its wavelet-based method compared to the traditional.

6.1.2. Source location

Improvements in source location were obtained using the wavelet transform due to a more precise estimation of the wave's arrival time. It is obtained from a better dissociation of propagating wave mode and reflections resulting of the time-frequency representation. Prosser et al. [242,243] studied the acoustic emission waves generated by pencil lead breaks on the surface of a unidirectional graphite/epoxy (AS4/3502) laminate. The arrival times for the lowest order symmetric (S_0) and antisymmetric (A_0) Lamb modes were determined from measurements of the time at which the respective peak amplitudes occurred in the pseudo Wigner-Ville distribution. The large dispersion of the A_0 mode could be clearly seen in both the time domain signals and the time-frequency images, the higher frequencies arriving at earlier times in this mode. The obtained spectrograms clearly showed the dispersion curves for the plates.

Jeong [128,254] proposed similar approach for acoustic emission source location using the dispersive waves in thin plates. The author applied the wavelet transform using the Gabor wavelet to the time-frequency analysis of dispersive flexural waves in unidirectional and quasi-isotropic laminates plates. The peaks of the magnitude of wavelet transform in a time-frequency domain were related to the arrival times of the group velocity. Experiments were performed using a lead break as the simulated acoustic

emission source on the surface. The group velocity of the flexural mode was obtained as a function of frequency. The experimental results showed good agreement with the theoretical predictions using the Mindlin plate theory, which includes the effects of shear deformation and rotatory inertia. Jiao et al. [134] adapted the same methodology for location in steel plate from a single acoustic emission transducer. Location was obtained from the difference of dispersion behaviour of A_0 and S_0 mode.

6.1.3. Damage discrimination

Kinjo et al. [112] used wavelet transform representation as a complementary tool to waveform analysis for damage identification. Mitzutani et al. [203] used this methodology to classify the acoustic emission events detected when carbon fibre reinforced plastic cross-ply laminates were subjected to point surface loading. The wavelet contour maps were used as a complement to the visual classification of the waveforms.

Hamstad et al. [258] proposed a potentially useful parameter for source identification. It consist of the ratio of the Gabor wavelet transform coefficients (i.e. local maxima in the time-frequency representation at a given frequency and group velocity) for A_0 and S_0 modes. When applied to acoustic emission waves simulated by finite element in the case of an aluminium plate, it could distinguish different source types when the sources were all centred at the same depth below the plate surface and with the same propagation distance. But, since the values of this ratio overlap for different source types at different depths, it is not possible to uniquely identify the source type.

Ni et al. [170] used the time-frequency method to obtain information about the microfailure modes at a fibre breakage and the microfracture mechanisms, such as the sequence of each failure modes ant their interaction. Information about the damage duration could be obtained from the three dimensional representation of the continuous wavelet transform of the acoustic emission signal.

Qi et al. [113,114] studied the energy of the different wavelet levels. The energy concept revealed different potential failure modes of the specimen by discriminating the energy quantity and frequency range. The energy carried by the acoustic emission signal was concentrated in three different levels. The energy emitted from fibres fractures, in

level 9, was about 75% of the total energy. The energy emitted from fibre/matrix debonding, in level 8, was about 15%. The energy emitted from matrix cracking, in level 7, was about 8% of the total energy. The accumulative wavelet level energy and total energy was used to predict the stress severity and residual strength.

Sung et al. [257] used the discrete wavelet transform to analyze the transient characteristics of acoustic emission waves due to low-velocity impact damage in $[0_2/90_4]_s$ graphite/epoxy composite laminate. The acoustic emission signals were decomposed in several levels. The Daubechies db4 mother wavelet was used for its high regularity. The frequency content of the observed acoustic emission signals attributed to matrix cracking was dominantly included in the 300-400 kHz range, whereas for delamination it was below 250 kHz.

6.2. Wavelet Transform

In the Fourier analysis, a signal is represented by a sum of sine and cosines waves of various frequencies. Similarly, in wavelet analysis a signal is expressed in a basis formed by shifted and scaled versions of a wavelet, which is a function having an oscillatory waveform of effectively limited duration, which decays quickly to zero and has an average value of zero. The signal being analysed is decomposed into different parts, which are studied separately to get more information about the occurrence of different frequency components.

The signal cutting corresponds to a convolution between the signal and a window. Due to Heisenberg's uncertainty principle, it is impossible to know the exact frequency and the exact time of occurrence of a frequency in a signal. In wavelet analysis the use of a fully scalable modulated window solves the signal-cutting problem. The window is shifted along the signal and for every position the spectrum is calculated. Then this process is repeated many times with a slightly shorter (or longer) window for every new cycle. In contrast to the short-time Fourier transform, which uses a single analysis window function, the wavelet transform can use short windows at high frequencies or long windows at low frequencies. The final result is a collection of time-frequency representations of the signal having different resolutions. Because of this collection of representations it is called a multiresolution analysis. The principal aspects of wavelet

transform are presented in this chapter. Extended information about wavelet transform can be found in the literature [259,260,261].

6.2.1. The Continuous Wavelet Transform

The continuous wavelet transform, WT , is defined by the following equation, which expresses the decomposition of the function $f(t)$ into a set of basis function $\psi_{a,b}(t)$.

$$WT_f(a,b) = \langle f, \psi_{a,b} \rangle = \int_{-\infty}^{+\infty} f(t) \frac{1}{\sqrt{a}} \psi^*\left(\frac{t-b}{a}\right) dt \quad (6.1)$$

where $t \in \mathbb{R}$, $a > 0$ is a scaling factor that stretches or compresses the mother wavelet, $\psi(t)$. $*$ denotes complex conjugation. The parameter b is a time translation factor which simply shifts a wavelet and so delays or advances the time at which it is activated. The factor $1/\sqrt{a}$ is used to ensure the energy of the wavelet versions are the same as the mother wavelet.

6.2.1.1. Wavelets properties

Considering a continuous time function $\psi(t)$ with the following properties

1. The function integrates to zero:

$$\int_{-\infty}^{\infty} \psi(t) dt = 0 \quad (6.2)$$

2. It is square integrable:

$$\int_{-\infty}^{\infty} |\psi(t)|^2 dt < \infty \quad (6.3)$$

The function $\psi(t)$ is a wavelet if it satisfies the admissibility and regularity conditions. The admissibility condition is expressed by the equation 6.4.

$$0 < \int_0^\infty \frac{|\hat{\psi}(w)|^2}{|w|} dw < \infty \quad (6.4)$$

where $\hat{\psi}(w)$ is the Fourier transform.

The admissibility condition can be used to first analyze and then reconstruct a signal without loss of information [261]. As for the regularity conditions, they state that the wavelet function should have some smoothness and concentration in both time and frequency domains. Therefore the wavelet transform decreases quickly with decreasing scale.

The mother wavelet is well localised in the time-frequency plan. An orthonormal basis is generated from the dilated and translated version of the mother wavelet. The wavelets have identical forms but variable size, inversely proportional to the scale factor. The acoustic emission signal is analysed on the different scales making a correlation with the wavelets, which allows the characterization of acoustic emission signal frequency content. The magnitude of the wavelet transform obtained by $|WT_f(a, b)|$ represents the time-frequency component of $f(t)$ around $t = b$ and $w = w_0 / a$. $|WT_f(a, b)|^2$ is called the scalogram of $f(t)$, it can be very useful to detect signal singularities.

The resulting representation is not a time-frequency representation but rather a time-scale representation. When the mother wavelet is well localised in time and frequency, it is possible to make a time-frequency analogy, considering $w = w_0 / a$, where w_0 is the central frequency of $\psi(t)$.

The Gabor wavelet, $\psi_g(t)$, which is known to provide a good resolution in time and frequency [128], is defined by

$$\psi_g(t) = \frac{1}{\sqrt[4]{\pi}} \sqrt{\frac{w_0}{\gamma}} \exp \left[-\frac{\left(\frac{w_0}{\gamma} \right)^2}{2} t^2 \right] \exp(iw_0 t) \quad (6.5)$$

and $\hat{\psi}_g(w)$, its Fourier Transform, defined by

$$\hat{\psi}_g(w) = \frac{\sqrt{2\pi}}{\sqrt[4]{\pi}} \sqrt{\frac{\gamma}{w_0}} \exp \left[-\frac{\left(\frac{\gamma}{w_0} \right)^2}{2} (w - w_0)^2 \right] \quad (6.6)$$

Its Fourier transform is represented in figure 6.2. It is a Gaussian window function centred at $w = w_0$. Although the Gabor wavelet doesn't satisfy the condition 6.4, it doesn't present any problem in practice when $\gamma = \pi\sqrt{2/\ln 2} \approx 5.336$ [254]. When setting $w_0 = 2\pi$, $1/a$ is equal to the usual frequency $f = w/2\pi$.

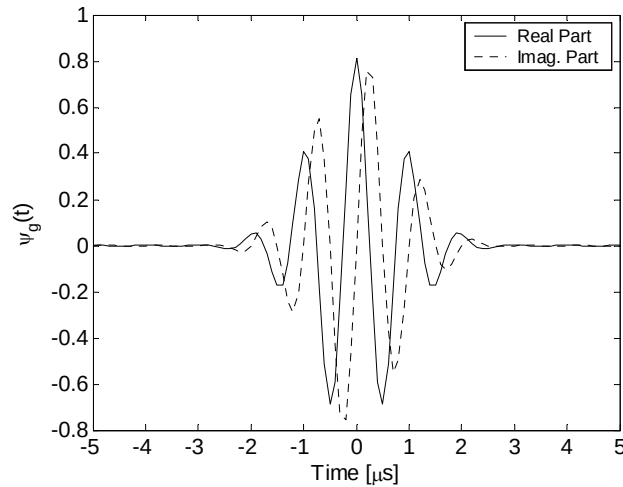


Figure 6.1 - Gabor function in time domain

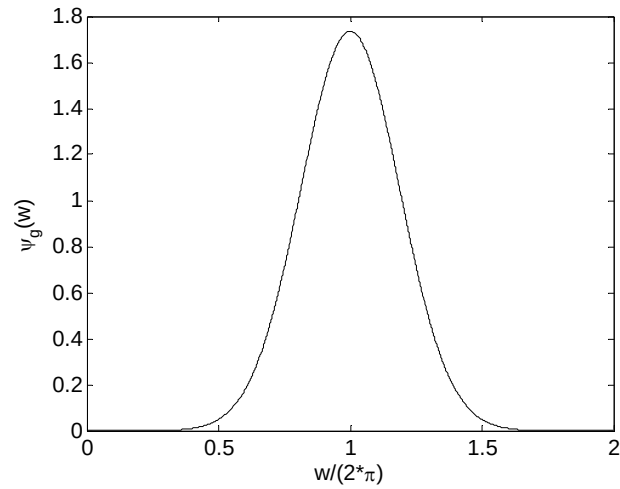


Figure 6.2 - Gabor function in frequency domain

In this study the Gabor wavelet transform is calculated using the AGU-Vallen wavelet tool [262]. It creates directly a time-frequency representation of the signal instead of the time-scale representation. AGU-Vallen wavelet tool creates a matrix that is transferred to MATLAB workspace for its treatment.

Chapter 7

Cross-ply laminate testing

When cross-ply laminates are subjected to mechanical loading, different failure mechanisms are induced [9,263,264,265,266,267] (figure 7.1): transverse matrix cracking in 90° plies, fibre/matrix decohesion, delamination, longitudinal matrix cracking which develops along the fibre direction of 0° plies, fibre fracture in 0° plies. In the case of uniaxial loading, the early stage of damage is dominated by transverse matrix cracking in 90° plies. In static tests, transverse cracks are initiated at the free edges of the test specimens and extended to the full width of the specimens almost instantaneously. After the first transverse crack occurs, the number of cracks increases progressively as the applied load is increased. The load is progressively transmitted to the layers oriented in the direction of the load until the rupture of the 0° plies due to the fibres rupture.

Different parameters (e.g. the laminate architecture, the ply thickness, the layers width) have an influence in the initiation and evolution of the transverse matrix cracking. While changing those parameters, it is possible, with a reasonable efficiency, to control the fracture process.

The sequence of microscopic fracture mechanisms can be monitored, in real-time, from the rapid release of elastic strain energy they generate, detected at the surface of the material in the form of elastic waves.

In this study, different test configurations (stacking sequence, ply thicknesses and specimen's width) have been considered as a change in the conditions of the transverse matrix cracking in order to analyse the influence on the acoustic emission activity. The signal processing method presented in chapter 5 and 6 was applied. The classifier was used for signals clustering and the time-frequency representation for enhancement of the acoustic emission signals characteristics.

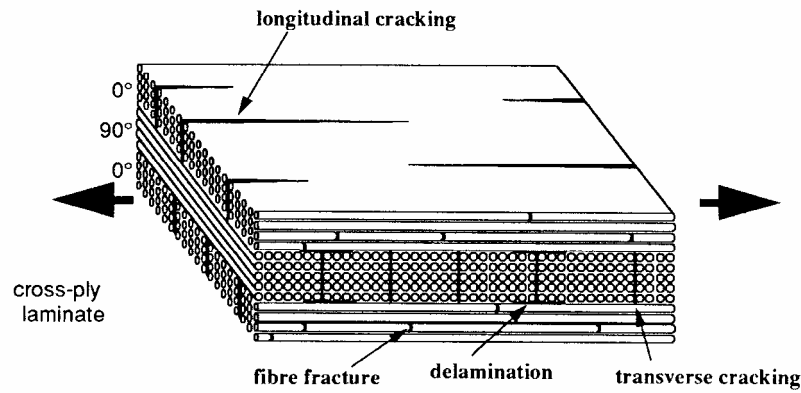


Figure 7.1 - Damage mechanisms in a cross-ply laminate [9]

7.1. Literature review

Acoustic emission has been successfully used for the discrimination of transverse matrix cracking from other damage mechanisms in composite laminates. In literature, some studies are focused in the particular case of cross-ply laminates. The most significant are dedicated to the waveform analysis of the acoustic emission signals. However, successes of damage discrimination by the classical parametric analysis are also reported.

Favre et al. [268] studied the transverse matrix cracking accumulation in the transverse layer of cross-ply carbon/epoxy composites under monotonic tensile loading by means of the amplitude distributions. Cracks were counted using X-rays observations. For thick 90° layers a one-to-one correspondence between the high-amplitude signals and the number of cracks was observed. For thin transverse layers laminates the amplitude distributions analysis was not efficient, but they didn't give any reason for this.

Surgeon et al. [269] studied the damage occurring in cross-ply $[0/90_3]_s$ SiC-fibre-reinforced BMAS glass-ceramic composites. They could correlate the observed acoustic emission events with transverse cracking from the analysis of the signal duration and energy. Short duration and low energy signals were attributed to matrix microcracking, while long duration high energy signals were attributed to the propagation of transverse matrix cracking and partial disbonding of the fibre/matrix interface between 90° and 0° plies.

Morsher [270] used the energy to measure the crack density. A relative good correlation was observed between the relative amount of cumulative acoustic emission energy and the relative number of matrix cracks.

Dzenis et al. [271] used a hybrid transient-parametric approach to separate overall acoustic emission histories into the histories for the different damage micromechanisms in cross-ply $[0/90_3]_s$ glass/epoxy composites. The shapes of the frequency spectrum and transient signals were studied. They exhibited less variability than the signal parameters. Three wave types were identified one with low amplitude, medium to long rise time, and frequency between 100 to 220 kHz. Another waveform type had medium to high amplitude, shorter rise time, and the peak frequency between 300 and 700 kHz. The last waveforms had a very wide frequency spectrum and a very long duration. These three signals were due respectively to matrix cracking, fibre breaks and delamination. The two first signals types had overlapping parameters. Amplitude and rise time correlation plots provided the best possible separation.

Qi et al. [113] performed an energy/frequency analysis of acoustic emission events detected during static loading of notched cross-ply carbon-fibre reinforced plastic composite specimens. The discrete wavelet transform was used to decompose the signals into different frequency bands. The signals were previously deconvolved to remove the unwanted effects from the detected signals (i.e. the transducer and propagation effects). The energy distribution of the decomposed acoustic emission signals was studied. The energy was concentrated in three frequency ranges of 50-150 kHz, 150-250 kHz, and 250-310 kHz, with 8, 15, and 75% of the total energy, respectively. The frequency content of signals due to matrix cracking was mainly in the 50-150 kHz range, and for fibre/matrix debonding and fibre fracture in the 150-250 kHz and 250-310 kHz range, respectively.

Gorman et al. [5,79,116] and Prosser et al. [3,117,118,119,120,121] studied the transverse matrix cracking occurring during tensile tests in cross-ply graphite/epoxy specimens. They analyzed the modal nature of acoustic emission waves due to transverse matrix cracking in plate-like composite laminates. They showed that transverse matrix cracking generate typical extensional waveforms. Different cross-ply laminates with $[0_n/90_n/0_n]$ lay-ups, n ranging from 1 to 6 were studied. Four wideband sensors were used to make planar location possible. The four transducers were mounted at the specimen

edges and permitted to provide the lateral position of the crack initiation site. A one-to-one correlation between acoustic emission detected cracks and cracks was confirmed with microscopy and backscatter ultrasonics. It was observed that an identical source mechanism, such as transverse matrix cracking, can produce a wide range of acoustic emission signal amplitudes due to dispersion and attenuation effects. Higher amplitudes were detected for thicker 90° layer specimens. For specimens with thin 90° layers ($n \leq 2$), much smaller amplitude acoustic emission signals were observed which were difficult to consistently detect. For those laminate a good correlation between the acoustic emission data and observed cracks was not established. Through the use of backscatter ultrasonics, destructive sectioning and microscopy, it was discovered that the cracks did not appreciably grow from the edge after initiation in specimens with a 90° layer of two or less ply thicknesses.

Surgeon et al. [4,272] applied the modal acoustic emission analysis for damage discrimination. Three different cross-ply carbon/epoxy prepreg laminates ($[0_2/90_2]_s$, $[0/90_3]_s$, and $[0_3/90]_s$) were submitted to tensile and bending tests. The acoustic emission signals attributed to matrix cracking showed a consistent increase in extensional mode frequency as the number of 90 -plies decreased. Besides the large extensional mode observed at matrix cracking a flexural component was observed in most cases. This was attributed to the asymmetric growth about the midplane. They observed that cracking do initiate at one of the outer plies and grow through the thickness to the other group of outer plies.

Johnson et al. [65,66,273,274] studied the transient signals recorded during the tensile tests of two glass/epoxy cross-ply laminates ($[0/90_2]_s$ and $[90_2/0]_s$). The objective of the study was to characterize the acoustic emission signals generated from various forms of microcracks developed under tensile loading for further comparison with numerical calculations. They studied the transient recordings from broadband transducers generated from matrix cracking, local delaminations and fibre breakage to see if characteristic features can be recognized and used to discriminate these different damage types. Six transducers were used (2 guard transducers for grip noise removal and two pairs of transducers for waveform acquisition). The two transducers pairs were mounted at the same location but on opposite sides of the specimen. When the extensional mode was detected, almost the same waveform was detected at opposite transducers. The signals

detected at opposite transducers were added or subtracted for signal enhancement. Three different types of signals were identified as being due to matrix cracking. They were detected at different strain levels. The first type occurred before the characteristic knee in the stress vs. strain curve. These emissions were thought to be emitted from various defects causing small crack initiations, not having enough elastic energy to substantially grow into the specimen and through the width, that may develop into transverse matrix cracks at higher strains. In the case of $[90_2/0]_s$ matrix cracking occurred in one of the surface layer, besides the extensional wave a flexural wave was observed as a consequence of the non-symmetric loading. When cracking occurred in the mid layer of the $[0/90_2]_s$ the extensional mode was detected due to symmetric loading.

7.2. Experimental method

7.2.1. Methodology

It is here intended to get a better understanding of the acoustic emission event associated to damage. The transverse matrix cracking process is changed in order to observe the effects on the detected acoustic emission events.

Transverse matrix cracking can be controlled with sufficient precision changing the 90° layer thickness, and the specimen width.

Acoustic emission signals are processed in order to find some characteristics that can be correlated to the testing configuration. Due to the high quantity of signals, an automated signal processing procedure is required for faster information extraction. The pattern clustering procedure presented in chapter 5 is used in this chapter. The classified waveforms are then represented in a time-frequency plan in order to enhance their characteristics.

7.2.2. Materials

Glass-fibre/polyester cross-ply laminates were produced by manual stratification assisted by vacuum in the form of plates of dimension $30\text{ cm} \times 30\text{ cm}$. Three different thicknesses of the 90° layers (0.5, 1 and 1.5 mm) were elaborated, corresponding to the

stacking sequences $[0/90]_s$, $[0/90_2]_s$ and $[0/90_3]_s$ of thicknesses 1 mm, 1.5 mm and 2 mm respectively. For good impregnation, an unsaturated orthophthalic polyester resin with low viscosity (ENDUR™ S 226 E, Ashland polyester S.A.S.) was used. The layers were built by stacking sequences of matrix and Silenka® glass unidirectional tissue (300 gm^{-2} , VEX300 cloth of Sicomin, France). Rectangular specimens with length of 250 mm were cut from the plates. Three different specimen widths were studied: 15 mm, 25 mm and 50 mm. The edges were polished with silicon carbide paper to avoid premature initiation of cracking. Aluminium tabs were mounted on the specimens to limit grip signal noise.

7.2.3. Mechanical testing

Monotonic tensile tests were performed using an INSTRON® Model 4208 universal testing machine, according to the ISO 527 standard [188]. The speed test was controlled by displacement to 1 mm.min^{-1} . In addition to the acoustic emission acquisition, an acquisition system, from HBM®, collected the load applied to the material and the strain values obtained by an electric extensometer, mounted on the test specimen.

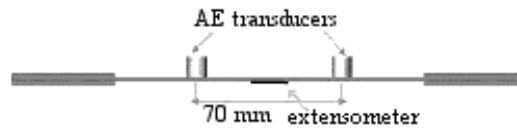


Figure 7.2 - Specimen configuration

7.2.4. Mechanical behaviour

The characteristics of the composite laminates are summarised in table 7.1. Typical stress-strain curves derived from the tensile tests for the three lay-ups are reported in figure 7.3.

Stacking sequence	E_1	E_2	m_f
	[GPa]	[GPa]	[%]
$[0/90]_s$	21.3	19.4	62.82
$[0/90_2]_s$	16.7	24.3	59.18
$[0/90_3]_s$	13.6	29.1	58.70

Table 7.1 - Laminates mechanical properties

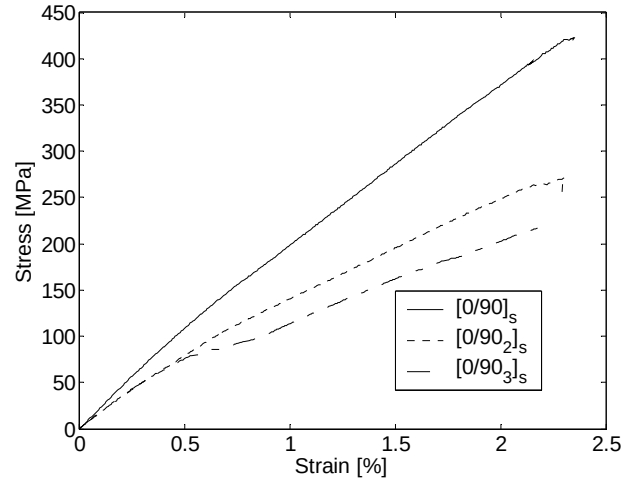


Figure 7.3 - Laminate longitudinal stress-strain curve.

7.2.5. Visual observations

Transverse matrix cracks in 90° ply were observed with naked eyes, thanks to the translucent properties of fibre glass.

Cracks extended to the full width of the specimens almost instantaneously for the specimens having 15 and 25 mm width. For higher specimen width, cracking initiation is delayed. Furthermore the time needed for the crack to extend to the full width of the specimens is higher, influencing the propagation process as most of the cracks propagate by steps, and final crack surface is higher.

During the tensile test, spacing between cracking decreases due to the creation of new cracking (figure 7.4). At the beginning of the test, for low cracking density, cracks are distributed randomly along the specimen's length (figure 7.4.a). As the elongation increases, cracking's distribution becomes more uniform until a saturation point, at which delamination appears at the free edges, as well as longitudinal cracking (figure 7.4.c).

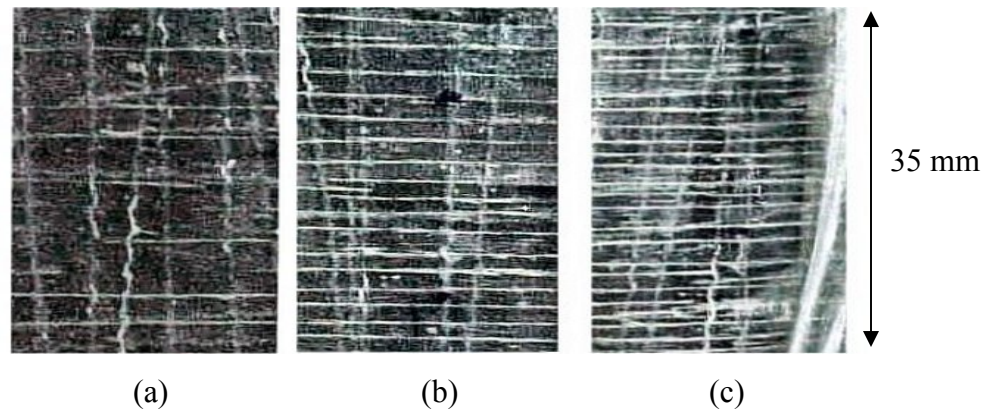


Figure 7.4 - Distribution of transverse matrix cracking observed in a $[0/90_3]_s$ laminate at different strain levels (a) $\epsilon=0.58\%$, (b) $\epsilon=1.12\%$, (c) $\epsilon=1.77\%$.

The stress corresponding to initiation of the first cracks can be derived from the stress-strain curve. This load corresponds to the knee of the curve (figure 7.5).

The values of the stress are reported in table 7.2. The stress increases when the thickness of 90° layers is decreased. Moreover, figure 7.6 shows the crack density observed at the saturation state at the end of the tests. It is observed that the crack density at the saturation state increases when the thickness of 90° layers is decreased. These experimental observations agree with the works of the literature [267].

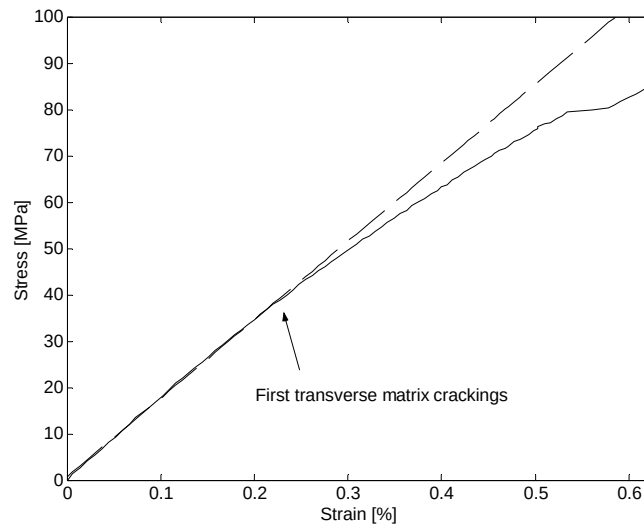


Figure 7.5 - First crack stress determination for $[0/90_3]_s$ laminate by longitudinal stress-strain curve

Stacking sequence	First crack stress from stress-strain curve [MPa]	First crack stress from acoustic emission activity [MPa]
$[0/90]_s$	69	70
$[0/90_2]_s$	49	50
$[0/90_3]_s$	40	41.3

Table 7.2 - First crack stress

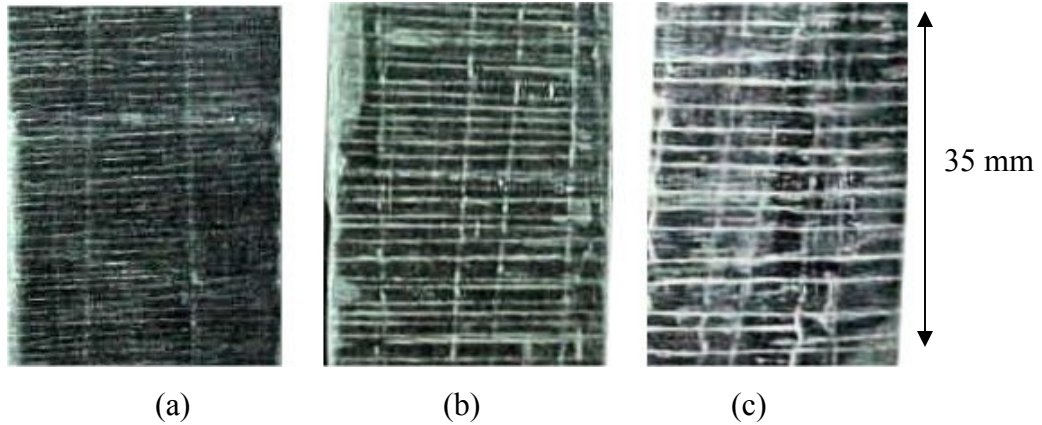


Figure 7.6 - Transverse matrix cracking density observed for the three different 90° ply thicknesses at $\epsilon=1.8\%$ (a) 0.5 mm (b) 1 mm (c) 1.5 mm.

Some cracks didn't initiate at specimen edges but at defects inside the material. They were especially observed at the beginning of loading.

Other cracks didn't reach the opposite edge. Those cracks stopped new cracks initiating at the opposite side when reaching their vicinity.

In figure 7.7 the transverse matrix cracking occurring at a $[0/90_3]_s$ specimen edge can be observed.

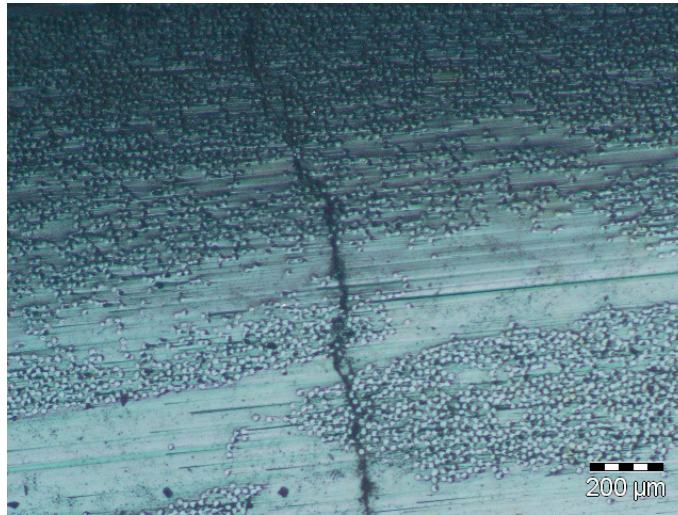


Figure 7.7 - Transverse matrix cracking at a $[0/90_3]_s$ specimen edge observed by optical microscopy

7.3. Acoustic emission analysis

The obtained acoustic emission signals are function of different factors. They depend on the source but also on the propagation and transfer function of the acquisition set-up. The acoustic emission signals produced by the same mechanism can have different waveform in function of the length of the crack, of the damage area, depending on whether the cracks extend immediately or if it propagates by steps. Acoustic emission signal depends also upon the position of acoustic emission event from the transducer.

7.3.1. Acoustic emission activity

The threshold value was adjusted to 40 dB in function of background noise. Acquisition parameters of the acoustic emission system (Rearm time and Duration Discrimination Time) were set to 0.3 ms and 150 μ s, respectively, to limit the acquisition of waves due to reflections.

The acoustic emission activity was measured during the tests as a function of the applied stress (figure 7.8), and transverse cracking initiation can be derived from the acoustic emission activity. The values obtained agree quite well with the results obtained from the stress-strain curve (table 7.2). However, as it is a graphical method, its

efficiency depends on the curves representation. The acoustic emission detected before first crack load is essentially due to grip noise and cracks initiating at defects in the specimens.

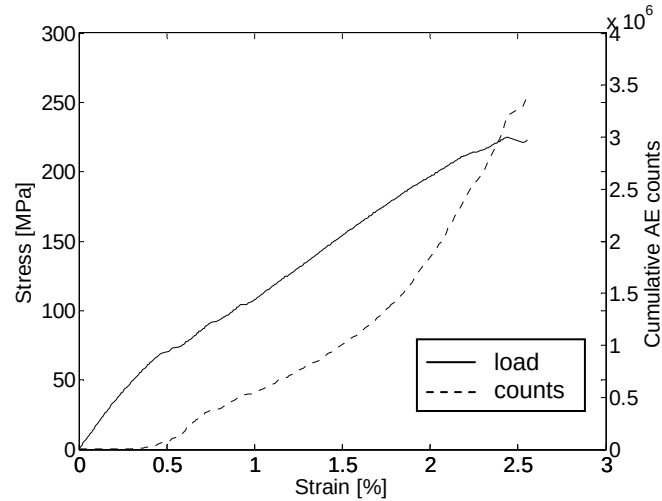


Figure 7.8 - Stress-strain curve of a $[0/90_3]_s$ laminate and corresponding acoustic emission counts.

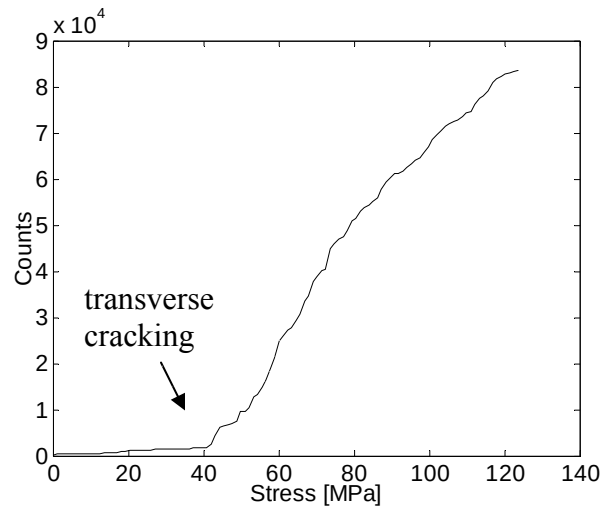


Figure 7.9 - Cumulative acoustic emission counts as a function of the applied stress for a $[0/90_3]_s$ laminate.

7.3.2. Wave propagation

The velocities, C_e and C_f , of propagation of the acoustic emission waves in the 0° and 90° direction were determined for the extensional and flexural modes, respectively. Pencil lead (2H, 0.5 mm diameter) breaks were performed at the edge of the samples to determinate the extensional mode velocity (figure 7.10.a), and at the surface for the flexural mode (figure 7.10.b). For velocity measurements, the broadband transducer was used for better distinction of the mode of propagation.

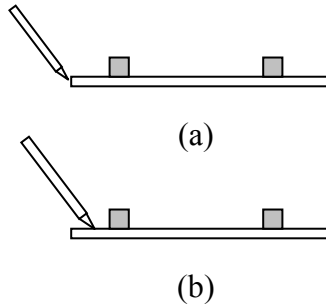


Figure 7.10 - Acoustic emission waves simulation procedure

The wave modes could be easily distinguished using the time-frequency representation. The A_0 mode is characterized by the higher frequencies components arriving first whereas for the S_0 mode almost all frequencies components arrive at the same time to the transducer. In figure 7.11 is reported a typical waveform observed when the lead was broken at the material's surface. A higher A_0 component is observed. The figure 7.12 represents a typical waveform observed when the lead was broken at the material's edge. In this case a higher S_0 component is observed. The obtained velocity values are reported in table 7.3.

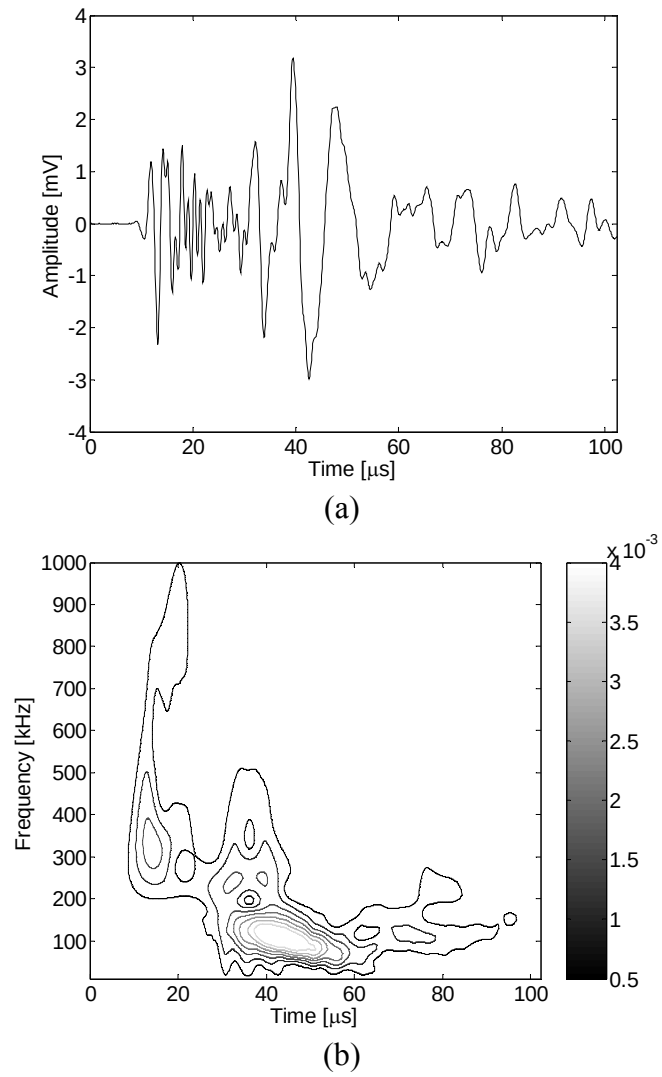


Figure 7.11 – (a) Time and (b) time-frequency representation of a simulated wave detected when pencil lead break on material surface

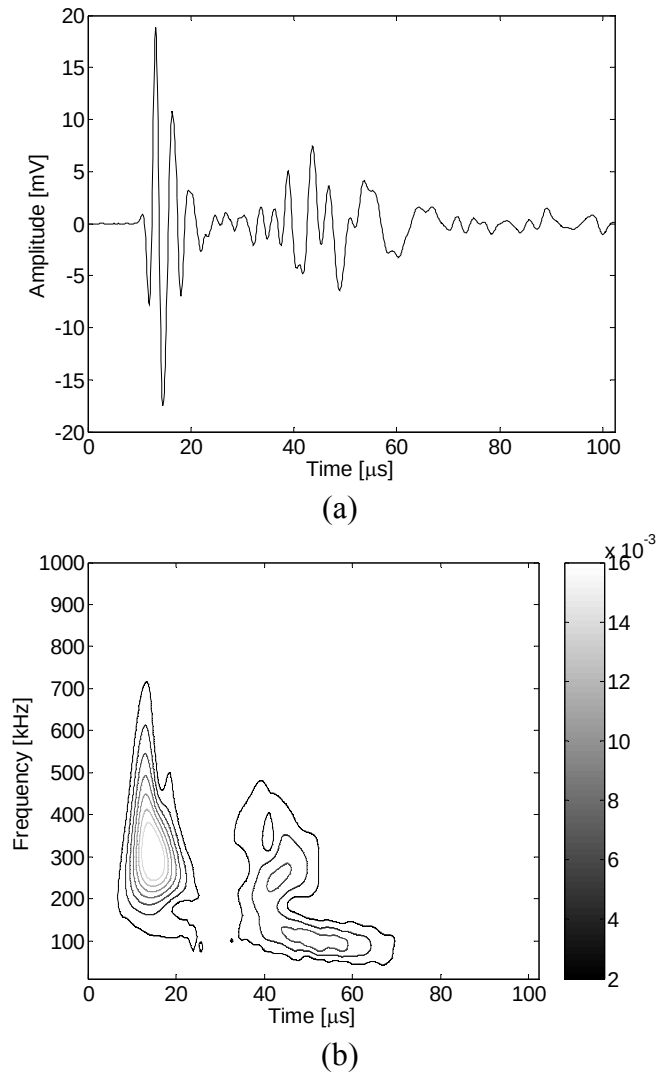


Figure 7.12 – (a) Time and (b) time-frequency representation of a simulated wave detected when pencil lead break at material edge

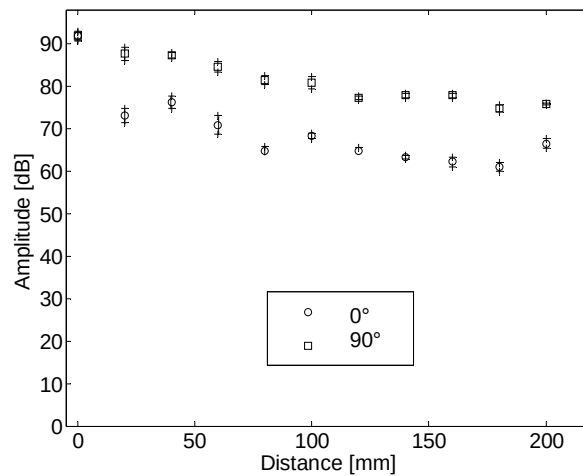
The extensional mode propagates faster than the flexural mode. The dependence of the velocity on the material rigidity can be observed in the values reported in table 7.3.

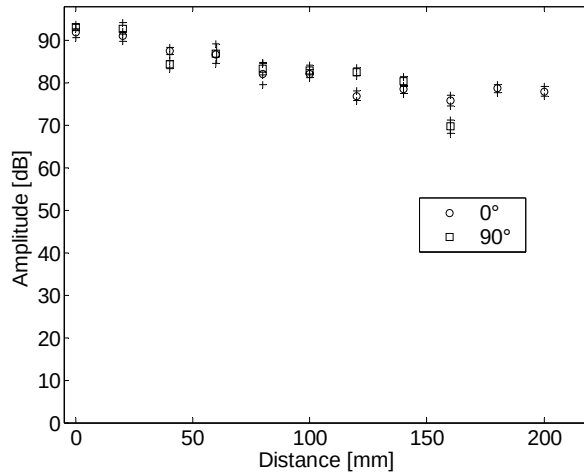
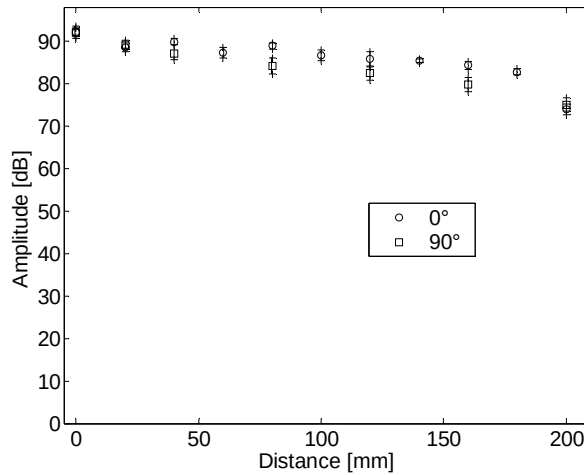
Stacking sequence	Direction of propagation	C_f ($f=150$ kHz)	C_e
		[m.ms ⁻¹]	[m.ms ⁻¹]
[0/90] _s	0°	1.388	3.700
	90°	1.349	3.799
[0/90 ₂] _s	0°	1.389	3.476
	90°	1.360	4.200
[0/90 ₃] _s	0°	1.280	3.230
	90°	1.430	4.420

Table 7.3 - Waves velocity

Attenuation is observed for acoustic emission waves simulated by pencil lead breaks for the three lay-ups. The amplitude of the simulated acoustic emission waves was measured for eleven different transducers spacing. Ten fibre breaks ruptures were made for each position. Coupling was repeated to avoid its influence on amplitude values. Results are represented in the figure 7.13 to figure 7.15. The error bars are +/- one standard deviation.

The attenuation is less important than in the previous case of the monofilamentar specimen, but it remains significant (about 6 dB for the transducer distance). No amplitude correction is made, as it is intended to proceed to a multivariable signal classification.

Figure 7.13 - Attenuation of S₀ mode in the [0/90₃]_s laminate

Figure 7.14 - Attenuation of S_0 mode in the $[0/90_2]_s$ laminateFigure 7.15 - Attenuation of S_0 mode in the $[0/90]_s$ laminate

7.3.3. Source location

According to Gorman [116], acoustic emission signals due to transverse matrix cracking have a higher extensional component, damage occurring in the plane of the plate. The classical plate theory predicts that this mode is dispersionless. The values of the velocity of S_0 mode are thus the most adapted to locate transverse matrix cracking.

As observed in table 7.3 the wave velocity decreases with the stiffness decrease. The velocity of the S_0 mode in the 0° direction of the laminate is expressed by the classical plate theory as [3]

$$C_e = \sqrt{\frac{A_{11}}{\rho h}} \quad (7.1)$$

where A_{11} is the plate in-plane stiffness, ρ is the density and h the thickness.

Toyama et al. [275] gave an expression for the velocity evolution as function of crack density D . They obtained this expression from the parabolic shear-lag analysis proposed by Berthelot et al. [263]. S_0 mode velocity was then used to monitoring transverse cracks in $[0/90_4]_s$ glass fibre reinforced plastic composite laminates.

$$\frac{C_e}{C_{e_0}} = \sqrt{\frac{E_1}{E_1^0}} = \sqrt{\left(1 + \frac{t_{90}}{t_0} \frac{E_{90}}{E_0} \frac{2t_{90}D}{\eta} \tanh \frac{\eta}{2t_{90}D}\right)^{-1}} \quad (7.2)$$

where C_{e_0} is the S_0 mode velocity for undamaged laminate, where E_1 and E_1^0 are the Young's module of the damaged and undamaged laminate, respectively. t_0 and t_{90} are the half thicknesses, and E_0 and E_{90} are the Young's module of the 0° layers and the 90° layers and η is the shear lag parameter. Thus, the error of the conventional location method increases with the crack density. Authors underlined the necessity to consider the velocity decrease for more precise location in large laminates.

Morscher et al. [122] observed experimentally that the decrease of extensional mode velocity as function of strain is proportional to the decrease of the square of the modulus in the propagation direction during load/unload/reload tensile tests.

In this dissertation S_0 mode velocity decrease is not considered. Linear location of damage is derived using the equation 4.9.

7.3.4. Clustering of acoustic emission signals

7.3.4.1. Clustering methodology

In order to identify the waveforms due to transverse matrix cracking, acoustic emission signals were clustered using the unsupervised method presented in chapter 5. The pattern clustering method is schematised in figure 7.16

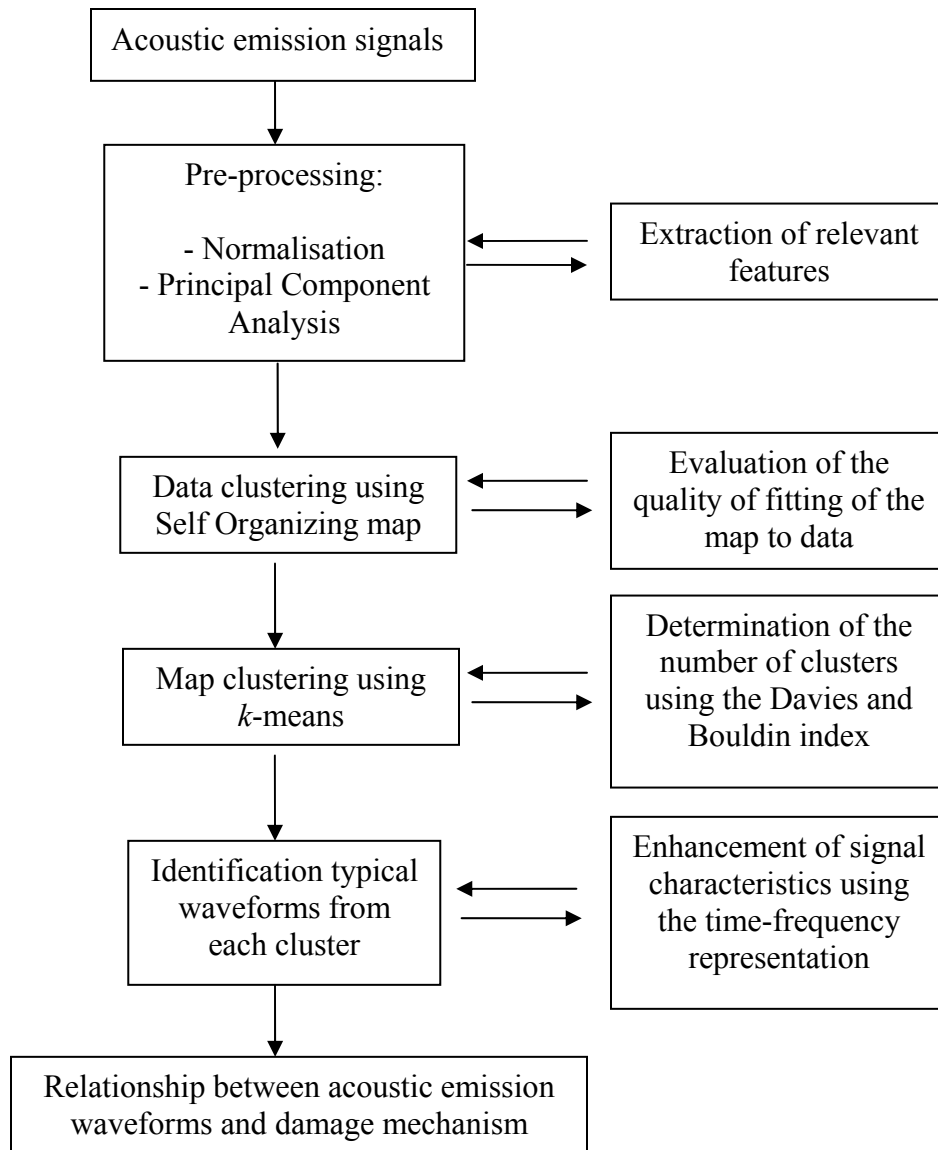


Figure 7.16 - Flow chart representation of the pattern recognition procedure

Signal processing was performed using MATLAB software. Clustering programmes were developed based on the freeware Self Organizing Map (SOM) toolbox for MATLAB of Kohonen's group at Helsinki University of Technology [276].

Once acquired, acoustic emission transient signals were saved in an independent computer in a format specific to VallenTR™ software. Transient signals were thus loaded in MATLAB workspace using a visual basic ActiveX control.

7.3.4.2. Features selection

The signals clustering from the entire signal time representation would be time consuming. Acoustic emission parameters were thus calculated from the acoustic emission signals in the time and frequency domain. Parameters were calculated from the acoustic emission waveforms using a MATLAB programme. A floating or adaptive threshold was used in order to remove the part of the signal due to reflections at specimen edges. Huguet [171] also used such floating threshold to isolate the effective component of the signal of the part due to the transducer natural resonance which influences the end of the waveform. Threshold value was fixed to 10% of the signal amplitude.

The results of the study of the monofilamentar specimen underlined the existence of a relation between the amplitude and frequency content of acoustic emission signals with damage mechanism. Besides transverse matrix cracking is known to generate a high frequency high extensional mode. It seems appropriated to use the amplitude and frequency values as features.

In order to avoid signals from grip noise to be treated, only the events located between the transducers were considered.

Fourteen features were extracted from the acoustic emission signals in the time and frequency domains. Besides the traditional acoustic emission parameters (the amplitude in mV, the counts number, the counts to peak, the duration, the rise time and the energy), other parameters were chosen related to the signal waveform (the counts/duration ratio, the ratio of the signal amplitude and the amplitude of the next peak, the ratio of the signal amplitude and the amplitude of the second next peak, the ratio of the amplitude of the first part (1-30 μ s) and second part (30-60 μ s) of the signal). In the frequency domain were selected the peak frequency of the first part (1-30 μ s) and second part (30-60 μ s) of the signal, the frequency value at the spectrum's centre of gravity and the maximum amplitude of the spectrum. Those parameters permitted to make a satisfying dissociation of the wave modes of propagation.

Selected features	Unit
Amplitude	mV
Rise time	μs
Duration	μs
Energy	$1\text{e}^{-7} \text{ V}^2\text{s}$
Counts	—
Counts to peak	—
Amplitude ratio 1	—
Amplitude ratio 2	—
E/F	—
Counts/duration	kHz
FFT peak frequency 1	kHz
FFT peak frequency 2	kHz
FFT amplitude	kHz
Spectrum's centre of gravity	kHz

Table 7.4 - The selected features of the acoustic emission signal

7.3.4.3. Features pre-processing

For an efficient and fast clustering, feature vector should not have too many components. Features must be the less correlated as possible. If some vector components have variance significantly higher than the variance of other components they will dominate the map organization. Feature values variances were thus normalized to one to insure that all components had the same importance. The correlation between features was studied using principal component analysis.

Principal components analysis is a linear technique which transforms a d dimensional vector x into a lower n dimensional vector y . This transformation is carried out by projecting the original vector x onto new orthonormal vectors φ_i that span a lower dimensional space. A new feature vector m composed of a new set of variables, called principal components, is created [192]. Each principal component is a linear combination of the original variables. The first principal component is the combination of variables

that explains the greatest amount of variation. The second principal component defines the next largest amount of variation and is independent to the first principal component. All the principal components are orthogonal to each other so there is no redundant information. Principal components whose variance was superior to 6% of the total variability were selected.

7.3.4.4. Classifier

For data clustering, the number of map units was determined using a heuristic formula which is function of the number of signals to be clustered. The batch version of the training algorithm (equation 5.5) was used for its computing efficiency. The neighbourhood radius decreased monotonically to reach a radius of 1 at the end of training.

The clustering of the map by k -means was repeated 1000 times due to the dependence of the result on the initial location of cluster centres.

In figure 7.17 is represented the adjustment of the map to the data. The map and acoustic emission signals are represented in the space of the two first principal components. A good fitting of the map to the data is observed.

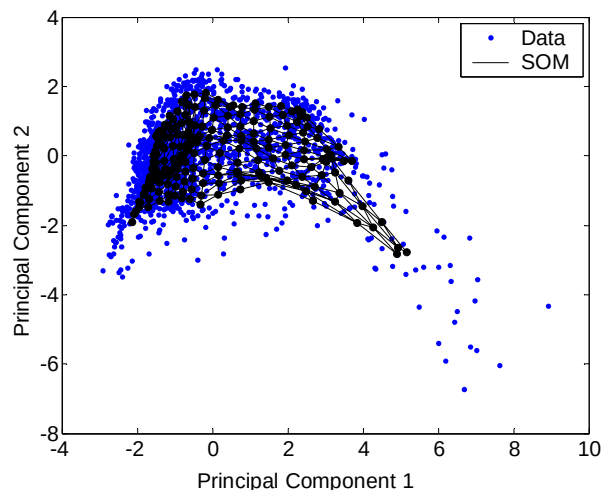


Figure 7.17 - Fitting of the map to the data

7.4. Acoustic emission results

The capability of the classifier to dissociate the different damage mechanisms was verified in the case of three $[0/90_2]_s$ specimens loaded until fracture. The remaining tests (three for each configuration) were interrupted around transverse matrix cracking saturation.

7.4.1. Tests to failure

During testing, of one of the $[0/90_2]_s$ specimens, 4243 events were located between the two transducers. A 45×29 map constituted of 1305 neurons was used for data clustering. In figure 7.18 is represented the map topology after training. It represents the average distance between neurons.

Map clustering by k -means resulted in 10 clusters (figure 7.19). In figure 7.20 is represented the Davies-Bouldin index as function of the cluster number

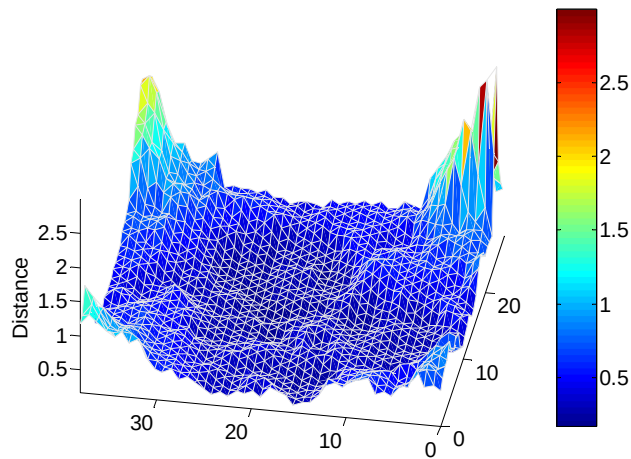


Figure 7.18 - Map topology

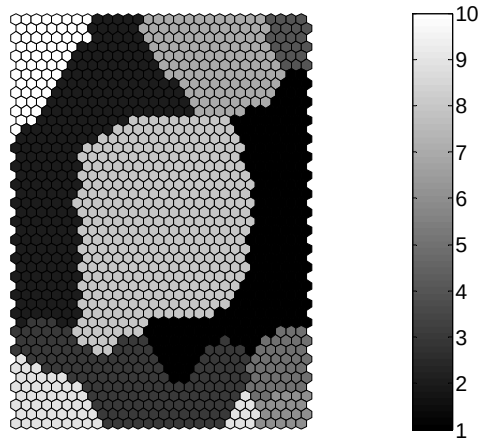


Figure 7.19 - Map clustering

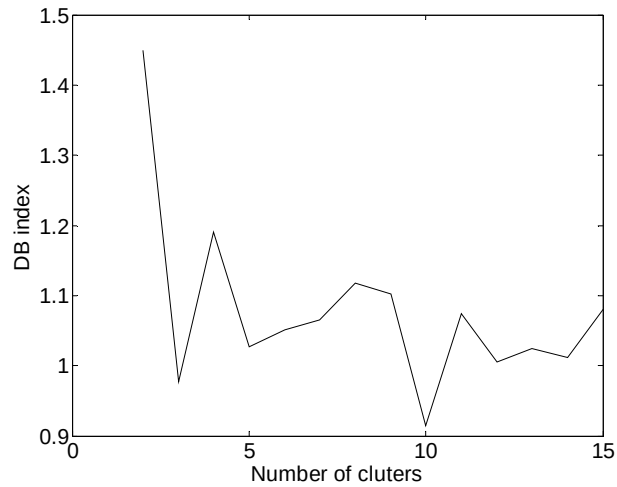


Figure 7.20 - Validity index of partitioning efficiency

In figure 7.21 is visualised the segmentation of the acoustic emission signals. Clusters are overlapping because features vectors, which have fourteen components, are represented in a two dimensional space.

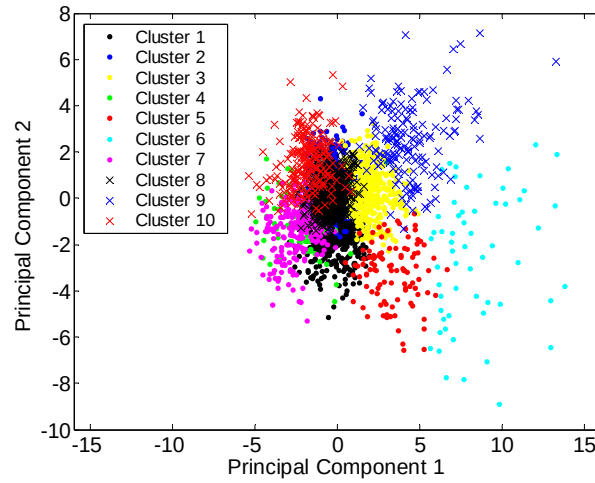


Figure 7.21 - Projections of clusters in the two first principal components space

The evolution of the cumulative events number for each cluster is represented as function of time in figure 7.22. In table 7.5 is summarised the signal repartition in the different clusters.

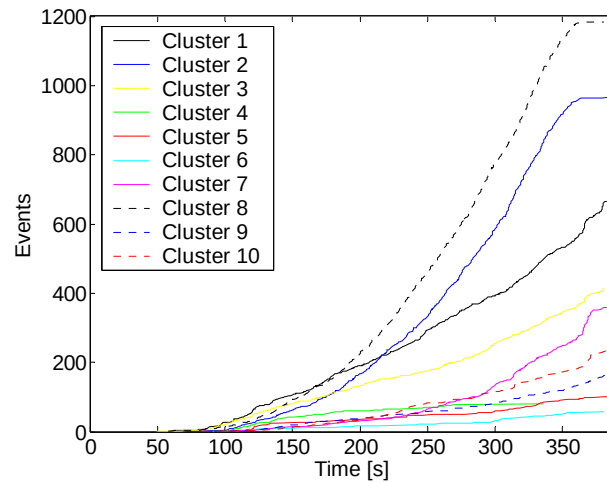


Figure 7.22 - Cumulative events for each cluster

Cluster	Signal repartition	
	number	[%]
1	666	15.7
2	968	22.81
3	415	9.78
4	80	1.89
5	102	2.4
6	58	1.37
7	369	8.7
8	1189	27.9
9	162	3.82
10	239	5.63

Table 7.5 - Repartition of signals in the clusters

The cumulative energy of all acoustic emission detected during testing permits to have an insight about the damage evolution. Matrix cracking initiates around 70 MPa, a decrease of matrix cracking rate is observed at 105 MPa, when delamination and longitudinal splitting is observed, fibre rupture are observed at 230 MPa.

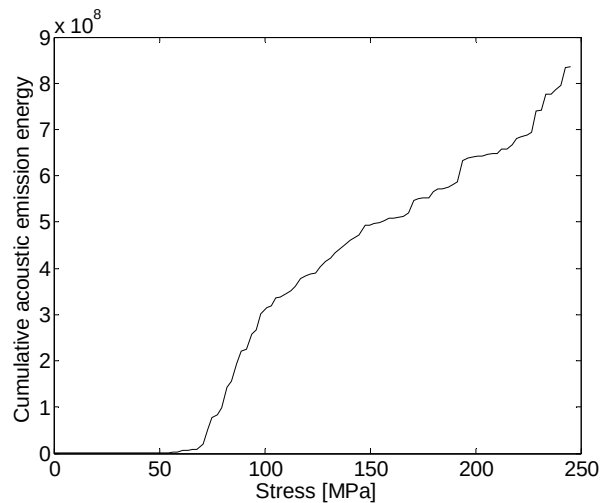


Figure 7.23 - Acoustic emission energy vs. stress

The temporal evolution of the cumulative energy plot can be correlated to the cluster evolution. The first signals to be detected belong to clusters 1 and 3. Then cluster 2 and 8 are observed becoming the dominant clusters after 200 s of testing. The other clusters are observed after 100 s of testing.

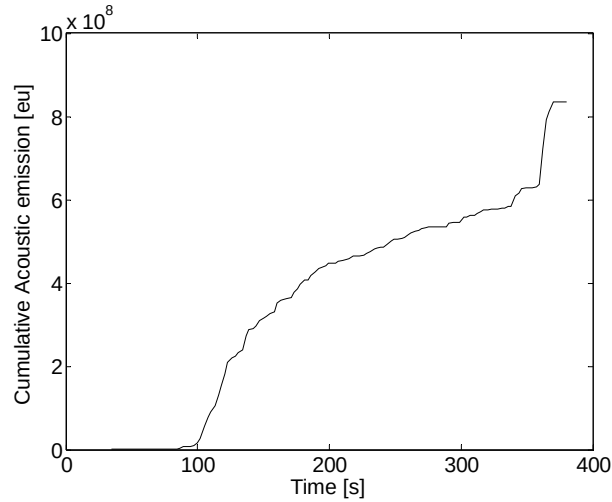
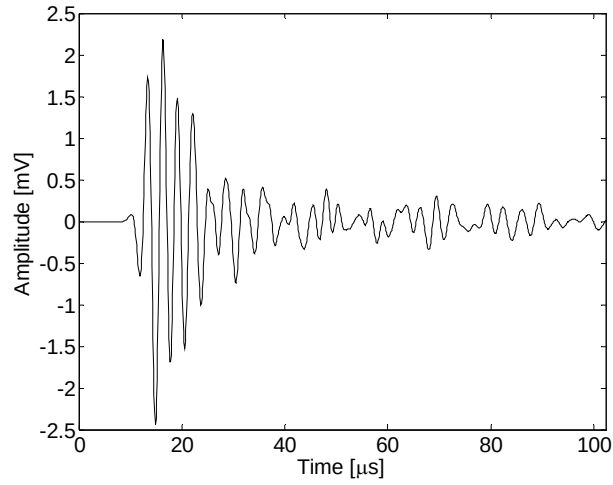


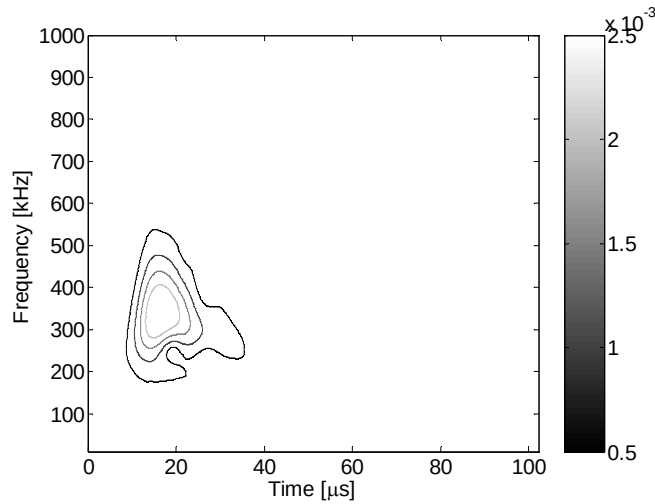
Figure 7.24 - Acoustic emission energy vs. time

The signal waveforms corresponding to the different clusters were analysed in order to find typical signals for the different clusters. The time-frequency representation was used as complementary tool to enhance the signal singularities.

The signal type I is characteristic of the signals observed in cluster 1. From its time-frequency representation it appears that the low frequencies arrived first. This is typical of the extensional mode. Since those clusters appeared at the very beginning of the test and that transverse matrix cracking is the dominant damage mechanisms at that stage, and also considering that transverse matrix cracking generate in-plane movement, those clusters can be attributed to transverse matrix cracking damage.



(a)



(b)

Figure 7.25 - (a) Time and (b) time-frequency representation of signal type I

The signal type II is characteristic of the signals observed in the cluster 3. It is an extensional mode. From the time-frequency representation, it appears to be almost dispersionless.

The peak of the wavelet scalograms for signal type I and II are around 400 kHz, besides the decrease of the matrix cracking rate, observed at around 130 s, is traduced by a decrease of the activity of both clusters 1 and 3. This cluster is thus also thought to be due to transverse matrix cracking.

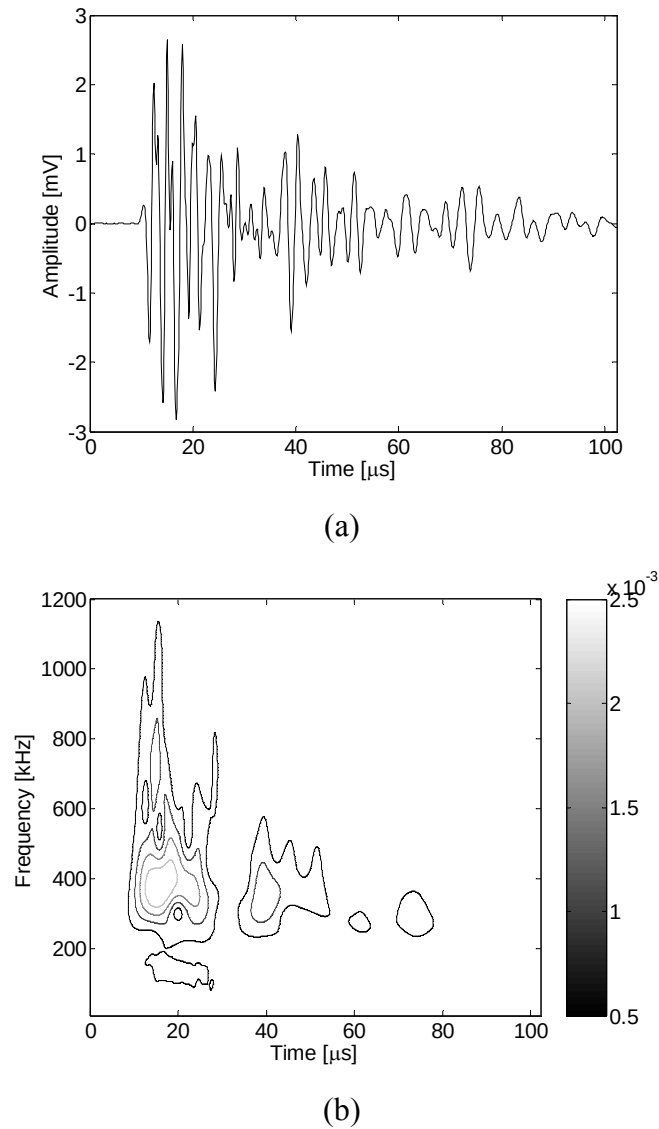
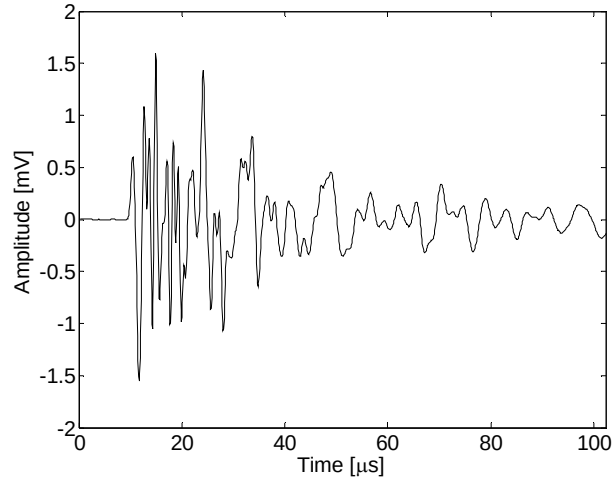
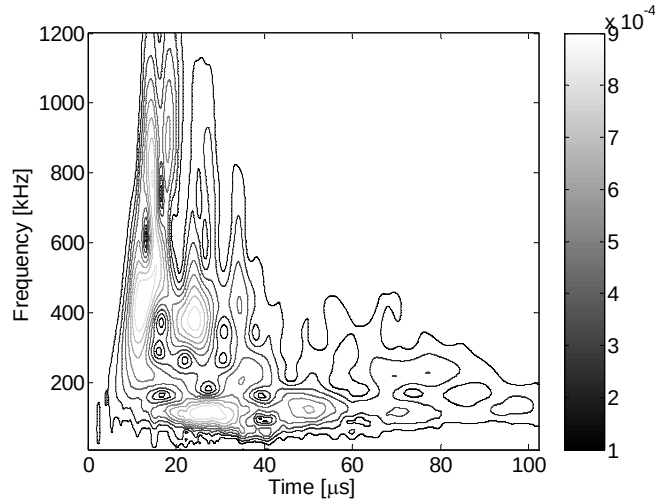


Figure 7.26 - (a) Time and (b) time-frequency representation of signal type II

For both clusters, the transverse matrix cracking saturation is not noticeable. Looking at the signals detected closer to the specimen fracture, a different waveform is noticed (type III).



(a)



(b)

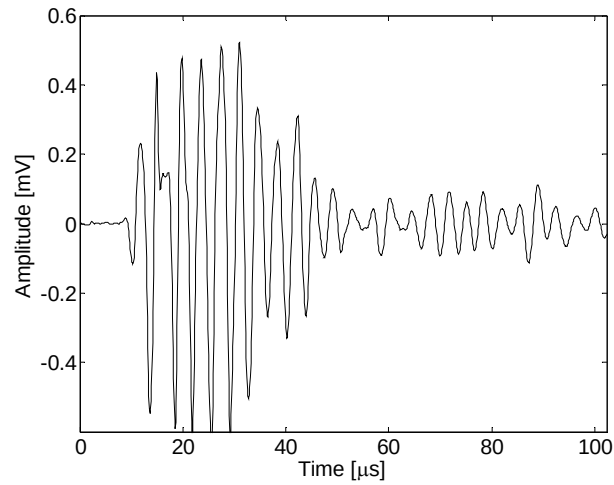
Figure 7.27 - (a) Time and (b) time-frequency representation of signal type III

This signal has a higher frequency content than the two previous signals. It is dominated by the extensional mode like for the two previous signals but a strong flexural mode is also observed, that was not seen in the two previous signals. Johnson [65] observed the same when transverse matrix cracking occurred in the outer layer of $[90_2/0]_s$ laminates. He attributed the existence of a high flexural mode component to matrix cracking with non-symmetric crack geometry as it occurs in the outer ply of laminate. In the case of the $[0/90_2]_s$ laminate, longitudinal matrix cracking occurred prior to fracture in

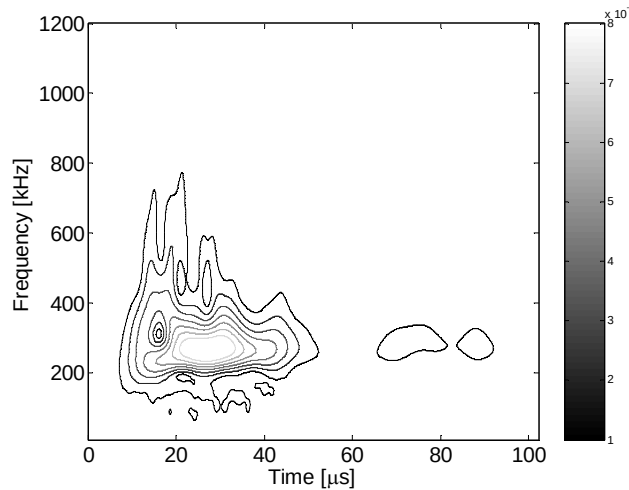
the 0° layer. The signal type III is observed at that phase of the test, it can thus be thought that the signal type III corresponds to longitudinal matrix splitting.

Both signals type II and III were also observed in the cluster 9.

The signals observed in clusters 2 and 8 have similar characteristics to the signal represented in figure 7.28.



(a)



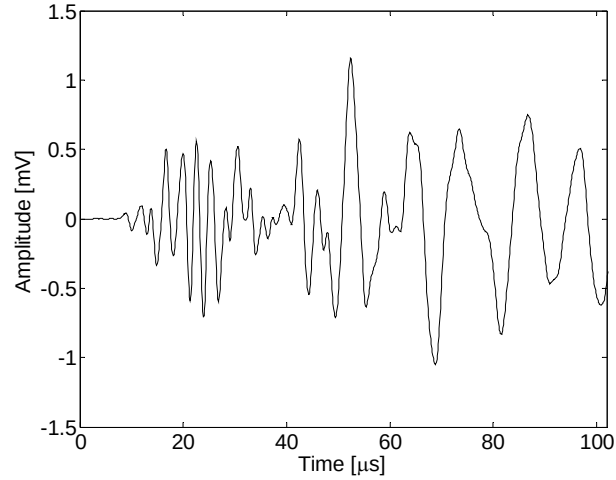
(b)

Figure 7.28 - (a) Time and (b) time-frequency representation of signal type IV

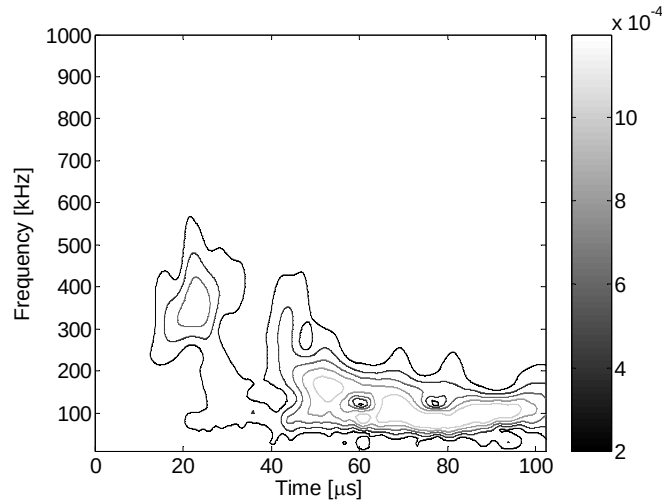
The dispersive nature of the wave is underlined in its time-frequency representation. This is typical of a flexural mode due to out-of plane displacement. Most of the signals in

this cluster are detected when delamination occurs. This signal can thus be thought to be due to delamination initiating at edges. However, delamination initiation occurs later in the test. Matrix/fibre decohesion also generates a motion that is largely out of plane and that promotes the flexural mode. These clusters are thus thought to be due to both damage mechanisms.

In clusters 7 and 10 are observed signals similar to signal type V.



(a)



(b)

Figure 7.29 - (a) Time and (b) time-frequency representation of signal type V

In this signal the extensional and the flexural modes are present. The flexural mode is dominant. This wave is thus due to out-of-plan displacement. The cluster's main activity is observed at the final part of the testing when extended delamination occurs. Those clusters are thus thought to be due to delamination.

The last signal type (VI) is observed in the clusters 5 and 6. These signals are observed at the end of test. They consist of a high frequency extensional mode. This is thought to be due to fibre cracking.

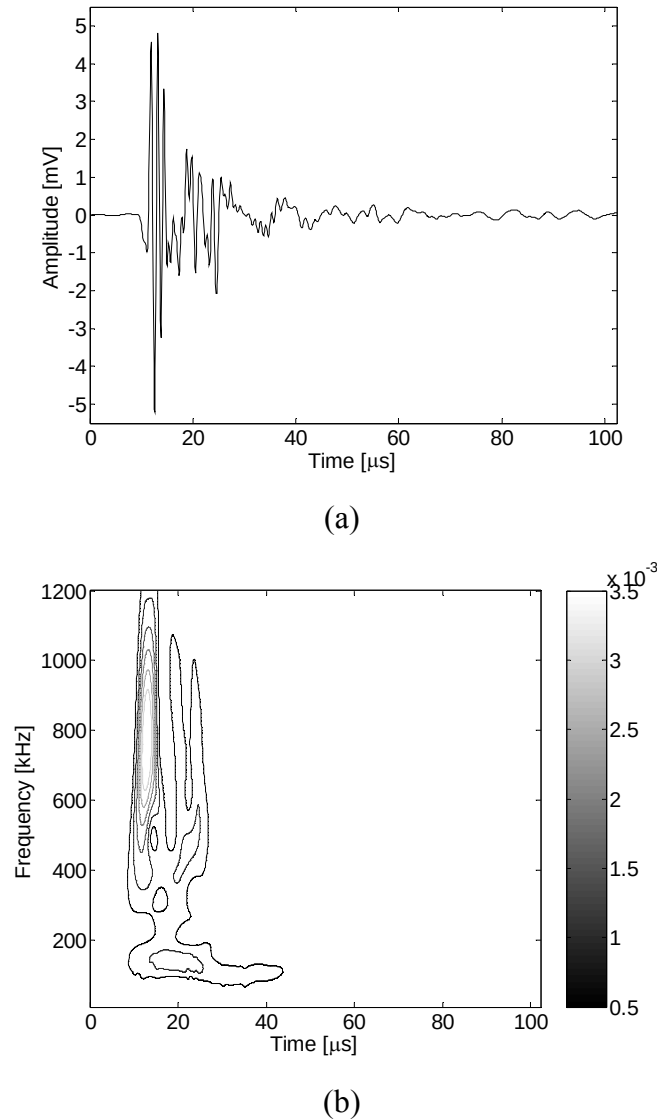


Figure 7.30 - (a) Time and (b) time-frequency representation of signal type VI

The signals observed in cluster 4 are thought to be due to frictional noise.

7.4.1.1. Conclusions

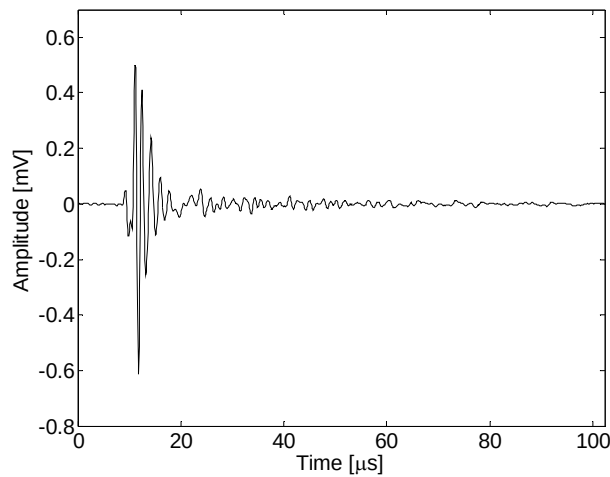
The case of the tensile test to failure of the $[0/90_2]_s$ 15 mm specimen permitted to validate the pattern recognition procedure. It successfully distinguished different signal waveforms along the test. The time frequency representation revealed to be particularly powerful to get an insight about the source of the acoustic emission signals.

7.4.2. Transverse matrix cracking analysis

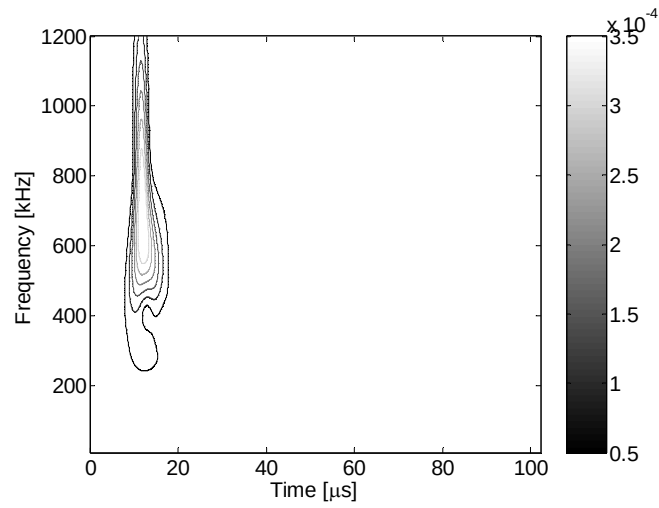
A particular attention was devoted to transverse matrix cracking. This damage mechanism was controlled as mentioned previously. Three specimens were tested for each configuration.

Were only considered the signals detected when transverse matrix cracking was the dominant damage.

Two signals types were identified in the different configurations. They are identified as signal A and B.

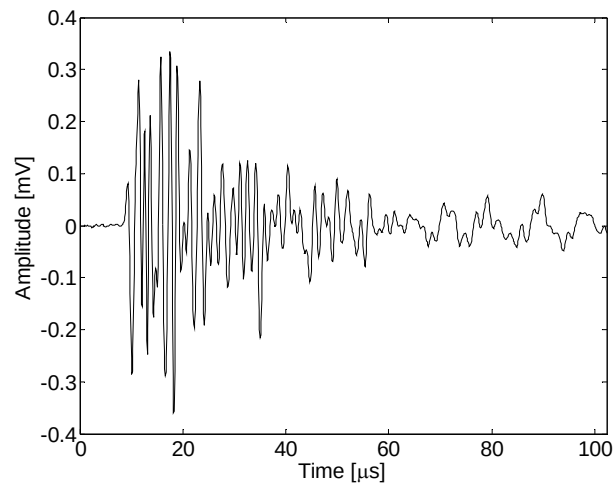


(a)



(b)

Figure 7.31 - (a) Time and (b) time-frequency representation of signal A observed in a $[0/90]_s$ specimen



(a)

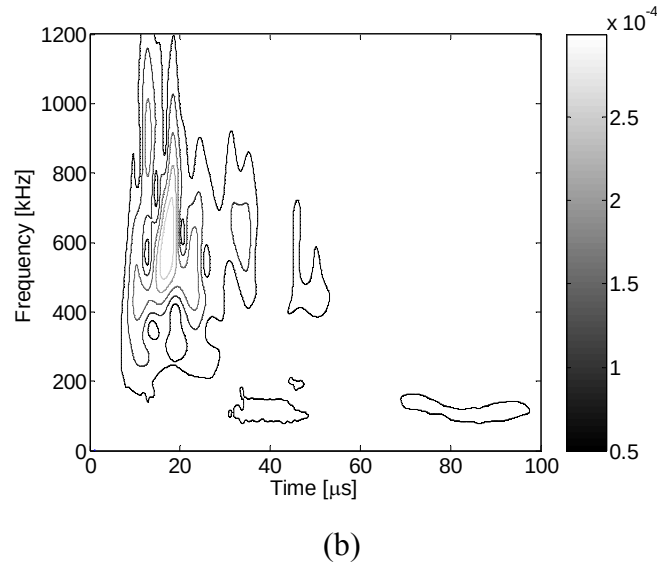


Figure 7.32 - (a) Time and (b) time-frequency representation of signal B observed in a $[0/90]_s$ specimen

The signals A and B are similar to the signals I and II in the previous case. The signal's characteristic parameters are summarised in the table 7.6. Parameters are obtained using the floating threshold.

	Signal	Amplitude [dB]	Rise Time [μs]	Duration [μs]	Counts	Peak Frequency [kHz]
$[0/90]_s$	A	45-59	1.1-3.1	4.5-33.5	3-13	400-840
	B	45-71	1.1-8.5	30.8-93.3	8-29	350-760
$[0/90_2]_s$	A	46-73.5	1.4-5.5	10.3-51.1	4-16	350-560
	B	45.7-73	1.9-13.6	42.3-95	9-27	290-590
$[0/90_3]_s$	A	47.4-71.2	1.7-8.6	12.3-48.3	5-14	275-520
	B	45.3-78.3	2.1-19.3	35.2-94.5	10-29	260-550

Table 7.6 - Acoustic emission signals parameters

Signal A is a short duration signal with fast damping aspect, whereas the signal B is a long duration signal. The signals amplitude doesn't vary significantly with the 90° layer thickness, but higher amplitudes are observed for the thicker 90° layers specimens.

Acoustic emission signals observed for thinner 90° layers specimens have higher peak frequency.

Signals A and B are observed for the three specimen widths. But more signals of the type A are observed for the lower width specimens (table 7.7). It is thus thought that the signal A is due to microcracking and signal B to the propagation of transverse matrix cracking.

Lay-up	Width [mm]	Signal repartition [%]	
		A	B
[0/90] _s	15	41.2	58.8
	25	30.47	69.5
	50	24.3	75
[0/90 ₂] _s	15	27	62.5
	25	14	79
	50	22	69.9
[0/90 ₃] _s	15	11	68
	25	10	78.25
	50	5	85

Table 7.7 - Signals repartition

7.5. Conclusions

In this chapter, it was proposed to develop an automated procedure for the analysis of the acoustic emission signals in order to identify the damage mechanisms source of acoustic emission. An unsupervised classifier based on artificial neural network was proposed which successfully clustered the signal waveforms detected during tensile loading of cross-ply laminates. Those laminates were chosen for having a damage sequence that is well known.

The application of intelligent processing procedure such as neural networks is sometimes subject to critics for not contributing to a deeper physical understanding of the acoustic emission phenomenon. In this chapter, the use of a broadband transducer

especially designed for modal acoustic emission and the application of the time-frequency analysis to the signals clustered by the classifier, permitted to obtain a more quantitative information about the damage. The damage mechanisms could so be discriminated.

For some damage mechanisms were attributed more than one cluster. It reveals that the Davies-Bouldin index values should be used as guideline rather than absolute truth. The index plot has several local minima that can also be considered worth.

Chapter 8

Optic fibre sensor

8.1. Introduction

The evolution in the fibre optic telecommunication and optoelectronic industries has enabled the development of optical fibre sensors. This development, in combination with advances in composite material technology, has opened up the new field of fibre optic smart material structures, the workability of composite materials ensuring a good embedding of fibre optic sensor into the material. The obtained structure has the ability to sense environmental changes inside or around. It can interpret and eventually react to that environmental effect, by the mean of actuators.

Fibre optic sensors are attractive because they offer a series of advantages over conventional electrical sensors [277,278,279]. They are immune to electromagnetic interferences. Due to their small size they can be easily embedded. They can be used for a conception of a distributed sensor system working over large distances. They can be multiplexed along a single line, allowing different physical measurand to be simultaneous sensed using a single optical fibre. They also support high frequency bandwidth necessary for large numbers of high-performance sensors. They can sustain high temperatures, can operate in a variety of chemical and aqueous environments, providing sometimes monitoring of otherwise inaccessible areas.

Embedding optical fibre sensors in composite materials can improve the manufacturing process by monitoring such parameters as temperature, pressure, strain, degree of cure, chemical content, and viscosity [277]. They can also be used, such as in this application, to assess the integrity of the structure during handling. It is here intended to verify the potentiality of fibre optic sensors for the detection of acoustic emission waves.

8.2. Optical fibre

Optical fibre is a cylindrical dielectric waveguide operating at optical frequencies. Optical fibres are fabricated from polymer, glass, or ceramic materials. They consist of a central core of material surrounded by a concentric cladding. The core and cladding are both composed of materials of similar composition, but with different indices of refraction, i.e. the ratio of the speed of light in a vacuum and the speed in matter [7,278,280]. The cladding reduces scattering loss resulting from dielectric discontinuities at the core surface, adds mechanical strength to the fibre, and protects the core [280].

For most low to moderate temperature applications, silica-based optical fibres with a melting temperature of about 1400 °C are adequate. For very high temperature, higher cost sapphire fibres can be used [277].

The optical fibres are classified according to their index of refraction profile, e.g. step-index or graded-index, which defines their optical waveguide properties. In step-index optical fibres, the index is uniform throughout the core and undergoes an abrupt change at the cladding boundary. In graded-index optical fibres, the core refractive index varies as a function of the radial distance from the centre of the fibre [280]. Core diameter is function of the desired waveguiding properties of the fibre. Typical diameter of optical fibre is more than 100 μm [7].

The index of refraction, of the core is required to be slightly greater than the index of the cladding. Therefore, the light will propagate along the fibre waveguide through multiple reflections at the core-cladding interface. To prevent the optical fibre from moisture and to improve its handability, it is also clothed by a coating [281]. This coating is either thermoplastic or thermoset and can be manufactured with a wide range of properties. Coating degradation during the composite cure process must be avoided. A special care must be taken to ensure the quality of the adhesion between the optical fibre and the host material. A good interface will allow a good stress transfer and accurate measurements. It is important for the coating to be chemically compatible with the resin of the host material.

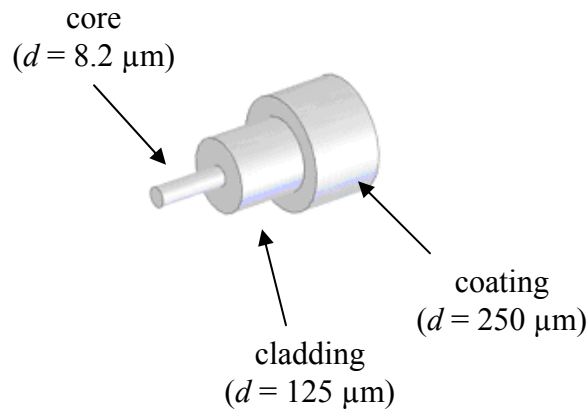


Figure 8.1 - Optical fibre

8.3. Light propagation in waveguides

The light is a dual phenomenon, presenting corpuscular and wave characteristics. Maxwell's work concerning the light determined its electromagnetic wave nature. The wave theory of light adequately accounts for all phenomena involving the transmission of light. However, in dealing with the interaction of light and matter, as occurs in dispersion, and in the emission and absorption of light, the wave theory of light is not appropriate. The quantum theory indicates that optical radiation has particle as well as wave properties. The particle nature arises from the observation that light is always emitted or absorbed in discrete units, called quanta or photons. The energy of photons depends upon the frequency. This frequency is measured by observing a wave property of light. The propagation of light along a waveguide can be described in terms of a set of guided electromagnetic waves called the modes. Each guided mode is a pattern of electric and magnetic field distributions that are unchanged along the propagation in the fibre. Only a certain discrete number of modes are capable of propagating along the guide. These modes are the electromagnetic waves that satisfy the homogeneous Maxwell's wave equation in the fibre and the boundary conditions at the waveguide surfaces. Light waves are transverse, i.e. the wave motion is perpendicular to the direction in which the wave travels. The standard wave equations of propagation of the electric and magnetic fields in cylindrical coordinates have the form [278,280].

$$\frac{\partial^2 E_z}{\partial r^2} + \frac{1}{r} \frac{\partial E_z}{\partial r} + \frac{1}{r^2} \frac{\partial^2 E_z}{\partial \phi^2} + (k^2 - \beta^2) E_z = 0, \quad (8.1)$$

$$\frac{\partial^2 H_z}{\partial r^2} + \frac{1}{r} \frac{\partial H_z}{\partial r} + \frac{1}{r^2} \frac{\partial^2 H_z}{\partial \phi^2} + (k^2 - \beta^2) H_z = 0, \quad (8.2)$$

where r is the radial parameter, E_z and H_z are, respectively, the longitudinal component of the electric and magnetic field, ϕ is the azimuthal angle, and β the component of the wave vector along the fibre axis. The solutions to these equations are Bessel functions [278,280].

Another method for theoretical study of the propagation characteristics of light in an optical fibre is the geometrical optics or ray-tracing approach. The rays are line drawn perpendicular to the wavefronts. This approach provides a good approximation to the light acceptance and guiding properties of optical fibres when the ratio of the fibre radius to the wavelength is large [278,280]. The concept of reflection and refraction, controlling light propagation through the fibre, can be interpreted most easily by considering the behaviour of light rays associated with plane waves travelling in a dielectric material [278,280]. When a light ray encounters a boundary separating two different media, part of the ray is reflected back into the first medium and the reminder is refracted as it enters the second material (figure 8.2). The reflected ray lies in the same plane as that of the incident ray and the normal to the boundary at the point of incidence, i.e. the plane of incidence. The angle of reflection equals the angle of incidence. The refracted ray also lies in the plane of incidence. The refraction of the light ray at the interface is function of the difference of index of refraction of the materials. The relationship at the core-cladding interface is known as Snell's law and is given by

$$n_0 \sin \phi_0 = n_1 \sin \phi_1, \quad (8.3)$$

where n_0 is the index of refraction of the core, n_1 the cladding index of refraction, ϕ_0 the angle between the incident ray and the normal to the interface, and ϕ_1 the angle between the refracted ray and the normal to the interface.

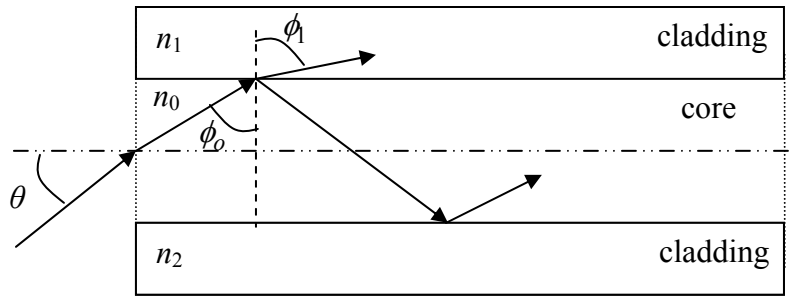


Figure 8.2 - Ray passage along a step-index optical fibre

For the light passing from a higher to a lower index medium, like in optical fibre, when increasing the incident angle a value of ϕ_0 will be reached, at which no refraction occurs. This angle is called the critical angle of incidence ϕ_c . In this case, the refracted ray propagates along the interface and does not penetrate into the core. For angles greater than ϕ_c , the ray is entirely reflected back into the core. This phenomenon is known as total internal reflection [278,280].

The advantage of the ray approach, compared with the electromagnetic wave modal analysis, is that it gives a more direct physical interpretation of the light propagation characteristics in an optical fibre. Despite the usefulness of the approximate geometrical optics method, it cannot be applied to the analysis of single-mode or few-mode fibre. In those cases, the electromagnetic theory must be used, as well as for the analysis of interferences [278,280].

When electromagnetic waves propagate along the waveguide, they are attenuated. The losses are due to absorption, scattering, microbending losses and reflection [278,280]. The optical signal becomes also increasingly distorted as it travels along a fibre because of the material dispersion and waveguide dispersion. Those phenomena must be taken into account when optical fibres are used in communications, long optical fibre lengths being involved. In most silica-based fibres, the least power loss occurs around 1550 nm [280].

8.4. Mechanics of embedded optical fibre in composite materials

8.4.1. Interface optical fibre/host material

Embedded optical fibres are foreign entities to the host material. Their presence alters the stress and strain state in the host material at their vicinity. In [281,282,283] are presented different analytical, numerical and experimental stress analysis studies, where the local interaction between the embedded optical fibre sensor and its host were investigated. Different materials and stacking sequences have been investigated. Almost all studied composites lay-ups consisted of laminas oriented at 0° and 90° according to the loading direction. A variety of optical fibre sizes, coating, and spacing were used. Optical fibres were embedded whether parallel or perpendicular to the adjacent fibre orientation and/or to the load, in the 0/90, 90/90, or 0/0 interfaces. No general theory could be proposed to determine the mechanical properties of a given composite lay-up, with a given embedded optical fibre, from all these investigations [3,281,283]. However some conclusions could be deduced, e.g. when the embedded optical fibre diameter is larger than the thickness of the lamina containing it, local distortions appear [284].

Strain concentrations at the vicinity of the optical fibre have been confirmed by Moiré interferometry observations [285,286,287]. The strain concentration seems to depend on the optical fibre diameter coating compliance, and composite lay-up [282,285].

The strain state in the optical fibre core is different from the far-field value in the host [282]. Thus, when using the optical fibre sensor to measure the strain state inside the material, a calibration is required in order to establish a relationship between the host strain and the strain measured by the sensor.

When embedding the optic fibre in a laminate, a resin pocket along the optical fibre is formed. Analytical [288] and numerical models [288,289] to understand the resin pocket geometry and its effect on strain concentration have been also elaborated. The resin pocket shape becomes smaller as the angle between the optical fibre and adjacent lamina reinforcement orientations and/or the laminate thickness decreases [282,290]. This resin pocket acts as an interlaminar discontinuity. Stress concentrations are observed at the vicinity of the optical fibre according to the resin pocket shape. From these stress concentrations, premature microcracking might appear. In the literature, few papers

handled this question. There exists no real consensus concerning whether the observed microcracks initiate from or terminate at the optical fibre, or simply pass through it. For compliant coating and low coating-optical fibre adhesion values, cracks may stop at the fibre and propagate along the interface coating-optical fibre, whereas for stiff coating, the crack will propagate through the fibre [282].

Seo et al. [291] studied the effect of the presence of embedded optical fibre sensors on the transverse crack spacing of cross-ply laminates using modified shear-lag analysis. It has been found that the transverse crack spacing was not affected significantly by the embedding of optical fibres at low volume fraction of optical fibres. However, the cracks of specimens with embedded optical fibres were initiated at a slightly lower stress level and showed smaller spacing at the same stress level than those of specimens without embedded optical fibres.

Single ended fibre optic sensors, like Fabry-Pérot interferometer, often involve the termination of the optical fibre within the host material. The termination of the optical fibre leads to the formation of a resin-cone at the tip of the optical fibre, what increases the risk of interfacial failure and raises the local stress concentration in the host material [292]. Leblanc [293] studied this problem and noted that by using a coating with the same stiffness as that of the host matrix, the effects of sharp stiffness discontinuity at the end of the optical fibre are eliminated. Polyimide and epoxy coating appeared to be satisfactory for the end-zone problems [293].

8.4.2. Influence of optical fibre on composite material mechanical behaviour

The embedding of the optical fibre must be very cautious, in order to avoid the compromising of the material integrity. It is then important to guarantee that the presence of the embedded optical fibre won't harm the performances of the host material. In [281,283,292] are reported investigations where the fracture toughness, the shear strength, the behaviour under quasi-static, low-velocity-impact, compression, and bending loading of composites with an embedded optical fibre were studied. The effect of embedded optical fibres on material long-term properties, i.e. the fatigue life, has surprisingly received little attention [4].

Not all mechanical properties are equally influenced by the optical fibre embedment [281,283,292]. The results depend heavily on the material structure, on the optical fibre diameter, placement, coating, and orientation. When the optical fibre is embedded parallel to the structural fibres and with appropriate coating, the structural integrity is less affected. The tensile strength is not measurably degraded for different optical fibre spacing, optical fibre size and orientation, neither the interlaminar shear strength nor the tension-tension fatigue properties [281,283].

Skontorp [294] has observed no influence on static strength, when the optical fibre was embedded in regions of stress concentrations. Experimental evidences suggest that the transverse strength of the host material is sensitive to the presence of the optical fibre [295]. On the other hand, it has been noticed that compressive strength can be seriously affected by the presence of the optical fibre [281].

In [3,296] an exhaustive investigation on optic fibre embedding influence on mechanical properties has been performed. Optical fibres, with a diameter of 140 μm and polyimide coating were embedded perpendicular to the load direction in [0,45,-45,90]_s carbon/epoxy laminates. Different optical fibre embedment locations were considered, namely at 0/45, 45/-45, 45/90, and 90/90 interfaces. The laminates were submitted to tensile, three-point bending and four-point bending static tests. A special attention was also devoted to fatigue behaviour. Continuous fatigue tests, with a 5 Hz frequency, a stress ratio (R) equal to 0.1 and at three maximum stress levels, respectively 50, 65 and 80 % of the ultimate tensile strength were performed. During the static tests, significant degradations of the tensile strength was observed, when the optical fibre were embedded in the 0/45 interface. The bending strength was degraded when it was embedded in the 0/45 and 45/-45 interface. During fatigue tests, stiffness degradation was observed. The results have clearly shown that some of the configurations cause serious degradations in fatigue properties. The results from all specimens subjected to the lowest stress level showed no sign of damage. For the intermediate stress level, for optic fibre placing in the -45/90 and -45/90 interfaces, it was noticed a degradation of the material properties evidenced by premature specimen failures imputed to large distortions in the vicinity of the optical fibre and, in some cases, delamination affected these interfaces. For the highest stress level, premature failures for all configurations were observed. The

embedment of the optical fibre in the 90/90 interface demonstrated to be the optimal configuration as no mechanical properties was degraded.

In [297] the embedded optical fibre sensor was not found to affect the fatigue life of the composite under both tension/tension and tension/compression loading of a sixteen plies [0/90] carbon/epoxy laminate.

Silva et al. [298] investigated the behaviour of eighteen plies carbon/epoxy unidirectional ($[0_{18}]$) and cross-ply laminates composed of the successions of $[0_2/90_2]$ plies, of prepregs subjected to three-point bending fatigue tests. The influence of optical fibre location was evaluated. The optical fibre was embedded, whether parallel or perpendicular to adjacent reinforcement orientation, in the laminate's middle plane or nearly the surface subjected to loading. Fatigue tests were performed with a 6 Hz frequency, at $R=0.1$, and for 75% and 90% of the ultimate tensile strength. Fatigue test damages were monitored by dynamic stiffness decaying as well as with acoustic emission. Static flexural tests demonstrated little influence in host mechanical properties, but optical fibre markedly prejudiced the fatigue performance of the material for some particular configurations. The most critical configurations contained the optical fibre in the laminates middle plane. For cross-ply laminates a reduction of about 20% of the stiffness was observed, and was related to high shear stress levels.

Cheol et al. [299] investigated the effect of embedded optical fibres on the interlaminar fracture behaviour of composite laminates. Double cantilever beam tests and end notched flexure tests were performed to obtain the mode I and mode II interlaminar fracture toughness, respectively. Two different stacking sequences of glass fibre/epoxy matrix composite laminates $[0_{18}/OF/0_{18}]$ and $[0_6/90_4/0_8/90/OF/90/0_8/90_4/0_6]$ were studied, where OF corresponds to the optic fibre. It was shown that the mode I and mode II interlaminar fracture toughness values were in general little affected by the optical fibres embedded in the same direction as the crack propagation. In contrast, for composites with optical fibres embedded in the direction perpendicular to crack propagation, the mode I fracture toughness was generally lower than for those without embedded optical fibres, while the mode I fracture toughness showed large increases at the locations of optical fibres where the crack arrested.

8.4.3. Conclusions

From the literature review, it appears that the optical fibre should be embedded parallel to the adjacent reinforcement, in order to avoid significant decrease of the host material mechanical performance. The nature of the optical fibre coating is also relevant for the interface quality. Epoxy and polyimide coating improve it.

8.5. Optical fibre sensor

Optical fibre sensors are a mean whereby light guided within an optical fibre can be modified in response to an external physical, chemical, biological or similar influence. The optical sensor translates the alterations observed in the light characteristics (intensity, frequency, wavelength, phase and/or polarization) caused by the variations of the measurand. Once we can control the external influences such as eventual variations in the optical power of the source, losses in the optical components, environmental noise, etc., it is possible to associate those alterations to the variations of the measurand.

Fibre optic sensors can be classified as extrinsic or intrinsic sensors. In the former, sensing takes place in a region outside of the fibre. Thus, the fibre essentially serves as a conduit for the transmission of light to the sensing region. In an intrinsic sensor, one or more of the physical properties of the fibre undergoes a change, which gives a measure of the external perturbation.

Fibre optic sensors can also be classified according to the parameters of the light that are modulated: the intensity, the wavelength, the phase and the polarization [279].

Intensity-modulated sensors detect an amount of light, which is perturbed by environmental effects. This perturbation is function of the measurand. Those sensors are low cost and simple to implement. The main causes for intensity modulation are transmission, reflection and microbending [279]. Those sensors are essentially used as strain, pressure and vibration sensor [300].

Wavelength-modulated, like the fibre Bragg grating, have a resonance condition at a specific wavelength. Light at that wavelength is reflected. Changes in strain and temperature cause a wavelength shift, which is a direct measure of the change in strain and/or temperature.

Phase-modulated sensors use interferometric techniques. The small phase variations caused by the action of the measurand can be quantified by comparing the phase of the radiation that is transmitted along the measure area with the phase of another coming radiation of the same optical source, not subjected to the action of the measurand. This kind of sensors is extremely sensitive. The recovery of the interferometric phase, which contains the information is not straightforward and requires a demodulation.

Polarization or polarimetric sensors are based on birefringent fibres for which the core refractive index is different depending on the polarization and direction of propagation of the light. When a linearly polarized light is launched into a birefringent fibre, the existence of the birefringence divides the light into two eigenmodes and allows it to travel along two orthogonal axes at different phase velocities. The variations of the velocities, being induced by the external load, can then be related to mechanical strains [301]. The entire fibre can be used for sensing. The major disadvantages of this type of sensor are their high cost, complexity of the sensing system, low axial strain sensitivity and three-dimensional nature in measured strain [301].

8.6. Damage detection in composite materials using optical fibre sensors

Different optical fibre sensors have been successfully used to assess damage in composite materials [301,302]. This was done from acoustic emission waves sensing but also from other methods such as the fracture of the optical fibre, or the strain measurement.

8.6.1. Damage detection by optic fibre failure

Such optical fibre sensors have been essentially used for impact and fatigue damage assessment, which are of major importance for aircraft structures.

To develop such damage system, an a priori knowledge of the location of the sensor as well as of the failure mode of the optic fibre is crucial, e.g. optical fibre sensor should be rather sensitive to shear cracking for impact damage assessment [302]. Embedding optical fibres at different depths and along different orientations, it is possible to determine the damage location and to monitor damage progression [303]. These optical

fibres were shown to fail in impacted specimens at higher impact energies than required to cause delamination in the material. It was observed that fibres failed only in the smaller specimens, as larger specimens were not free to bend, and that the fibres near the tensile surface were much more sensitive [303].

Glossop et al. [304] observed that severe impact damage could appear without fracturing the optical fibre. One solution proposed to overcome this problem was to use a weaker optical fibre, by applying a surface treatment prior to embedding. Controlling the strength of the optical fibres, different levels of damage could be detected.

Waite [305,306] applied this methodology to monitor fatigue damage in composite materials. Distinction was made between early fatigue damage detection and significant fatigue damage detection. For early fatigue damage detection silane solution-treated optical fibres, with shorter fatigue life than that of the glass reinforced plastic composite material, were used. For significant fatigue damage detection stronger optical fibres (hard clad silica fibres) were used, which didn't fail due to their proper fatigue process. In presence of damage the cladding of these optical fibres became damaged, resulting in a progressive attenuation of light with damage extend. The quantitative assessment of the emitted light could therefore be used to estimate the extent of the damage [307]. However the distinguishing of the damage nature is not possible.

8.6.2. Damage detection by strain measurement

The most common method for damage detection using optic fibre sensors consists of measuring the strain. The strain data is used to compute the stiffness when the corresponding stress is known. The consequences of all types of damage in smart structures are local and/or global changes in strengths and stiffness. Fibre optic strain sensors via one of the optical properties, i.e. intensity, wavelength, phase or state of polarization, can measure these changes. Any one of these optical properties can be related to mechanical axial strain.

Fibre Bragg gratings sensors have been the most used for strain measurement as they provide a direct measure of strain. They also have been used for transverse matrix cracking monitoring.

Takeda [308] and Okabe et al. [309] used such sensor to detect and monitor the transverse crack evolution in composite cross-ply laminates. They observed that the local strain distribution within the fibre Bragg grating gage length due to transverse cracking alters the power spectrum of the light reflected from the sensor. The optical power spectrum revealed to be a good indicator for the quantitative evaluation of the transverse crack density in real-time. Delamination could also be detected from the form of the spectrum [310] as it changes sensitively, as the delamination length increased. The authors proposed an intensity ratio in the spectrum for the prediction of the delamination length.

The same authors could determine the transverse cracking locations using chirped fibre Bragg gratings instead of classical fibre Bragg gratings [311]. Normal fibre Bragg gratings sensors, have uniform grating period along the entire length of the gratings, so that the Bragg wavelength is also uniform, and the reflection optical power spectrum has one narrow peak at the Bragg wavelength. Chirped fibre Bragg gratings sensors have grating period that increases monotonously. Thus, the Bragg wavelength is different depending on the position, and the reflection spectrum becomes broad. As a result, the spectra had dips corresponding to locations of transverse cracks.

8.6.3. Acoustic emission detection

Acoustic emission has permitted the damage detection with a higher sensibility than the two previous methods as the lower accessible defect size is not dictated by the spacing between the fibres.

Due to their high sensibility, phase-modulated sensors are obviously the best optical sensor candidates for acoustic emission signals detection. However, they do require a more complicated set-up for signal recovery, what can be a handicap. Among the different interferometers (Fabry-Pérot, Mach-Zehnder, Michelson, and Sagnac), the Michelson and Fabry-Pérot interferometers have been the most employed. Those sensors are based on the same working principle but use slightly different configurations. Michelson optic fibre sensors are easier to fabricate and the signal demodulation is easier than for Fabry-Pérot interferometer sensors. However, its two-optical-fibre arrangement, i.e. the sensing and the reference fibre, makes it quite unsuitable for embedding on smart

structures [312]. It has served as a useful demonstrator of what should be possible with Fabry-Pérot sensors, as their sensitivity is comparable [312].

It is essential to maintain the phase at quadrature point of operation for maximum sensitivity. Various techniques have been developed to stabilize single mode interferometric systems as reported in this literature review.

8.6.3.1. Acoustic emission sensing using optical fibre interferometers

Liu et al. [313,314] embedded optical fibre Michelson interferometers in $[45/-45]_{2s}$ Kevlar/epoxy laminate. The sensor was composed of a pair of unbuffered optical fibre with mirrored ends embedded within the composite material. The quadrature detection was ensured by a low-frequency piezoelectric phase modulation feedback system that also eliminated drifts and slowly varying strains. The composite panels were subjected to out-of-plane loading. Acoustic emission signal from matrix cracking, fibre breakage, or delamination could be detected. Enhanced backlighted images [315] revealed delamination associations with the detected acoustic signals. By plotting the ratio of acoustic energy in the frequency range 100 to 300 kHz and 300 to 600 kHz in function of delamination size a trend was suggested leading to a method of assessing the extent of delamination detected by means of acoustic emission.

Maslouhi et al. [316] also used an optical fibre Michelson interferometer. The characteristics of the signal were extracted in order to classify the data according to the damage type. The classification was performed by automated pattern recognition algorithms. Acoustic emission sensing from standard broadband piezoelectric transducers and Michelson interferometric were compared. The piezoelectric transducer proved to be more sensitive. The authors remarked that the detected waveforms changed during the test but did not established conclusive correlation of these changes. However, they distinguished the different damage modes from the calculated energy distributions.

Tsuda [317] investigated the response of a surface-mounted Michelson interferometric fibre optic sensor to acoustic emission with either in-plane or out-of-plane motion. He distinguished the extensional and the flexural Lamb waves modes, in a thin unidirectional carbon fibre-reinforced plastic plate. Acoustic emission signals were simulated by pencil lead break.

Gong et al. [318] used an amplitude division multiplexed Mach-Zehnder interferometer composed of three arms (two sensing arms and a reference arm) for acoustic emission source location. One-dimensional source location was obtained from signal delays at two sensors. A location accuracy better than 1cm was achieved.

Baillie et al. [319] also used a Mach-Zehnder optical fibre sensor to detect acoustic emission in fibre-reinforced composites. Simulated acoustic emission signals as well as signals resulting from tensile tests were detected. Despite the successfully detection of the onset of damage in the material and reproducible results, the optical fibre sensor was less sensitive than the piezoelectric transducer.

Gunther et al. [320] embedded high finesse extrinsic Fabry-Pérot interferometric sensors in a graphite/epoxy composite laminate for impacts location. The acoustic signals generated from the impact were detected by four optical fibre sensors. An algorithm was developed for damage location from the arrival time difference at the four sensors. The impact location could be determined with a 0.5 mm resolution and accuracy typically less than five millimetres. For lecture of the interferometric signal a simple 50/50 coupler was used to direct the reflected signal to the photodetector. Such set-up is not optimum as it is not stable. Moreover, for low-velocity impacts where the maximum displacement was less than half a fringe, the change in output could be employed to determine the impact magnitude. Thus, it was possible to simultaneously detect the location and strength of an impact using high finesse extrinsic Fabry-Pérot interferometric cavities.

Dorighi et al. [321] used an intrinsic Fabry-Pérot interferometer sensor, embedded in an epoxy plate, for detection of pencil lead breaks simulated acoustic emission signals. In presence of dynamic strains, a stabilization procedure for the interferometer, based on a control loop to shift the laser frequency was used for more reliable results.

Hong et al. [322] developed an optic fibre sensor system for simultaneous sensing of acoustic emission and strain using a single extrinsic Fabry-Pérot. The sensor was based on two single-mode fibres. The second mirror was obtained by gold deposition at fibre's end. A laser diode was used. The extrinsic Fabry-Pérot interferometer was embedded in a twenty layer symmetric $[0_2/OF/90_{16}/0_2]$ graphite/epoxy laminate. The sensor was illuminated by two light sources (a broadband for strain measurement) and a laser diode (for acoustic emission sensing) using a wavelength division multiplexer. Tensile tests were performed to obtain the failure signals. A time-frequency analysis of the signal by

the short-time Fourier transform and the discrete wavelet transform was necessary to enhanced acoustic emission results. Signals due to matrix cracking and fibre breakage were detected.

Borinski et al. [323] employed two optical fibre sensors, with broadband and resonant sensor design, based on the extrinsic Fabry-Pérot interferometer sensing technology to measure both in-plane and out-of-plane acoustic stress waves. The broadband sensor is a conventional extrinsic Fabry-Pérot interferometer displacement sensor formed by the alignment of two optical fibres in a capillary tube. Such sensor is sensitive to displacement along the axis of the sensor. An original alternative out-of-plane sensor was developed using micromachining technology. It consists of a micromachined micro-cantilever beam positioned over an optical fibre. The cantilever beams are formed by etching a silicon substrate. The optical fibre was polished to a 45° angle at the end, which causes the light to propagate perpendicularly out of the fibre. Thus, the light reflects off at the cantilever surface and then is coupled back to the fibre, creating an extrinsic Fabry-Pérot interferometer cavity. The movement of the cantilever is then deduced from the cavity length. The obtained sensor is resonant at approximately 200 kHz. The detected acoustic emission signals by the two sensors were amplified using commercially available acoustic emission preamplifiers, and signal demodulation was performed by a laser-diode and photodetector. The extrinsic Fabry-Pérot interferometer was able to detect events in composites such as fibre breakage or delamination. The resonant sensor demonstrates high variance sensitivity and its signal showed considerable noise, but its performance to simulated waves sensing was comparable to conventional piezoelectric sensors.

Read et al. [324] reported the detection by extrinsic Fabry-Pérot interferometers of the damage induced acoustic emission in an aerospace like carbon fibre composite panel. The sensors were both surface-mounted and embedded within the structure. The low finesse cavity consists of a bare fibre end-face and high-reflectivity metal-coated fibre end-face. Two fixed laser source with different wavelengths were used to recover the sensor signal, In order to compensate the induced sensor dimensions changes due to temperature and/or quasi-static strain effects, laser wavelengths were separated by a quarter of the sensor's free spectral range to allow at least one wavelength to be modulated by the acoustic emission waves. An isolator was used to eliminate reflections back into the laser cavities.

The laser light was routed to the sensor through another (2×1) coupler so that the reflected light could be picked off. The reflected light was then passed through another isolator, required to eliminate unwanted interference effects. The light was divided in two by a (2×1) coupler. A filter gratings on each coupler's output arms rejects one of the two laser wavelengths. Thus a detector at each of the two outputs receives light from only one laser. Pencil lead breaks were performed at different angles from the optic fibre axis to determine the directional nature of the sensor. The panel was cyclically loaded in compression, after the centre of the convex side of the panel was impacted and followed by more cyclic loading. The process was repeated with increasing impact energy. The apparatus had a bandwidth of 1 MHz.

Kim et al. [325] used a low finesse extrinsic Fabry-Pérot interferometer sensor composed of a bare fibre end-face and a gold deposited fibre end-face with high reflectivity. To compensate the fade-out problem a phase-stabilization control sensor system was developed. It is composed of an erbium-doped fibre amplifier source, a fibre Fabry-Pérot tuneable filter and a control-circuit board. The circuit board was developed to control the Fabry-Pérot tuneable filter through which the proper wavelength is able to pass. The light wavelength shift was needed to maintain the phase at the quadrature. The set-up was used as a low cost alternative to a tuneable laser. The system was applied to the detection of simulated waves by lead pencil-break and fracture signals generated during a tensile test of a cross-ply composite specimen.

Yuan et al. [326] studied the possibility of using a Sagnac-like fibre-loop interferometer sensor for acoustic emission sensing in concrete specimens. Its potential for non-destructive evaluation was demonstrated.

8.6.3.2. Acoustic emission sensing using alternative optical fibre sensors

Surgeon [3] developed an acoustic emission intensity-modulated sensor based on the microbending concept. The author applied that sensor for continuous damage monitoring in quasi-isotropic [0/45/-45/90]_s carbon fibre composites. The stress field in a damaged layer was observed to be different to that in an undamaged layer, causing the optical fibre to bend in the material. This change in stress state only was apparent after transverse

matrix cracking had initiated. The sensor could detect the initiation and growth of significant damage by the decrease in the intensity of the transmitted light.

Rippert et al. [327] explored further this concept. They considered that when the wave hits an optical fibre, the stress bends it locally and that some light might be lost. The sensor was embedded into a $[0_2/90_4]_s$ carbon fibre laminates submitted to tensile tests. The obtained optic signal was filtered (adaptive filtering and spectral subtraction filtering) and post-treated by a time-frequency analysis (short-time frequency transform). The sensor could detect damage initiation and characterise its frequency content. Similarities between optical and modal acoustic emission analysis were observed and demonstrated that it should be possible to identify damage phenomena.

Fibre Bragg gratings have also been proposed to sense acoustic emission waves. Perez et al. [328] intended to determine the fibre Bragg grating sensitivity to acoustic emission waves, when attached to an aluminium plate surface. For demodulating the optical response signal, a tuneable matching fibre Bragg grating was used. Acoustic emission events simulated by pencil lead breaks were successfully detected.

Ohsawa et al. [329] developed an original acoustic emission sensor using a simple conventional optical fibre. The principle of the sensor is based on the Doppler-effect in curved optical fibre, i.e. when light with a constant frequency is irradiated on a moving object the frequency of the reflected light changes. A laser Doppler velocimeter was used to measure the phase shift due to acoustic emission waves. The loop-type optical fibre sensor could detect acoustic emission to the same level as piezoelectric transducers. The sensor sensitivity was observed to increase when increasing the number of turns of loops and decreasing the curvature radius of the loop.

Badcock et al. [330,331] developed a new optical sensor based on a fused-tapered optical fibre coupler. The sensor is fabricated by thermally fusing two optical fibres. The fibre sensor was made by placing two single-mode optical fibres (cut-off wavelength 600 nm) in intimate parallel contact and then stretching them under a heat source. The sensor principle is based on the change in the coupling ratio of the fused tapered coupler when it interacts with an acoustic emission event. The feasibility of detecting acoustic emission when the fibre optic sensor was surface-mounted was demonstrated. Correlation between the acoustic emission detected using a conventional transducer and the optic fibre sensor

was obtained for simulate waves and acoustic emission events generated during quasi-static testing of a composite coupon.

8.6.4. Conclusion

Optical fibre sensors have proven to be a good candidate for conception of a nervous system for smart materials, permitting to sense damage. Different sensor configurations have been applied for acoustic emission waves sensing. The majority of the studies on acoustic emission, up to now, have only demonstrated the feasibility of using an optical fibre sensor for acoustic emission detection. Phase-modulated sensors have been the most used as they offer the highest sensitivity. It has been shown that this type of sensor is capable of detecting each individual damage event (e.g. single matrix cracks, fibre breaks) by detection of the transient acoustic emission waves. The difficulty when using such sensor remains the phase recovery and the excess of information. Different interrogation procedures involving feedback control loops, tunable lasers, or piezoelectric have been proposed.

In this dissertation is proposed an interrogation procedure based upon the generation of two quadrature-shifted signals for phase recovery.

8.7. Acoustic emission optic fibre sensor

Generally, in the phase-modulated optical fibre sensors, the light is split and injected into a sensing fibre and a reference one. When the environment disturbs the sensing fibre its length changes, causing a phase shift which can be detected by an interferometer. Both light beams are recombined afterwards. Upon recombination, the phase shift will cause an interference pattern, which can be detected by a photodiode [279].

The optic fibre Fabry-Perot interferometer eliminates the need for a reference fibre by causing two reflections in an optical fibre region bounded by partially transmitting mirrors.

8.7.1. Interference

Optical interference consists on an interaction of two or more lightwaves yielding a resultant irradiance that deviates from the sum of the component irradiances. In order to simplify the representation, let us consider only the case of two coherent monochromatic plane waves, E_1 and E_2 , of the same frequency in a homogeneous medium.

$$E_{1,2}(x, y, z, t) = R_e \left\{ E_{1,2}(x, y) e^{i(wt - kz)} \right\} \quad (8.4)$$

where w is the angular frequency and k the wave vector.

The intensity of the resultant wave has strong variations in space and time. The variation of the intensity is called interference. The intensity, or irradiance, is the light energy flowing per second across the unit area perpendicular to the propagation direction of the wave. It is given by the relation

$$I = \frac{1}{2} \epsilon_0 v E_0^2 \quad (8.5)$$

where E_0 represents the time-independent amplitude of the wave, v the velocity of light in free space and ϵ_0 the permittivity of vacuum. The resulting intensity is

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos \delta \quad (8.6)$$

$I_{12} = 2\sqrt{I_1 I_2} \cos \delta$ is known as the interference term, δ is the phase difference between two lighthwaves.

If the waves have equal amplitude and are coherent, i.e. δ is independent of time, the total intensity can be zero, when δ is an integer multiple of π . In this case, the two waves undergo total destructive interference. By contrast, when δ is an integer multiple of 2π , the total intensity can be double the sum of the intensities of the separate wave. In this case, the two waves undergo total constructive interference.

8.7.2. The Fabry-Pérot interferometer theory

Interferometers are based on the interference of electromagnetic waves. The Fabry-Pérot is the simplest configuration. It consists on two parallel plans separated by a distance, L , varying from a few microns to a few centimetres. The parallel mirrors are aligned with their normal in the direction of propagation of a plane lightwave.

In the cavity, multireflections will occur as the light is repeatedly sent back by the mirrors. In order to determine the cavity Fabry-Pérot transfer function, in transmission and/or reflection, let consider a plane, monochromatic lightwave of angular frequency ω and amplitude E_0 , of incidence angle θ_i , r , t , and r' , t' are the amplitude reflection and transmission coefficients at the first and second interface respectively. The coefficients r , r' , t and t' are related by the Stokes equations [332]:

$$tt' = 1 - r^2 \quad (8.7)$$

and

$$r = -r' = e^{i\pi} r' \quad (8.8)$$

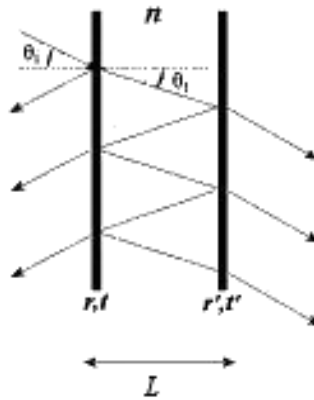


Figure 8.3 - Multiple reflections within a plane mirror Fabry-Pérot interferometer

In figure 8.3 are illustrated the internally reflected rays. The difference in optical path length between two adjacent rays is given by

$$\Lambda = 2nL \cos \theta_t \quad (8.9)$$

The corresponding phase difference associated with the optical path-length difference is the product of the free-space propagation number, k_0 , and Λ :

$$\delta = k_0 \Lambda = \frac{4\pi nL \cos \theta_t}{\lambda_0} \quad (8.10)$$

The interference problem can be treated considering the complex representation of the optic fields. Considering the incident wave $E_0 e^{i\omega t}$, the reflected optical fields are

$$\begin{aligned} E_{1r} &= E_0 r e^{i\omega t} \\ E_{2r} &= E_0 t r' t' e^{i(\omega t - \delta)} \\ E_{3r} &= E_0 t r'^3 t' e^{i(\omega t - 2\delta)} \\ &\vdots \\ E_{Nr} &= E_0 t r'^{(2N-3)} t' e^{i[\omega t - (N-1)\delta]} \end{aligned} \quad (8.11)$$

The resultant reflected scalar wave is then

$$\begin{aligned} E_r &= E_{1r} + E_{2r} + E_{3r} + \dots + E_{Nr} \\ &= E_0 e^{i\omega t} \left\{ r + r' t t' e^{-i\delta} \left[1 + \left(r'^2 e^{-i\delta} \right) + \left(r'^2 e^{-i\delta} \right)^2 + \dots + \left(r'^2 e^{-i\delta} \right)^{N-2} \right] \right\} \end{aligned} \quad (8.12)$$

If $r'^2 e^{-i\delta} < 1$, and if the number of terms in the series approaches infinity, the series converges, and in the case of no energy being taken out of the waves, i.e. zero absorption, that is, $tt' + r'^2 = 1$, the resultant wave can be rewritten.

$$E_r = E_0 e^{i\omega t} \left[\frac{r(1 - e^{-i\delta})}{1 - r'^2 e^{-i\delta}} \right] \quad (8.13)$$

The reflected intensity, I_r , is proportional to the product of the E-field vector with its complex conjugate over a time interval much longer than the period of the wave

$$I_r = \frac{2r^2(1 - \cos \delta)}{(1 + r^4) - 2r^2 \cos \delta} I_i \quad (8.14)$$

Using the trigonometric identity $\cos \delta = 1 - 2 \sin^2(\delta/2)$ the equation becomes

$$I_r = \frac{F \sin^2\left(\frac{\delta}{2}\right)}{1 + F \sin^2\left(\frac{\delta}{2}\right)} I_i \quad (8.15)$$

The irradiance of the transmitted wave can be similarly obtained

$$I_t = \frac{I_i}{1 + F \sin^2\left(\frac{\delta}{2}\right)} \quad (8.16)$$

where the term $\left[1 + F \sin^2(\delta/2)\right]^{-1}$, known as the Airy function, represents the transmitted flux density distribution, $I_i = E_0^2/2$ represents the incident flux, and F the coefficient of finesse, which is a measure of the sharpness of the fringes and is defined by

$$F = \frac{4r^2}{(1 - r^2)^2} \quad (8.17)$$

The Fabry-Pérot interferometer is characterized by its reflectance, R , and transmittance, T , which are normalized functions of the transfer in reflection and transmission, respectively

$$R = \frac{I_r}{I_i} = r^2 = \frac{F \sin^2\left(\frac{\delta}{2}\right)}{1 + F \sin^2\left(\frac{\delta}{2}\right)} \quad (8.18)$$

and

$$T = \frac{I_t}{I_i} = tt' = \frac{1}{1 + F \sin^2\left(\frac{\delta}{2}\right)} \quad (8.19)$$

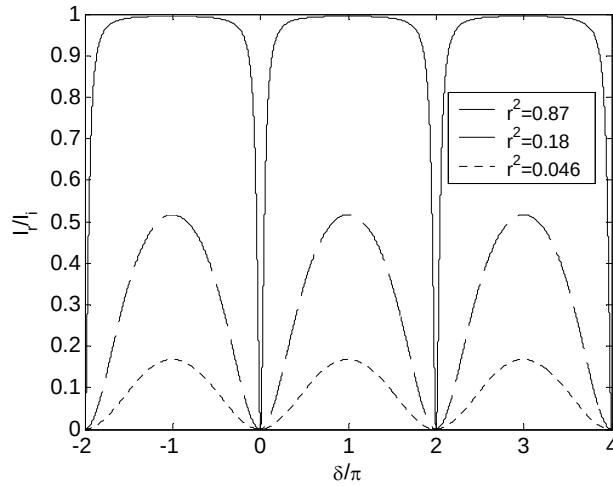


Figure 8.4 - Variance of reflectance of the extrinsic Fabry-Pérot interferometer for different reflectivity values

In figure 8.4 are represented the reflected flux density distribution for different values of r . For $\delta = 2m\pi$, $m \in \mathbb{N}$ (waves are in phase), maximal transmission occurs. This is independent of the reflectivity of the surface, i.e. high transmission may occur for highly reflective surface, even for $R > 99\%$. When $R \ll 1$ the Fabry-Pérot interferometer is called a low-finesse Fabry-Pérot interferometer or Fizeau interferometer.

8.7.2.1. The two-beams approximation

In the case of the optical fibre Fabry-Pérot interferometer, any subsequent reflections, other than the fundamental ones, can effectively be neglected, and a simplified two beam interference analysis can be carried out. For a low finesse cavity, the reflected intensity expressed by equation 8.14 is then approximated by

$$I_r \approx 1 - \cos \delta \quad (8.20)$$

8.7.3. The extrinsic optic fibre Fabry-Pérot interferometer

In this study a low finesse optic fibre Fabry-Pérot interferometer is used for acoustic emission waves sensing. Such sensor is cheap and quite easy to fabricate. It is represented in the figure 8.5.

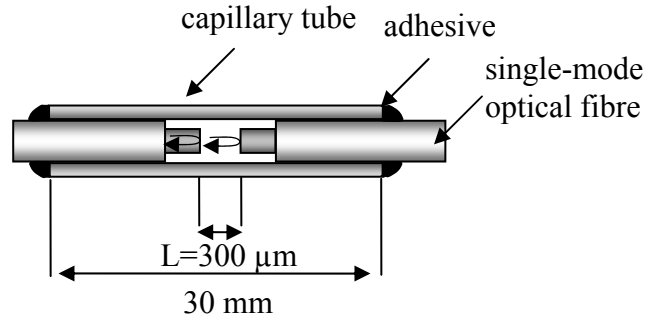


Figure 8.5 - Extrinsic optic fibre Fabry-Pérot interferometer acoustic emission sensor

The reflective plans consist of single-mode optic fibres ends cut at 90° providing a reflection of Fresnel of 4% of the light at the air/silica interface. To improve the amount of reflected light, thin mirrors or coating could be added at the optic fibres ends. The alignment of the optic fibres is guaranteed by a glass capillary tube having an interior diameter slightly superior to the optic fibre ($256 \mu\text{m}$) and an outer diameter of $600 \mu\text{m}$. The medium between the two plans is air, with an index of refraction n . The resulting interferometer is a two beam interferometer. Part of the light propagating in the optic

fibre is reflected back by the Fabry-Pérot cavity but most of the light is transmitted through.

The optic fibre Fabry-Pérot interferometers are very sensitive to transitory phenomena. When the acoustic emission waves propagate inside the material, they induce instabilities in the optic fibre which cause variations of the distance between the two mirrors in the cavity. To these variations correspond alterations of the interference pattern due to a modulation of the phase by the elastic waves (figure 8.6).

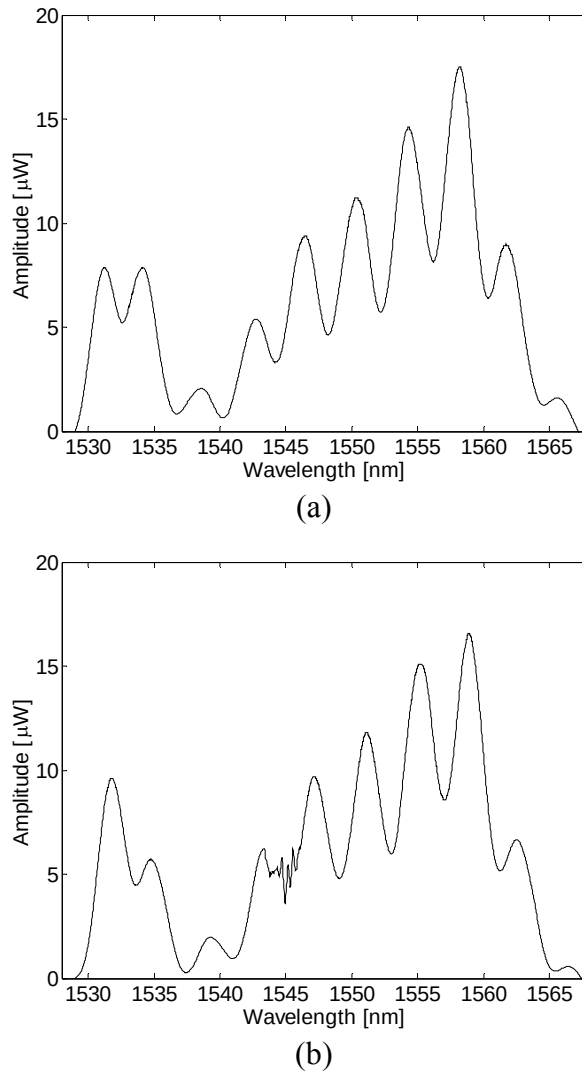


Figure 8.6 - Interference pattern (a) before and (b) at impact

Figure 8.6 (a) and (b) were obtained illuminating the cavity by a broadband source. Interference pattern could be isolated subtracting the optical source component.

8.7.4. The extrinsic Fabry-Pérot interferometer interrogation

The extrinsic Fabry-Pérot interferometer doesn't give a direct value of the wave displacement. To obtain definitive results it is necessary to proceed to a demodulation.

Elastic waves propagating in the host material produce small phase shifts. When measuring small phase shifts it is desirable to operate along the linear region of the response curve (figure 8.7), i.e. the region between the peaks and valleys, as it gives the largest change in reflected intensity for a given phase shift of light. At quadrature, the relation between phase shift and reflected intensity is linear.

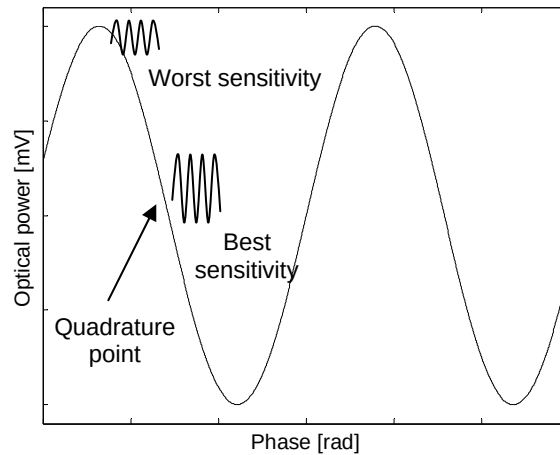


Figure 8.7 - Transfer function curve of the extrinsic Fabry-Pérot interferometer

In operation mode, signal fades and phase drifts due to fluctuations in ambient temperature and pressure. The effect of temperature, quasi-static strain or both produces phase shifts greater than π [324]. On the other hand, the phase shift induced from an acoustic emission is relatively smaller than π [325]. Thus the sensitivity of the extrinsic Fabry-Pérot interferometer to the acoustic emission varies continuously if the sensor is under external quasi-static change [325].

It is essential to maintain the quadrature point of operation for maximum sensitivity, as acoustic emissions which occur near the least sensitive range are hardly detected.

Numerous techniques have been developed to stabilize interferometric systems, as reported in the literature review, e.g. the use of frequency and phase modulators for

active stabilization by tuning the frequency of the laser source, or phase compensation using piezoelectric devices [333].

Using two phase signals out of phase by 90° , it is possible to stabilize the interferometer readout sensitivity.

In this dissertation two set-ups are proposed for stabilization of the extrinsic Fabry-Pérot interferometer based on this principle.

8.7.4.1. Interrogation process

The interferometric phase of the light reflected from the extrinsic Fabry-Pérot interferometer is function of the wavelength. Using two wavelength discriminators at distinct wavelengths, λ_1 and λ_2 , the interferometric phase at each wavelength can be expressed as

$$\delta_j = \frac{4\pi nL}{\lambda_j}, \quad j = 1, 2, \quad (8.21)$$

where n is the effective refractive index of the Fabry-Pérot cavity, and L its length. The relative phase between the two correspondent interferometric signals is given by

$$\Delta\delta = 4\pi nL \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right). \quad (8.22)$$

For a resonant wavelength separation odd multiple of $\lambda^2/(8nL)$, the signals will be in quadrature. The light at the interferometer output is read as an instantaneous voltage at a photodetector assessing the fringe pattern. The output voltages v_1 and v_2 at two photodiodes measuring the light back reflected at each wavelength are given by

$$v_1 = V_1 (1 + \kappa_1 \cos \delta), \quad (8.23)$$

$$v_2 = V_2 (1 + \kappa_2 \sin \delta), \quad (8.24)$$

where V_1 , V_2 are constant voltages dependent on the optical power and gain in the detection electronics, and κ_1 , κ_2 are the fringe visibility at each wavelength.

Adjusting the gain, i.e. $\kappa_1 V_1 = \kappa_2 V_2$, it is possible to recover the interferometric phase through the following relation

$$\delta = \tan^{-1} \left(\frac{v_2 - V_2}{v_1 - V_1} \right). \quad (8.25)$$

The unambiguous phase recovery from $-\pi$ to π can be computed using this equation.

8.8. Material fabrication and sensor embedding

The Fabry-Pérot cavity was embedded in a $[0/90_4]_s$ carbon/epoxy laminate. The optic fibre was embedded perpendicular to the loading direction, parallel to the adjacent reinforcements, in the middle plane. Single mode optical fibres with a diameter of 250 μm were used.

When fabricating the composite system special care was devoted to the optic fibre embedding process. Optical fibre integrity must be guaranteed during all the process.

Cross-ply carbon/epoxy laminate were fabricated from unidirectional pre-impregnated layers in autoclave. Specimens with final dimension $220 \times 50 \times 1.2 \text{ mm}^3$ of a $[0/90_4]_s$ lay-up were made.

Optic fibre ingress/egress point to the composite material is a critical point since the transition from the stiff composite structure to the flexibility of the free optical fibre is very abrupt. In order to protect the fibre at that point, a small diameter steel tube was partially embedded in the composite and partially free, the optic fibre passing through it (figure 8.8).

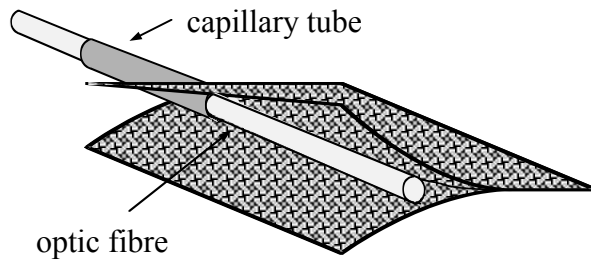


Figure 8.8 - Embedding of optic fibre sensor

The quality of embedding process was monitored by optical microscopic observations (figure 8.9).

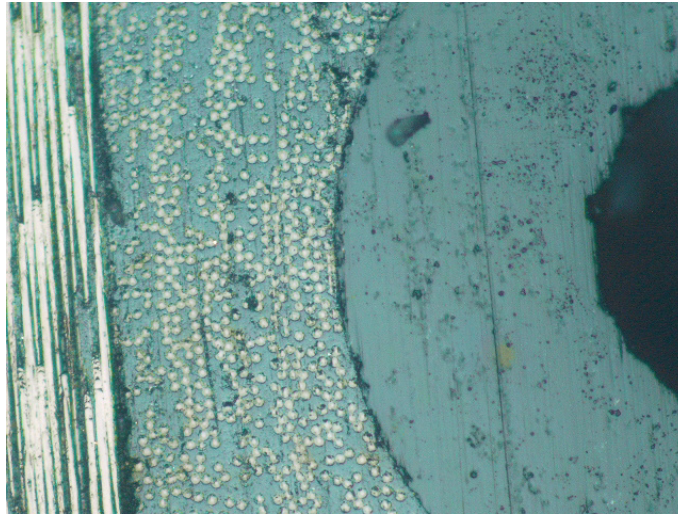


Figure 8.9 - Microscopic observation of the interface extrinsic Fabry-Pérot interferometer/host material ($\times 200$)

8.9. Generation of the two quadrature-shifted signals using fibre Bragg gratings

The fibre Bragg gratings spectral discrimination capacity was used to satisfy the quadrature condition.

8.9.1. Fibre Bragg grating

Fibre Bragg grating sensors are wavelength-modulated sensors. Gratings are simple, intrinsic sensing elements, and give an absolute measurement of the physical perturbation it senses. Their basic principle of operation is to monitor the wavelength shift associated with the Bragg resonance condition. The wavelength shift is independent of the light source intensity. Their characteristics justify that they are the favourite candidate for strain and temperature sensing. The change in the wavelength is directly related to the variation of strain and temperature. These relations are not presented in this dissertation, but can be found in the literature [279].

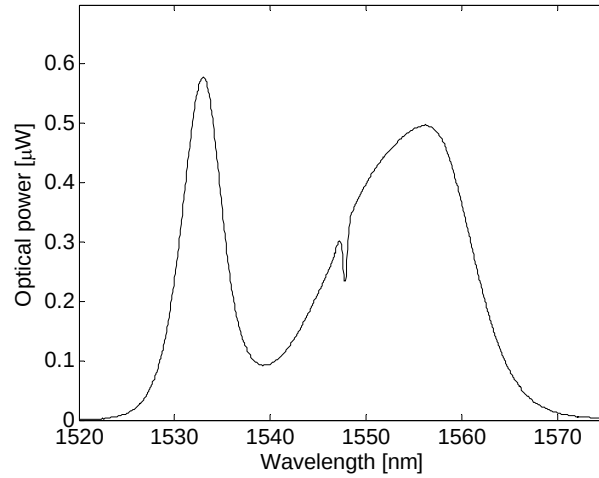
Fibre Bragg gratings are formed when a periodic variation of the index of refraction of the core is created along a section of an optic fibre, by exposing the optic fibre to an interference pattern of intense ultra-violet light. The photosensitivity of silica glass permits the index of refraction in the core to be increased by the intense laser radiation.

The strength of the grating is proportional to the depth of the index modulation. When it increases, the back-reflected light also increases. Bragg grating can be considered as a set of spatially separated partial reflectors. At each interface between two regions of different indices of refraction, refractions occur [279].

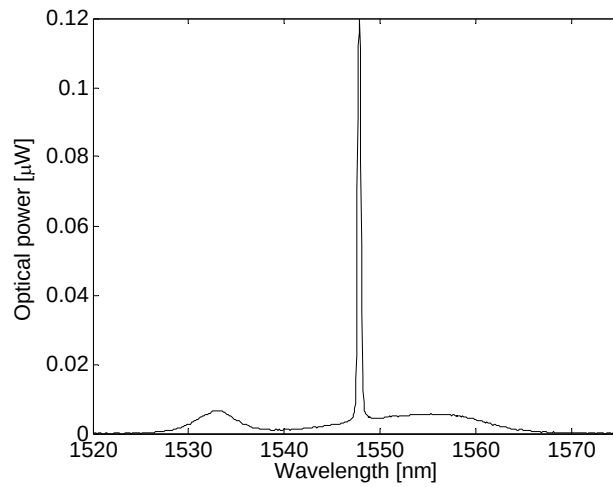
The reflected wave results from the superposition of the components of all the reflections. Maximum amplitude is obtained when those individual components are in phase. That explains fibre Bragg gratings capacity to select optical power spectrum for a given wavelength. This resonance condition is given by the expression [279]:

$$\lambda_B = 2n_0\Lambda_B \quad (8.26)$$

where Λ_B is the spacing between grating periods and n_0 is the effective index of the core. In figure 8.10 is represented the optical power spectrum of the transmitted and reflected light by the fibre Bragg grating, when the sensor is illuminated by a broadband optical source.



(a)



(b)

Figure 8.10 - Optical power spectrum of the (a) transmitted and (b) reflected light by the fibre Bragg grating.

The interferometer cavity interrogation schema and set-up are presented in figure 8.11 and figure 8.12, respectively.

A broadband light source (erbium-doped broadband light source) with central wavelength of about 1550 nm was used to illuminate the cavity through a circulator (OC1). The interferometric signal was reflected by the cavity and coupled to two fibre Bragg gratings through 50:50 couplers (C_1 , C_2 , C_3). The two fibre Bragg gratings had a resonant wavelength of 1551.98 and 1553.4 nm (about 0.2 nm of spectral bandwidth).

The reflected light at each wavelength was monitored by photodiodes (D_1 , D_2), which converted the optical signal to an electrical signal.

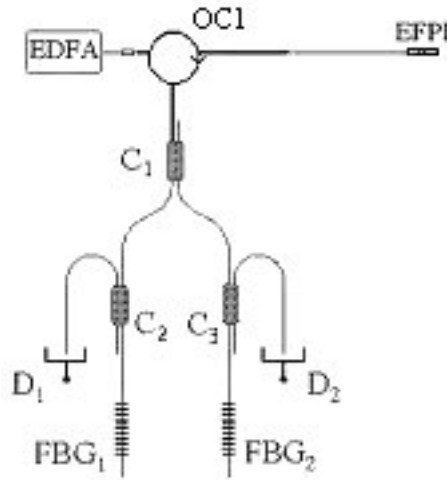


Figure 8.11 - Experimental setup for generation of quadrature phase-shifted outputs

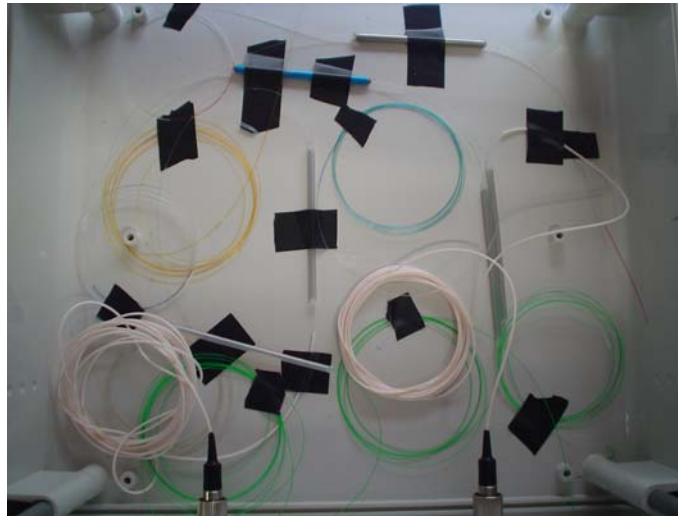


Figure 8.12 - Mounted setup for generation of quadrature phase-shifted outputs by the fibre Bragg gratings.

The signals were acquired in a Tektronix TS200 series oscilloscope controlled by LabVIEW™. This low-cost interrogation system of interrogation of the extrinsic Fabry-Pérot cavity was previously applied with success when low finesse extrinsic Fabry-Pérot interferometers were used as a temperature sensor [334].

In figure 8.13 is represented the optical power spectrum of the light observed, by an optical spectrum analyser, at the reflection of the coupler C_1 . It is obtained allowing the light to be reflected at the extremities of the two fibre Bragg gratings. The interference pattern as well as the reflections of the two gratings are visible.

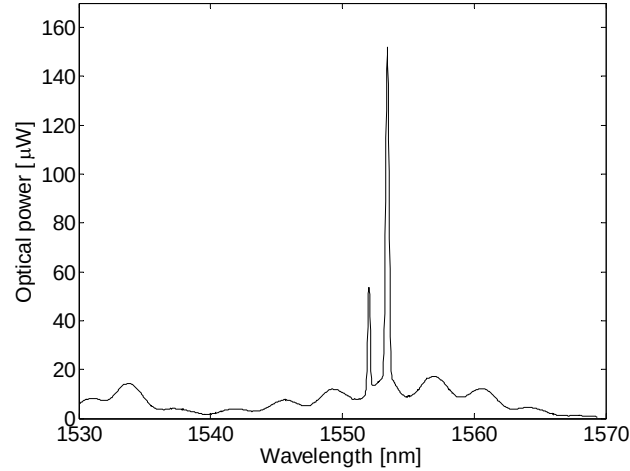


Figure 8.13 - Optical power spectrum of the interferometric signal and the reflected light by the fibre Bragg gratings.

8.9.2. Detection of simulated periodic ultrasonic waves

The fringe visibility was determined for a signal frequency of about 12 kHz. The optical source power was fixed to 306 mW. Measurements were made in DC mode. The fringe visibility, k , is given by

$$k = \frac{V_{\max} - V_{\min}}{V_{\max} + V_{\min}} \quad (8.27)$$

where $V_{\max}$ and $V_{\min}$ are the maximal and minimal tension values, respectively.

Their values were $V_{\max}=1.70$ V and $V_{\min}=1.52$ V. The resulting value for the fringe visibility was 0.0559.

In order to be able to recover the phase data, the photodiodes gain was previously adjusted. For that purpose, periodic waves were generated into the material by a

piezoelectric device connected to a sinusoidal signal generator (figure 8.14). Measurements were made in AC mode.

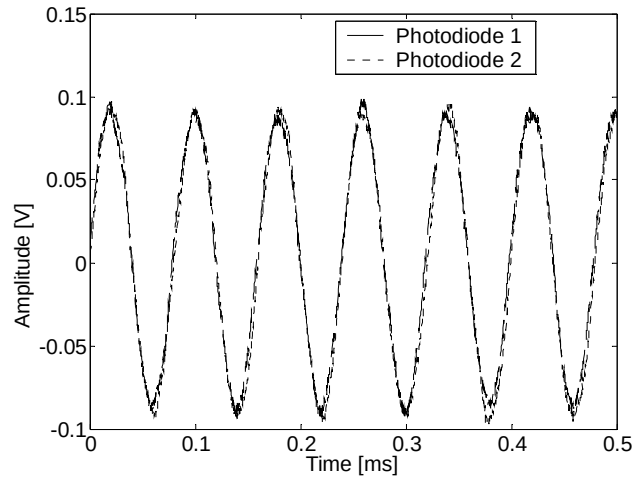
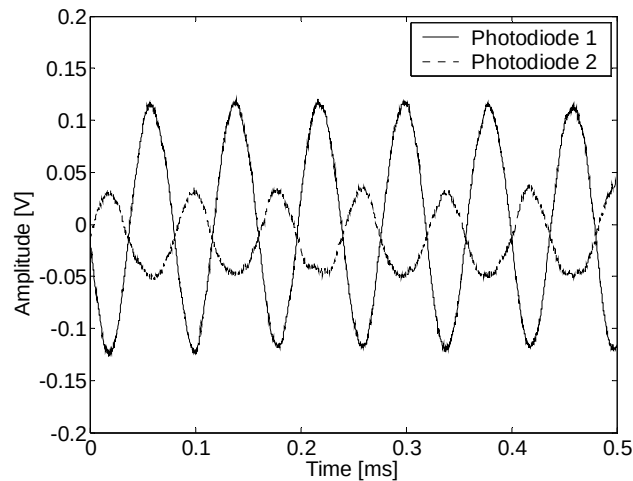
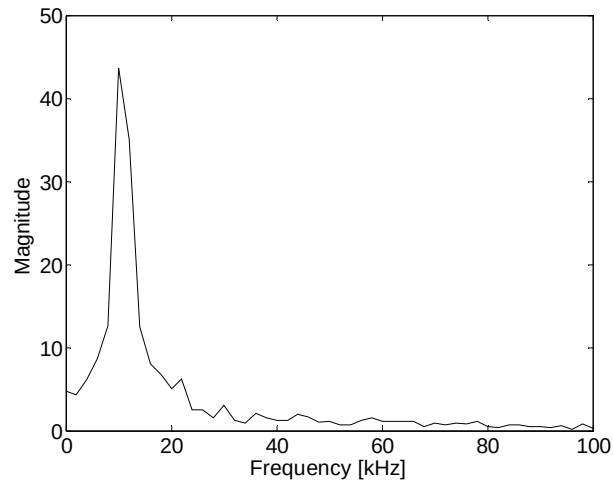


Figure 8.14 - Photodiode gain adjustment

Once the gain of the photodiodes adjusted, the optical fibre system was applied to the detection of periodic ultrasonic waves, generated in the material by the piezoelectric device. In figure 8.15 to figure 8.17 are represented the answer of the two photodiodes to periodic ultrasonic waves with frequency of 10, 20 and 66 kHz respectively. The two signals are in quadrature. Signal amplitude decreases when the frequency increases. This is due to the piezoelectric device, which generates lower amplitude signals when increasing the frequency, but also to the low frequency bandwidth of the photodetector (<100 kHz).

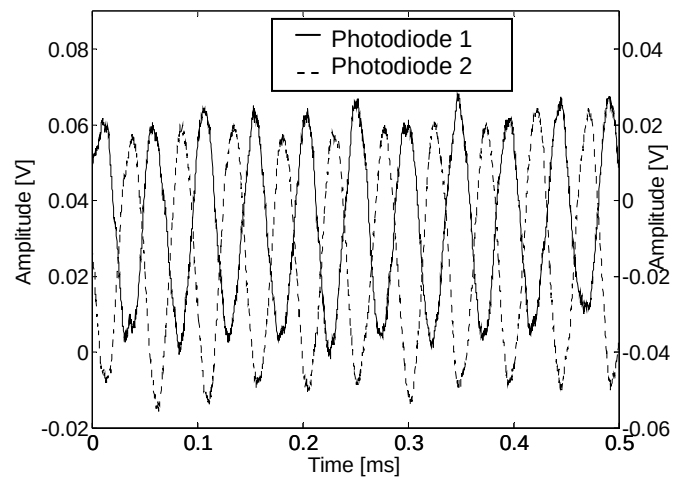


(a)

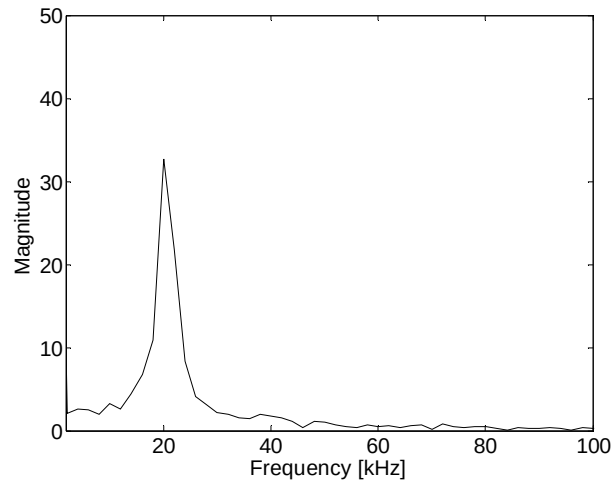


(b)

Figure 8.15 - (a) Time representation (b) and spectrum of signals detected at 10 kHz

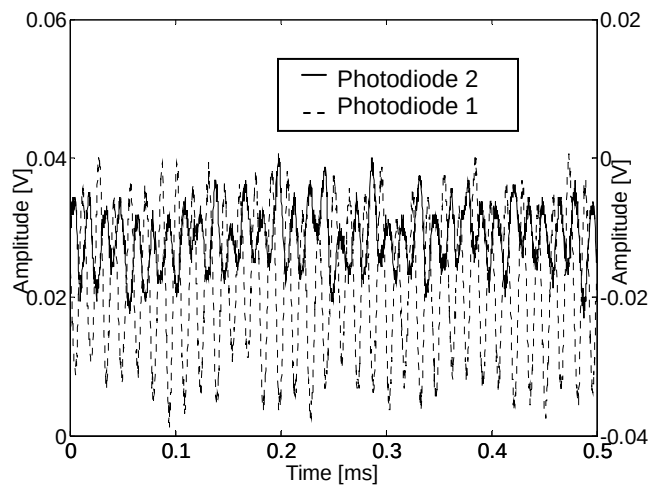


(a)



(b)

Figure 8.16 - (a) Time representation (b) and spectrum of signals detected at 20 kHz



(a)

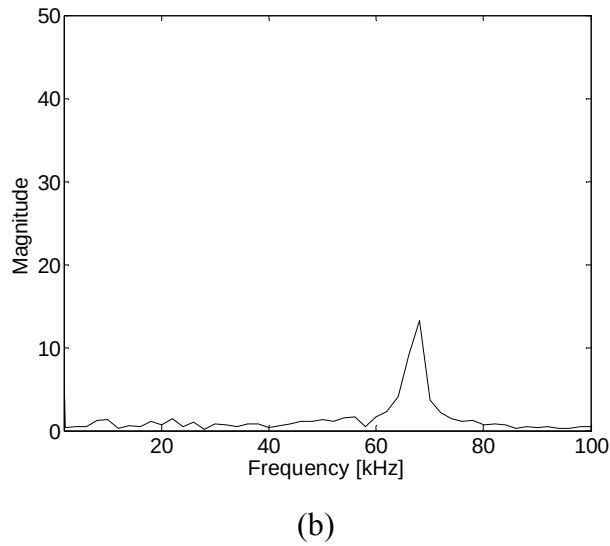


Figure 8.17 - (a) Time representation (b) and spectrum of the signals detected at 66 kHz

Photodiodes with bandwidth larger than 1 MHz were then used. An amplifier was added to the set up to compensate the weak gain of the photodetector due to its larger bandwidth. The amplifier considerably increased the electronic noise. It was thus impossible to see the signal (figure 8.18).

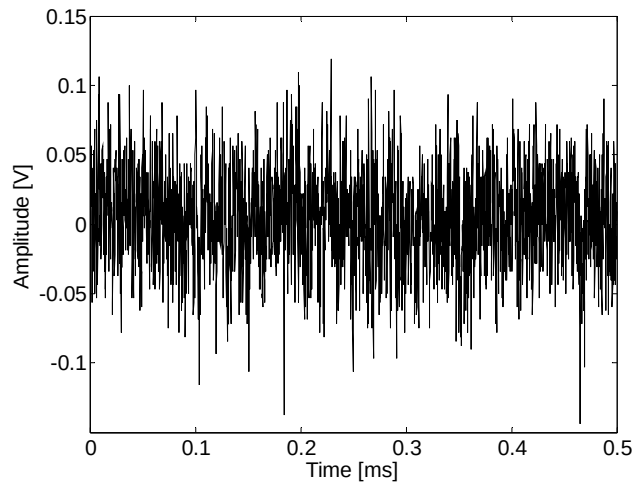
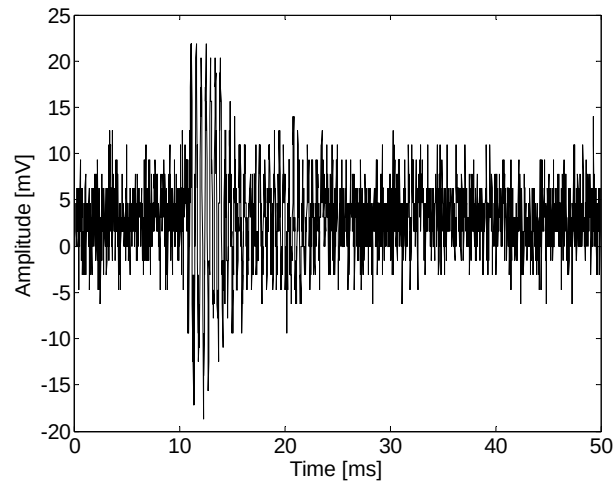


Figure 8.18 - Time representation of the signal detected at 66 kHz with the second serie of photodetectors

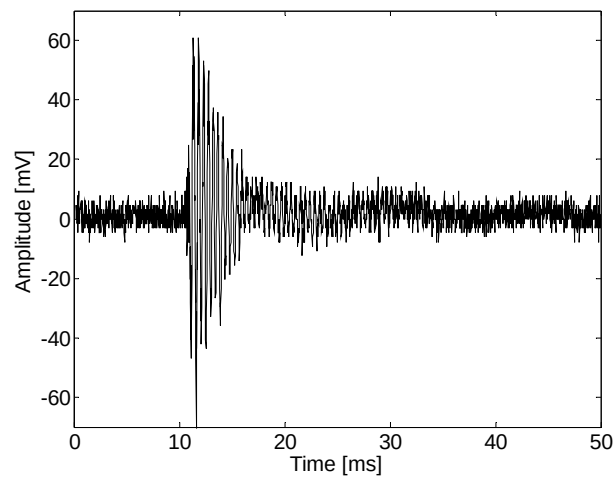
8.9.3. Detection of simulated acoustic emission waves

The capability of the optical fibre system to detect acoustic emission fibre was demonstrated from simulated waves. Acoustic emission waves were simulated according to the Hsu-Nielsen method [95]. The first photodetectors were used.

In figure 8.19 is represented the optic fibre sensor answer to a pencil lead break observed at both photodetectors.



(a)



(b)

Figure 8.19 - Response to a pencil break of the extrinsic Fabry-Pérot interferometer observed at the two photodiodes

An important noise is observed. Part of this noise can be removed from the equation 8.25. In figure 8.20 is represented the phase variation induced by the propagating wave. The cavity length variation can be obtained from the equation 8.21.

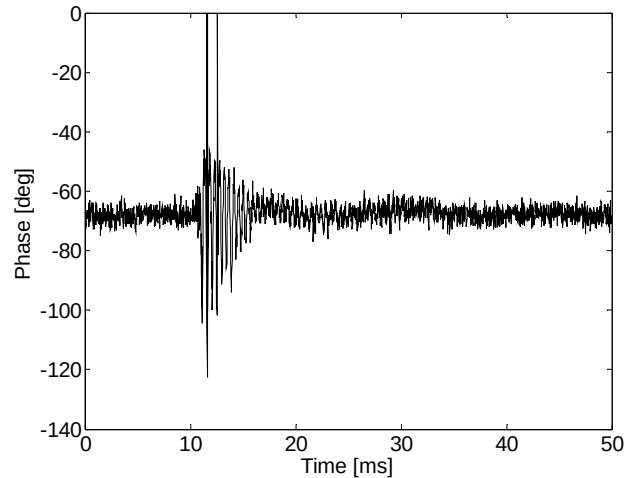


Figure 8.20 - Phase variation due to the propagating wave

8.9.4. Discussion

From the results obtained by this first configuration some conclusions appeared. The optic fibre sensor successfully detected ultrasonic waves (periodic and transient waves). A low signal-to-noise ratio is obtained for high waves frequencies.

It appeared that the use of fibre Bragg gratings as spectral bandwidth selectors as well as the use of a broadband optical source is not the most appropriate for acoustic emission waves sensing. The optical signal power at photodetector input is not sufficiently important, too much of the optical power being lost. As a consequence high gain photodetectors are required, which have a too limited frequency bandwidth for acoustic emission waves.

Besides in this configuration the electrical signal at the photodetector output was digitalised by the oscilloscope and transferred to a computer by a GPIB (IEEE488.2) interface. This configuration suffers some limitations. Indeed the oscilloscope buffer is not sufficiently high for acoustic emission acquisition and the data transfer by the GPIB interface is not sufficiently fast.

It has thus been decided to use another interrogation set-up resulting of the questions raised in the implementation of this first interrogator.

8.10. Generation of the two quadrature-shifted signals using two lasers

The use of two lasers permits to overcome the limitation observed in the previous set-up. Tuneable lasers have been used in the literature as previously mentioned in the literature review. However, such lasers are difficult to produce and expensive.

In this dissertation, two standard DFB telecommunication laser diodes with fixed wavelengths were used for the generation of the quadrature phase-shifted interferometric signals. The schema of the interrogation system is presented in figure 8.21. The set-up is presented in figure 8.22. The interrogator permits to address simultaneously two extrinsic optical fibre Fabry-Pérot interferometers. In this dissertation only one sensor is used.

The two laser diodes (DFB1, DFB2) have two different wavelengths, 1545.36 and 1550.20 nm, respectively. Laser diodes wavelengths have the tendency to fluctuate do to their temperature variations. To avoid this, lasers temperature control loops were implemented using wavelength lockers (WL1, WL2), which are recursively used to stabilize the lasers.

In this configuration, the extrinsic Fabry-Pérot cavity is illuminated through a circulator (OC1). The interferometric signals are reflected back by the cavity and transmitted through the circulator (OC1) to a bandsplitter (OAD1), which separates the two interferometric signals at the two wavelengths. The optical signals are then converted to electrical signal by two photodiodes (D1, D2):

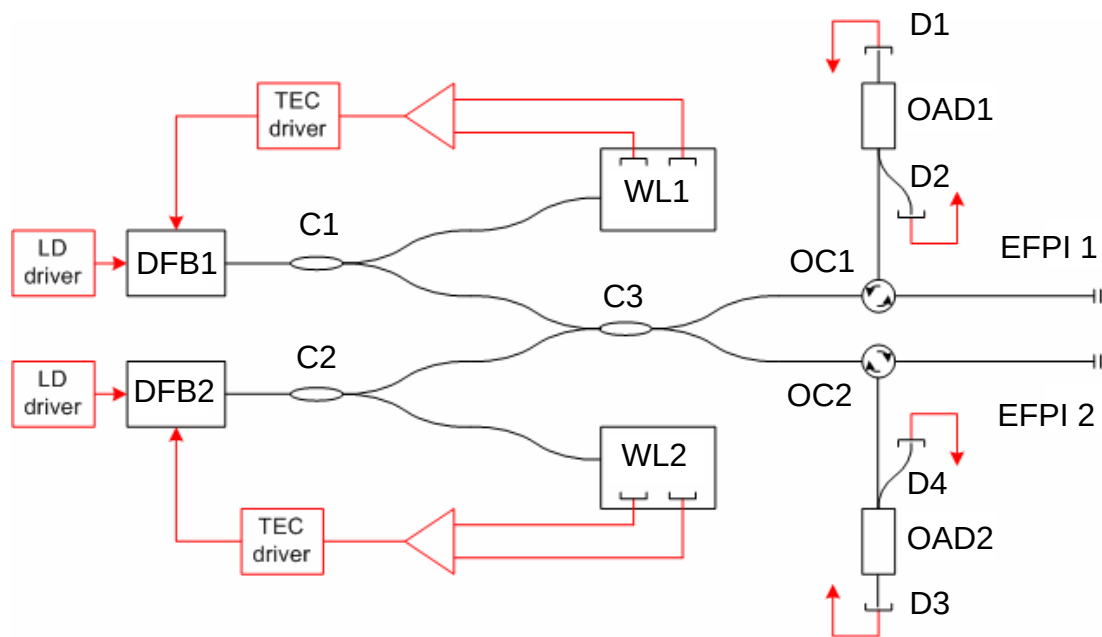
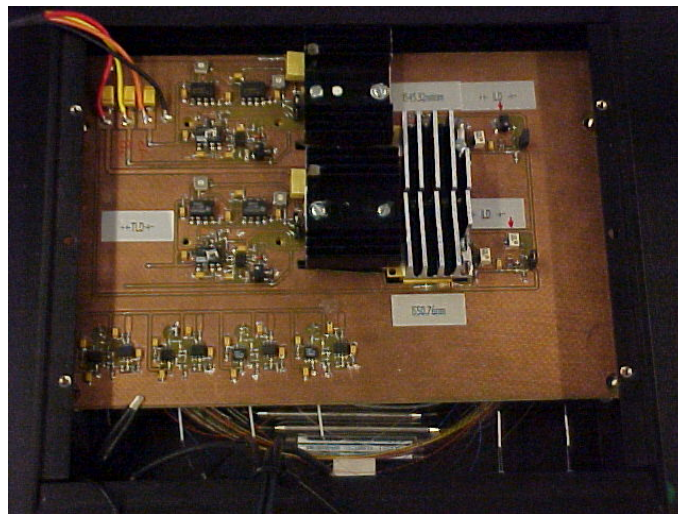
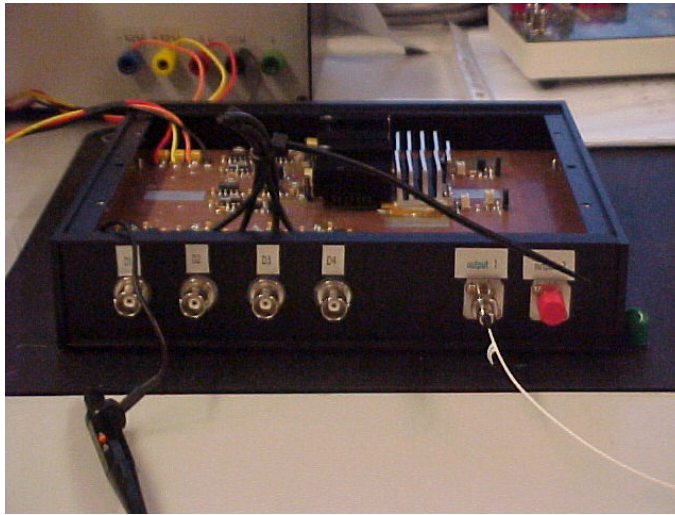


Figure 8.21 - Experimental setup for generation of quadrature phase-shifted outputs



(a)



(b)

Figure 8.22 - (a) Upper and (b) front view of the interrogator

BNC connectors were mounted at photodiode's conditioning signal output for further transfer of the signal to analogical/digital converters. In this dissertation, the oscilloscope used in the previous configuration was used for signal digitalisation.

8.10.1. Detection of simulated acoustic emission waves

The efficiency of the new interrogation procedure was verified. Acoustic emission waves were simulated in the host material by the Hsu-Nielsen test.

The optical power of the two laser diodes were equally adjusted (figure 8.23).

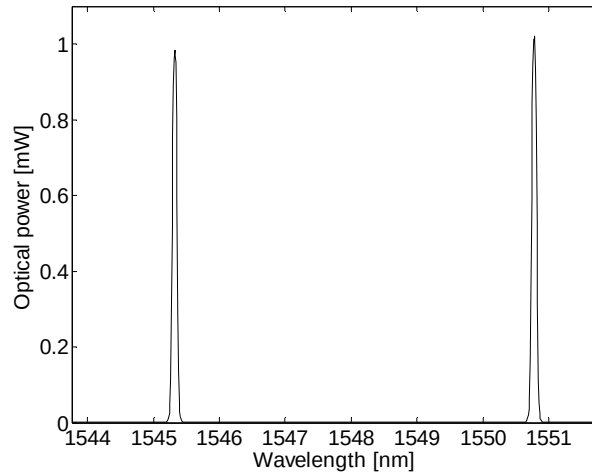


Figure 8.23 - Optical power spectrum of the light illuminating the cavity

In figure 8.24 is observed the optical power spectrum of the light reflected back by the cavity when it is illuminated by a broadband light source and the two laser diodes. The output of the laser diodes was attenuated of 20 dB for the image convenience. In this figure, the quadrature condition can be verified.

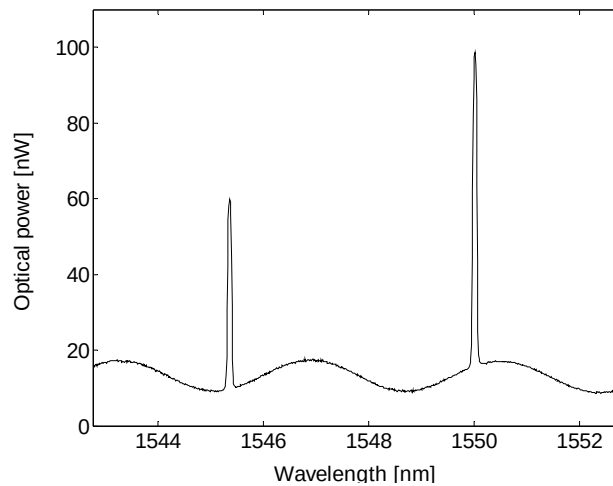


Figure 8.24 - Verification of the quadrature condition

The host plate was submitted to a slight bending to observe the variation of the cavity length. The resulting variation of the optical power is presented in figure 8.25, where three curves are observed corresponding to the original case, and two different radius of curvature.

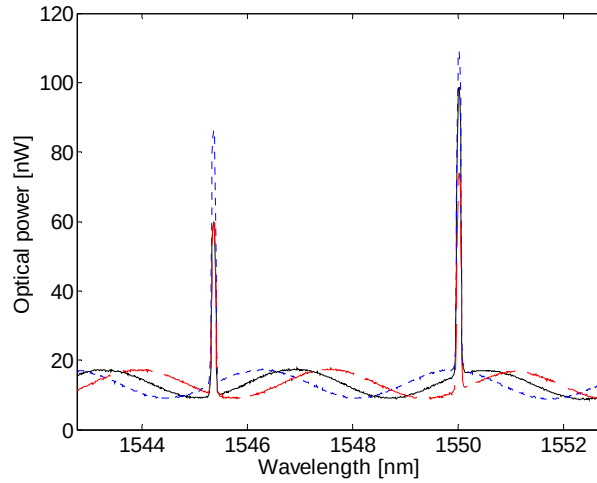
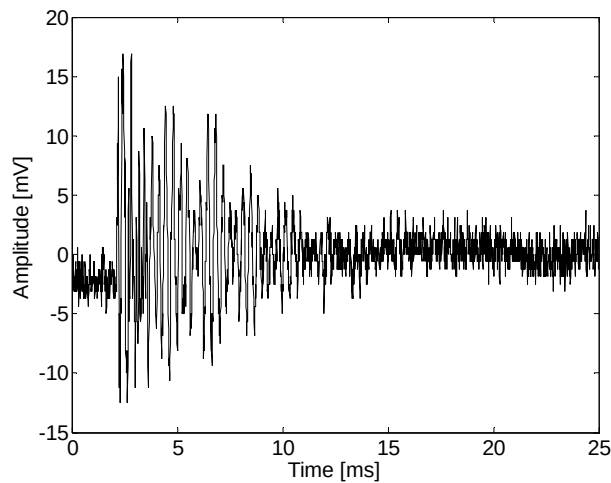


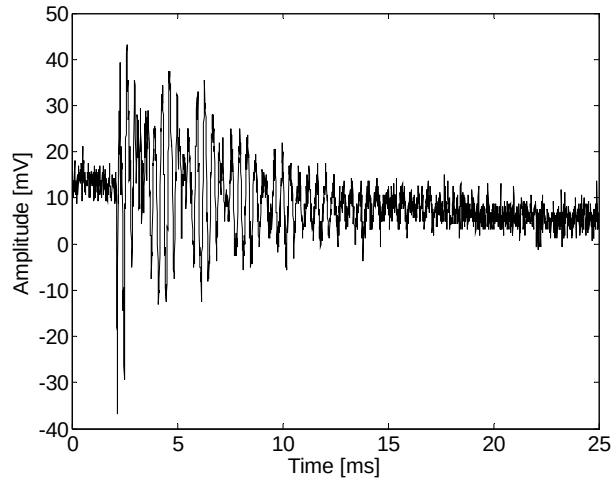
Figure 8.25 - Variation of the cavity length under curvature

In figure 8.26 is reported the response, observed at the two photodetectors, of the extrinsic optical fibre Fabry-Pérot interferometer sensor to a pencil lead break at the surface of the host material.

Some noise is observed in the two signals, but this noise can be removed using the phase recovery expression (equation 8.25). Longer duration acoustic emission signals were observed compared to signals traditionally detected by piezoelectric transducers. This agrees with results observed in literature. This is partially due to the wave reflections at host material edges, but is also due to the Fabry-Pérot sensor configuration.



(a)



(b)

Figure 8.26 - Response of the sensor to a pencil lead break observed at the two photodetectors outputs

The host material was submitted to an impact. In figure 8.27 is reported the answer of the sensor observed at one of the photodiodes output.

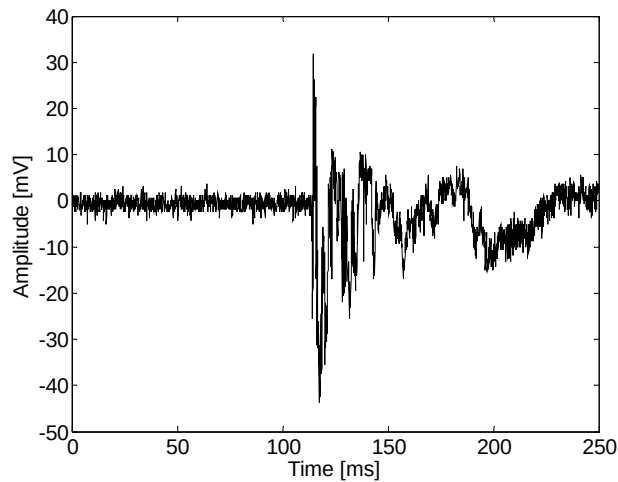


Figure 8.27 - Response of the sensor to an impact observed at one photodetector

8.10.2. Conclusions

The interrogation of the optic fibre Fabry-Pérot interferometer using two lasers demonstrated to be more efficient than the first configuration, mainly due to the higher

optical power available at the detection. Thus, a higher signal-to-noise ratio was obtained. Photodetectors having larger frequency bandwidth could then be used, permitting to detect elastic waves having higher frequency.

8.11. Discussion

The main objective of this chapter was to develop an optic fibre system for acoustic emission waves detection in composite materials. The optic fibre Fabry-Pérot interferometer was chosen for being the more sensitive to transient events. However, such sensor requires to be stabilized for efficient sensing.

Two innovative configurations were proposed based on two fibre Bragg gratings and two laser diodes, respectively.

The first configuration revealed to be limited for frequencies higher than 100 kHz, due to the low optical power, whereas the second configuration was more efficient for simulated acoustic emission waves detection.

The optical fibre system was conceived for sensing of acoustic emission waves in the frequency range of 50-1000 kHz.

The capability of the optical fibre system for sensing acoustic emission waves was demonstrated from simulated waves by pencil lead breaks. Long duration signals were observed. This agrees with results found in some investigations in literature. Different sensors were used in the two cases. This was traduced by a significant difference on the signal waveforms.

Chapter 9

Conclusions and discussions

9.1. Conclusions

The main objective of this dissertation was the elaboration of an on-line health monitoring procedure capable to detect, acquire, and identify damage in fibre reinforced plastic composite materials. Among the different non-destructive techniques, acoustic emission was chosen for its ability to detect evolutive defects during in-service life of structures.

The initial part of the work consisted of the study of the acoustic emission waves detected during the tensile testing of two materials whose damage sequence is well established. The objective of these tests was to improve the understanding of the relation between the acoustic emission waves and the damage source. This is crucial for the implementation of a procedure capable to identify the damage mechanisms occurring in loaded material from the acoustic emission waves.

The first configuration to be tested was the single-fibre specimen. Fibres having different diameter, sizing, and mechanical characteristics were embedded in epoxy resin in order to change the fibre fracture event. Fibre ruptures were observed and counted after testing by optical microscopy. A direct relation between the fibres ruptures number and the acoustic emission events was observed. Different fibre fracture aspects were observed due to the interface quality. Larger decohesion was observed when the interface was weakened. Acoustic emission signal waveforms and frequency content were analysed. This permitted to establish some relationship between the detected acoustic emission signals and the observed damage despite the high attenuation observed due to the epoxy resin. Indeed, the signal amplitude and peak frequency appeared to be related to the damage condition. The acoustic emission signals amplitude is clearly function of the fibre diameter. Higher signal amplitudes were observed for higher fibre diameter. Higher frequency acoustic emission waves were also detected when decohesion occurred

and when a long fibre gap was observed. Signal waveform couldn't be related to damage condition. This was partially due to the considerably high attenuation. Only acoustic emission located close to the broadband transducer could be considered. In this condition, the detected signal waveforms appeared to be influenced by the transducer characteristics, signals having almost similar waveforms being observed in the different configurations. This underlined the necessity of removal of the contribution of the transducer characteristics on the detected acoustic emission wave.

The second configuration to be tested was the cross-ply laminate. Specimens having different ply thicknesses and width were tested in order to influence the initiation and the evolution of the transverse matrix cracking. Cracks extended to the full width of the specimens almost instantaneously for the specimen having lower width. For higher specimen width, cracking initiation was delayed. As the elongation increased, cracks distribution became more uniform until a saturation point, at which delamination appeared at the free edges, as well as longitudinal cracking. It was also observed that the crack density at the saturation state increased when the thickness of 90° layers was decreased. Acoustic emission signals waveform and frequency content were analysed. Due to the large amount of data, an automated procedure was developed, for acoustic emission waves clustering, based on the self-organizing maps artificial neural networks. An unsupervised classification methodology was developed for its capacity to discover patterns among the input data without any a priori knowledge. This is the most judicious choice considering that it can be applied for any case. The classifier successfully clustered the acoustic emission waveforms. The damage sequence being well known, it was possible to relate the different clusters to damage mechanisms once knowing their evolution along the test. The use of a time-frequency representation of the classified signals permitted a more efficient relation of the cluster to the damage mechanisms. Six signal types were identified which were associated to transverse matrix cracking, decohesion, delamination, longitudinal matrix splitting and fibre breaks. Two of the signals type were attributed to transverse matrix cracking. The study of the acoustic emission waves detected for the specimens having different ply thicknesses and width permitted to identify one of these signal types with short duration to matrix microcracking. The other signal type having long duration was attributed to the propagation of transverse matrix cracking.

The time-frequency representation permitted to relate the powerful processing capabilities of artificial neural networks with the quantitative information resulting of the modal analysis of acoustic emission waves. The analysis of the modal nature of the acoustic emission waves has already proven to be more judicious in the case of complex geometry structures. The resulting automated acoustic emission signal procedure permits to obtain quantitative information about the damage. Due to its unsupervised nature such procedure can be applied in any structures.

The final part of this work was devoted to the sensing of acoustic emission waves. The use of traditional piezoelectric transducers mounted on the material surface is not always very appropriate. Besides, piezoelectric transducers cannot be used at high and low temperatures. They are also very sensitive to electromagnetic interference. Optical fibre sensors have been used for their capabilities to be embedded in composite materials. Optic fibre Fabry-Pérot interferometers were used for their high sensitivity to transient events. Such sensor doesn't provide a direct measure of the displacement induced by the propagation of the elastic wave. In order to obtain this information it is necessary to proceed to a demodulation. Two innovative interrogation procedures based upon the generation of two quadrature-shifted signals for phase recovery were proposed. The first configuration based on two fibre Bragg gratings revealed to be limited for frequencies higher than 100 kHz. The second based on two laser diodes was conceived for sensing of acoustic emission waves in the frequency range of 50-1000 kHz. It had a good signal-to-noise ratio compared to the first interrogator. The capability of fibre optic system to detect acoustic emission signals was demonstrated from simulated waves.

9.2. Future work

The classifier developed in this work revealed some difficulties to distinguish the signals due to longitudinal matrix splitting of the signals due to transverse matrix cracking. The use of artificial neural network requires a certain experience. It is thus believed that the classifier can be improved.

The optical fibre system has demonstrated to have a great potential, but some aspects, which were not treated in this dissertation, must be considered for future efficient application in smart structures. The cavity sensor will require a certain attention in order

to increase its sensitivity. Deposition at fibre ends can be considered to increase the mirror reflectivity. The influence of the cavity on the long duration signal detected at pencil lead break will have to be evaluated, in order to obtain shorter signals. The embedding process will have to be optimised. The influence of the presence of the sensor on the host behaviour in static and dynamic will have to be determined. Finally, the analogical/digital conversion will be considered. In the actual configuration, the electrical signal at the photodetector output is digitalised by the oscilloscope and transferred to a computer by a GPIB (IEEE488.2) interface. This configuration suffers some limitations. Indeed the oscilloscope buffer is not sufficiently high for acoustic emission acquisition and the data transfer by the GPIB interface is not sufficiently fast. The interrogator will be adapted to the acoustic emission system, which is especially designed for this acoustic emission signals.

The signal processing procedure developed in this work will be adapted to the acoustic emission waves detected by optical fibre sensor.

Reference:

1. Berthelot J.-M., "Relation between amplitudes and rupture mechanism in composite materials", *Journal of Reinforced Plastics and Composite*, Vol. 7, 1988, pp. 117-128.
2. Benmedakhene S., Kenane M., Benzeggagh M.L., "Initiation and growth of delamination in glass/epoxy composites subjected to static and dynamic loading by acoustic emission monitoring", *Composites Science and Technology*, Vol. 59, N°2, 1999, pp. 201-208.
3. Prosser W.H., "The propagation characteristics of the plate mode of acoustic emission in thin aluminum plates and thin graphite/epoxy composite plates and tubes", PhD. Thesis, Johns Hopkins University, United-States of America, 1991.
4. Surgeon M., "Continuous damage monitoring techniques for laminated CFRP composite materials", PhD. Thesis, Katholieke Universiteit Leuven, Belgium, 1999.
5. Gorman M.R., Prosser W.H., "AE source orientation by plate wave analysis", *Journal of Acoustic Emission*, Vol. 9, N°4, 1991, pp. 283-288.
6. Hamstad M.A., McColskey J.D., "Wideband and Narrowband Acoustic Emission Waveforms From Extraneous Sources During Fatigue of Steel Samples", *Journal of Acoustic Emission*, Vol. 15, N°1-4, 1997, pp. 1-18.
7. Claus R.O., Sudarshanam V.S., Murphy K.A., "Interferometric optical fiber sensors for ultrasonic wave measurement", *Smart Structures*, ISBN 0-471-55448-0, Ed. E. Udd, 1995, pp. 563-580.
8. Kim B.W., Nairn J.A., "Observation of fiber fracture and interfacial debonding phenomena using the fragmentation test in single fiber composites", *Journal of Composite Materials*, Vol. 36, N°15, 2002, pp. 1825-1858.
9. Le Corre J.-F., "Analyse du développement de la fissuration transverse et du délaminage dans les stratifiés croisés", PhD. Thesis, Le Mans University, France, 1999.
10. Bar-Cohen Y., "Emerging NDE Technologies and Challenges at the beginning of the 3rd Millennium- Part I", *The e-Journal of Non-destructive Testing*, ISSN 1435-4934 , www.ndt.net, Vol. 5, N°1, January 2000.

- 11.** Georgeson G., “NDT - A Continuing Responsibility in the Future of Aerospace”, Proceedings of the 10th APCNDT, Brisbane, www.ndt.net, 2001.
- 12.** Cawley P., “Low frequency vibration methods for NDT of composites”, Short Course on NDT of Composite Materials, Imperial College, 23-25 January 1996.
- 13.** Puttick K.E., “Thermal NDT Methods”, Non-Destructive testing of fibre-reinforced plastics composites, Vol. 1, Edited by John Summerscales, Elsevier Applied Science, ISBN 1-85166-093-3, 1987, pp. 65-104.
- 14.** Dillenz A., Wu D., Breitrück K., Busse G., “Lock-in thermography for depth resolved defect characterization”, Proceedings of the 15th World Conference on Non-destructive Techniques, Rome, www.ndt.net, 2000.
- 15.** Khan M.A.U., “Non-destructive Testing Applications in Commercial Aircraft Maintenance”, The e-Journal of Non-destructive Testing, ISSN 1435-4934, www.ndt.net, Vol. 4, N°6; June 1999.
- 16.** Weimin B., Wong B.S., Murukeshan V.M., “Thermographic and laser shearographic evaluation of composite materials”, The e-Journal of Non-destructive Testing, ISSN 1435-4934, www.ndt.net, Vol. 8, N°2, February 2003.
- 17.** Zweschper T., Dillenz A., Buss G., “Inspection of aerospace structures with ultrasound lock-in-Thermography”, Proceedings of the 15th World Conference on Non-destructive Techniques, Rome, www.ndt.net, 2000.
- 18.** Hemanth J., Narayana B., Sriraman P.C.N., Vijay N.A., Venkatraman B.P., Baldev R., “A Step Towards Automatic Defect Pattern Analysis and Evaluation in Industrial Radiography using Digital Image Processing”, Proceedings of the 15th World Conference on Non-destructive Techniques, Rome, www.ndt.net, 2000.
- 19.** Nafaâ N., Redouane D., Amar B., “Weld Defect Extraction and Classification in Radiographic Testing Based Artificial Neural Networks”, Proceedings of the 15th World Conference on Non-destructive Techniques, Rome, www.ndt.net, 2000.
- 20.** Blom A.F., Gradin P.A., “Radiography”, Non-Destructive testing of fibre-reinforced plastics composites, Vol. 1, Edited by John Summerscales, Elsevier Applied Science, ISBN 1-85166-093-3, pp. 1-24.

21. Aymerich F., Priolo P., Vacca D., “Static Loading and Low-Velocity Impact Characterization of Graphite/PEEK Laminates”, The e-Journal of Non-destructive Testing, ISSN 1435-4934, www.ndt.net, Vol. 4, N°3, March 1999.
22. Oster R., “Computed Tomography as a Non-destructive Test Method for Fiber Main RotorBlades in Development, Series and Maintenance”, The e-Journal of Non-destructive Testing, ISSN 1435-4934, www.ndt.net, Vol. 4, N°7, July 1999.
23. Helfen L., Baumbach T., Banhart J., Stanzick H., Cloetens P., Ludwig W., Baruchel J., “High-resolution radioscopy and tomography for light materials and devices”, 15th World Conference on Non-destructive Techniques, Rome, www.ndt.net, 2000.
24. Iovea M., Georgescu Gh., Rizescu C., Chitescu P., “Some Aspects Concerning the 2d and 3d Computerized Tomography Applied in Non-Destructive Testing”, The e-Journal of Nondestructive Testing, ISSN 1435-4934, www.ndt.net, Vol. 4, N°7, July 1999.
25. Gros X.E., Takahashi K., De Smet M.-A., “On the efficiency of current NDT methods for impact damage detection and quantification in thermoplastic toughened CFRP materials”, The e-Journal of Non-destructive Testing, ISSN 1435-4934, www.ndt.net, Vol. 4, N°3, March 1999.
26. Tietz H.-D., Palm T., Behrends A., “Testing of fibre reinforced light metals”, The e-Journal of Non-destructive Testing, ISSN 1435-4934, www.ndt.net, Vol. 2, N°2, February 1997.
27. Khandetsky V.S., Antonyuk I.N., “Signal processing at eddy Current defectoscopy of composites using an artificial neuron network”, Proceedings of the 15th World Conference on Non-destructive Techniques, Rome, www.ndt.net, 2000.
28. Walker C.A., McKelvie J., “Optical Methods”, Non-Destructive testing of fibre-reinforced plastics composites, Vol. 1, Edited by John Summerscales, Elsevier Applied Science, ISBN 1-85166-093-3, pp. 105-149.
29. Petillon O., “New Developments of Pulsed Holography for Industrial Applications”, The e-Journal of Non-destructive Testing, ISSN 1435-4934, www.ndt.net, Vol. 3, N°9, September 1998.
30. Sirohi R.S., “Speckle Metrology”, Marcel Dekker Edition, New York, 1993.

- 31.** Ferreira F., “Análise do Comportamento Dinâmico de Componentes Estruturais sob Solicitações Generalizadas”, PhD Thesis, Faculty of Engineering, University of Porto, Portugal, 2003.
- 32.** Gerhard H., Busse G., “Deformation measurement with speckle interferometry by ultrasound excitation”, The e-Journal of Non-destructive Testing, ISSN 1435-4934, www.ndt.net, Vol. 8, N°2, February 2003.
- 33.** Hurlebaus S., “Nondestructive Evaluation of Composite Laminates”, The e-Journal of Non-destructive Testing, ISSN 1435-4934, www.ndt.net, Vol. 4, N°3, March 1999.
- 34.** Martínez-Antón J.C., Canabal H., Quiroga J.A., Bernabeu E., Álvaro Labajo M., Cortés Testillano V., “Shadow moiré and the use of flexible gratings to adapt to curved surfaces”, Proceedings of the 15th World Conference on Non-destructive Techniques, Rome, www.ndt.net, 2000.
- 35.** Smith R.A., “An introduction to the ultrasonic inspection of composites”, Review of Progress in Quantitative NDE, Western Washington University, 14-19 July 2002.
- 36.** Djordjevic B., Green Jr. R.E., “Non-contact ultrasonic techniques for process control of composite fabrication”, The e-Journal of Non-destructive Testing, ISSN 1435-4934, www.ndt.net, Vol. 2, N°11, November 1997.
- 37.** Djordjevic B., “Remote Non-Contact Ultrasonic Testing of Composite Materials”, Proceedings of the 15th World Conference on Non-destructive Techniques, Rome, www.ndt.net, 2000.
- 38.** Hillger W., “Ultrasonic Testing of Composites-From laboratory Research to In-field Inspections”, Proceedings of the 15th World Conference on Non-destructive Techniques, Rome, www.ndt.net, 2000.
- 39.** Monchalín J.-P., Néron C., Choquet M., Drolet D., Viens M., Bouchard P., Héon R., Padioleau C., Monchalín J.-P., “Laser-Ultrasonics inspection and characterization of aeronautic materials”, The e-Journal of Non-destructive Testing, ISSN 1435-4934, www.ndt.net, Vol. 3, N°11, November 1998.
- 40.** Capriotti R., Dati E., Silvestri P., Trivisonno G., Marinetti S., Dal Toè S., Bison P.G., Grinzato E., “NDT Techniques for the Evaluation of Impact Damage on Aeronautical Structures”, Proceedings of the 15th World Conference on Non-destructive Techniques, Rome, www.ndt.net, 2000.

- 41.** Wu T.T., Liu Y.H., “On the measurement of anisotropic elastic constants of fiber reinforced composite plate using ultrasonic bulk wave and laser generated Lamb wave”, *Ultrasonics*, 37, 1999, pp 405-412.
- 42.** Baste S., “Determination of elastic properties by an ultrasonic technique”, *Proceedings of the 12th International Conference on Composite Materials*, Paris, 1999.
- 43.** Margueres P., Meraghni F., Benzeggagh M.L., “Determination of stiffness reduction and damage accumulation monitoring in composite materials using ultrasonic techniques”, *Proceedings of the 12th International Conference on Composite Materials*, Paris, 1999.
- 44.** *Nondestructive Testing Encyclopedia*, Ultrasonic Testing, www.ndt.net/article/az/ut_idx.htm
- 45.** Cawley P., “Rapid scanning techniques”, *Short Course on NDT of Composite Materials*, Imperial College, 23-25 January 1996.
- 46.** Agostini V., Delsanto P.P., Zoccolan D., “Flaw Detection in Composite Plates by Means of Lamb Waves”, *Proceedings of the 15th World Conference on Non-destructive Techniques*, Rome, www.ndt.net, 2000.
- 47.** Guo N.Q., Cawley P., “Lamb wave for the NDE of composite laminates”, *Review of Progress in Quantitative NDE*, Vol. 11, DO Thompson and DE Chimenti Eds, Plenum Press, 1992, pp. 1443-1450.
- 48.** Guo N.Q., Cawley P., “Lamb wave reflection for the quick NDE of large composite laminates”, *Material Evaluation*, Vol. 52, 1994, pp. 404-411.
- 49.** Seale M.D., Smith B.T., Prosser W.H., “Lamb wave assessment of fatigue and thermal damage in composites”, *Acoustical Society of America*, Vol. 103, N°5, 1998, pp 2416-2424.
- 50.** Seale M.D., Smith B.T., Prosser W.H., Zalameda J.N., “Lamb Wave Assessment of Fiber Volume Fraction in Composites”, *Journal of the Acoustical Society of America*, Vol. 104, N°3, September 1998, pp. 1399-1403.
- 51.** Wu T.-T., Liu Y.-H., “On the measurement of anisotropic elastic constants of fiber-reinforced composite plate using ultrasonic bulk wave and laser generated Lamb wave”, *Ultrasonics*, Vol. 35, 1999, pp. 105-412.

52. Fahr A., Komorowski J.P., Forsyth D.S., Chapman C.E., "Review of IAR NDI Research in support of Ageing Aircraft", The e-Journal of Non-destructive Testing, ISSN 1435-4934, www.ndt.net, Vol. 4, N°1, January 1999.
53. Kwon O.-Y., Kim T.-H., Lee K.-J., "Monitoring of Fatigue Damage in Adhesively Bonded Composite-Metal Joints by Acoustic Methods", Proceedings of the 15th World Conference on Non-destructive Techniques, Rome, www.ndt.net, 2000.
54. Vary A., "The acousto-ultrasonic approach", in Acousto-Ultrasonics: Theory and Application, Duke, Jr., J. C. Ed., Plenum Press, New York, 1988, pp. 1-22.
55. Rawlings R.D., "Acoustic emission and acousto-ultrasonics", Short Course on NDT of Composite Materials, Imperial College, 23-25 January 1996.
56. Miller R.K., McIntire P., "Acoustic emission testing", nondestructive handbook (2nd Ed.), ASTM, Vol. 5, 1987.
57. Scott I.G., "Basic Acoustic Emission", Gordon and Breach Science Publishers, vol.6, USA, New York, ISBN 2-88124-352-5, 1991.
58. Arrington M., "Acoustic Emission", Non-Destructive testing of fibre-reinforced plastics composites, Vol. 1, Edited by John Summerscales, Elsevier Applied Science, ISBN 1-85166-093-3, 1987, pp. 25-63.
59. Pollock A.A., "Acoustic emission inspection", Non Destructive Evaluation and Quality Control (Metals Handbook, Volume 17, ASM International), 1989, pp. 278-294.
60. ANSI/ASTM E610-77, "Standard definitions of terms relating to acoustic emission", ANSI/ASTM E610-77: 675-677, 1977.
61. Fowler T.J., Blessing J.A., Conlisk P.J., Swanson T.L., "The MONPAC System", Journal of Acoustic Emission, Vol. 8, N°3, 1989, pp. 1-8.
62. Brunner A.J., Bohse J., "Acoustic Emission standards and guidelines 2002: a comparative assessment and perspectives", The e-Journal of Non-destructive Testing, ISSN 1435-4934, www.ndt.net, Vol. 7, N°9, September 2002.
63. Åberg M., "Wave propagation and damage in composite laminates", PhD. Thesis, Institute of Technology, Department of Solid Mechanics, Stockholm, 2000.
64. Guo D., "Lamb waves from microfractures in composite plates", PhD. Thesis Mechanical Engineering, UCLA, 1996.

65. Johnson M., "Acoustic emission damage development in composite laminate", Licentiate Thesis, Institute of Technology, Department of Solid Mechanics, Stockholm, 2000.
66. Johnson M., "Acoustic Emission in Composite Laminates - Numerical Simulations and Experimental Characterization", PhD. Thesis, Institute of Technology, Department of Solid Mechanics, Stockholm, 2002.
67. Ohtsu M., Ono K., "A generalized theory and source representation of acoustic emission", *Journal of Acoustic Emission*, Vol. 5, N°4, 1986, pp. 124-133.
68. Burridge R., Knopoff L., "Body force equivalents for seismic dislocations", *Bulletin of the Seismological Society of America*, Vol. 54 N°6, 1964, pp. 1875-1888.
69. Guo D., Mal A., Ono K., "Wave theory of acoustic emission in composite laminates", *Journal of Acoustic Emission*, Vol. 14, N° 3-4, 1996, pp. S19-S46.
70. Ohtsu M., Ono K., "AE Source Location and Orientation Determination of Tensile Cracks from Surface Observation", *NDT International*, Vol. 21, 1988, pp. 143-152.
71. Kim K.Y., Sachse W., "Characterization of AE Signals from Indentation Cracks in Glass," *Progress in Acoustic Emission II*, JSNDI, 1984, pp. 163-172.
72. Landis E.N., "Micro-macro fracture relationships and acoustic emission in concrete", *Construction and Building Materials*, Vol. 13, 1999, pp. 65-72.
73. Grosse C.U., Reinhardt H.W., Dahm T., "Localization and classification of fracture type in concrete with quantitative acoustic emission measurement techniques", *NDT & E international*, Vol. 30, N°4, 1997, pp. 223-230.
74. Yuyama S., Li Z.-W., Ito Y., Arazoe M., "Quantitative analysis of fracture process in RC column foundation by moment tensor analysis of acoustic emission", *Construction and Building Materials*, Vol. 13, 1999, pp. 87-97.
75. Roger D., Dieulesaint E., "Ondes élastiques dans les solides, Tome 1, Propagation libre et guidée", Masson Ed., 1996.
76. Hamstad M.A., Downs D.K., "On characterization and location of acoustic emission sources in real size composite structures - A waveform study", *Journal of Acoustic Emission*, Vol. 13, N°1-2, 1995, pp. 31-41
77. Lamb H., "On waves in an elastic plate", *Proc. Royal Society*, Vol. A93, 1917, pp. 114.

- 78.** Gorman M.R., "Plate Wave Acoustic emission", *Journal of the Acoustical Society of America*, Vol. 1, 1990, pp. 358-364.
- 79.** Tang B., Henneke E.G. II, Stiffler R.C., "Low Frequency Flexural Wave Propagation in Laminated Composite Plates," *Proceedings on a Workshop on Acousto-Ultrasonics: Theory and Applications*, Blacksburg Virginia, 1987, pp. 45-65.
- 80.** Mindlin R.D., "Influence of Rotatory Inertia and Shear on Flexural Motions of Isotropic, Elastic Plates," *Journal of Applied Mechanics*, Vol. 2, 1951, pp. 31-38.
- 81.** Dunegan H.L., "Multiple channel AE testing of complex structures", DECI report, www.deci.com, July 2000.
- 82.** Dunegan H.L., "Considerations for selection of advanced AE transducers", DECI report, www.deci.com, May 2003.
- 83.** Proctor T.M., "An improved piezoelectric acoustic emission transducer", *Journal of the Acoustical Society of America*, Vol. 71, 1982, pp. 1163.
- 84.** Wagner J.W., Huber R.D., "Optical sensor for detection of acoustic emission", *Proceedings of the 12th International AE Symposium*, Sapporo, Japan, 17-20 October 1994.
- 85.** Nordstrom A., "Acoustic Emission Characterization of Microstructural Failure In the Single Fiber Fragmentation Test", PhD. Thesis, Swiss Federal Institute of Technology Zurich, Switzerland, 1996.
- 86.** Suzuki H., Kinjo T., Saito N., Takemoto M., Ono K., "Integrity evaluation of glass-fibre composites with varied fibre/matrix interfacial strength using acoustic emission", *NDT&E International*, Vol. 33, 2000, pp. 173-180.
- 87.** Převerocksy Z., "Notes on wave and waveguide concept in AE", *Proceedings of the 25th European Conference on Acoustic Emission Testing*, Prague, 11-13 September 2002, Vol. II, pp. 83-90.
- 88.** Kwun H., Hanley J.J., Teller C.M., "Performance of non-contact sensor on a steel rod", *Journal of Acoustic Emission*, Vol. 11, N°1, 1993, pp. 27-32.
- 89.** Hsu N.N., Simmons J.A., Hardy S.C., "An approach to AE signal analysis-theory and experiment", *Materials Evaluation*, 1977, Vol. 35, pp. 100-106.
- 90.** McBride S.L., Hutchison T.S., "Helium gas jet spectral calibration of AE transducers and systems" *Canadian Journal of Physics*, Vol. 54, 1976, pp. 1824-1830.

91. American National Standard, ASTM E 1106:1986, "Standard Method for Primary Calibration of Acoustic Emission Sensors", 2002.
92. Hsu N.N., Beckenridge F., "Characterisation and calibration of AE sensors", *Materials Evaluation*, Vol. 39, 1981, pp. 60-68.
93. Hatano H., Mori E., "AE transducer and its absolute calibration", *Journal of the Acoustical Society of America*, Vol. 59, 1976, pp. 344-349.
94. Hatano H., Chaya T., Watanabe S., Jinbo K., "Reciprocity calibration of impulse responses of acoustic emission transducers", *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, Vol. 45, N°5, 1998, pp. 1221-1228.
95. American National Standard, ASTM E 976-00, "Standard guide for determining the reproducibility of acoustic emission sensor response", ASTM, 1994, pp. 3980-385.
96. Yan T., Jones B.E., "In-situ AE transducer calibration using artificial AE energy source", *Proceedings of the 25th European Conference on Acoustic Emission Testing*, Prague, Vol. II, 2002, pp. 279-286.
97. Bradshaw T., Holford K., Cole P., Davies A., "Ball bearing calibration of concrete structures using AE", *Proceedings of the 25th European Conference on Acoustic Emission Testing*, Prague, Vol.I, 2002, pp. 91-98.
98. Goujon L., Baboux J.C., Zhang F., "Reciprocity calibration of AE transducers", *Proceedings of the 25th European Conference on Acoustic Emission Testing*, Prague, Vol. I, 2002, pp. 217-222.
99. Theobald P.D., Esward T.J., Dowson S.P., "Towards traceable calibration of AE transducers: a new development at the UK's NPL", *Proceedings of the 25th European Conference on Acoustic Emission Testing*, Prague, Vol. II, 2002, pp. 211-218.
100. Vallen H., "AE testing fundamentals, Equipment, Applications", *The e-Journal of Non-destructive Testing*, ISSN 1435-4934, www.ndt.net, Vol. 7, N°9, September 2002.
101. Hájek K., Šikula J., Tacano M., Hashiguchi S., "Signal to noise ratio and preamplifier noise of AE measuring systems", *Proceedings of the 25th European Conference on Acoustic Emission Testing*, Prague, Vol. I, 2002, pp. 223-228.

- 102.** Benzeggagh M.L., Barré S., Echallier B., Jacquemet R., “Étude de l’endommagement de matériaux composites à fibre courtes et à matrice thermoplastique”, 8^{èmes} Journées Nationale sur les Composites, Palaiseau, France, 16-18 November 1992, pp. 703-715.
- 103.** Chen O., Karandikar P., Takeda N., Kishi T., “Acoustic emission characterization of a glass-matrix composite”, *Nondestructive Testing Evaluation*, Vol. 8-9, 1992, pp. 869-878.
- 104.** Karger-Kocsis J., Harmia T., Czigany T., “Comparison of the fracture failure behavior of polypropylene composites reinforced by long glass fibres and by glass mats”, *Composite Science and Technology*, Vol. 54, 1995, pp. 287-298.
- 105.** Kim S.-T., Lee Y.-T., “Characterization of damage and fracture process of carbon fiber reinforced plastic under loading-unloading test by using AE method”, *Material Science and Engineering*, Vol. A234-236, 1997, pp. 322-326.
- 106.** Kotsikos G., Evans J.T., Gibson A.G., Hale J., “Use of acoustic emission to characterize corrosion fatigue damage accumulation in glass fibre reinforced polyester laminates”, *Polymer Composites*, Vol. 20, N°5, 1999, pp. 689-696.
- 107.** Zimcik D.G., Proulx D., Roy C., Maslouhi A., “Real time monitoring of carbon-epoxy composites using acoustic emission NDE”, *SAMPE Quarterly*, Vol. 19, N°2, 1988, pp. 5-11.
- 108.** De Groot J., Wijnen A.M., Janssen B.F., “Real-time frequency determination of acoustic emission for different fracture mechanisms in carbon/epoxy composites”, *Composite Science and Technology*, 1995, Vol. 55, pp. 405-412.
- 109.** Giordano M., Calabro A., Esposito C., Lizza A., D'Amore A., Nicolais L., “An acoustic emission characterization of the failure modes in polymer-composite materials”, *Composite Science and Technology*, 1997, Vol. 58, pp. 1923-1928.
- 110.** Calabro A., Esposito C., Lizza A., Giordano M., Tedesco S., D'Amore A., Nicolais L., “A frequency spectral analysis of the fiber failure acoustic emission signal in a single fiber composite”, *Proceedings of the 1997 IEEE Ultrasonics Symposium, Part 1*, 5-8 October 1997, Toronto, Canada, Vol. 1, 1997, pp. 649-652.

- 111.** Ramirez-Jimenez C.R., Papadakis N., Reynolds N., Gan T.H., Purnell P., Pharaoh M., “Identification of failure modes in glass/polypropylene composites by means of the primary frequency content of the acoustic emission event”, *Composites Science and Technology*, Vol. 64, N°12, 2004, pp. 1819-1827.
- 112.** Kinjo T., Suzuki H., Saito N., Takemoto M., Ono K., “Fracture-mode classification using wavelet”, *Journal of Acoustic Emission*, Vol. 15, N°1-4, 1997, pp. 19-32.
- 113.** Qi G., Barhorst A., Hashemi J., Kamala G., “Discrete wavelet decomposition of acoustic emission signals from carbon-fiber-reinforced composites”, *Composites Science and Technology*, Vol. 57, N°4, 1997, pp. 389-403.
- 114.** Qi G., “Wavelet-based AE characterization of composite materials”, *NDT&E International*, Vol. 33, 2000, pp. 133–144.
- 115.** Stephens R.W.B., Pollock A.A., “Waveforms and frequency spectra of acoustic emissions”, *Journal of the Acoustical Society of America*, Vol. 50, N°3, 1971, pp. 904-910.
- 116.** Gorman M.R., Ziola S.M., “Plate waves produced by transverse matrix cracking”, *Ultrasonics*, Vol. 29, 1991, pp. 245-251.
- 117.** Prosser W.H., Dorigi J., Gorman M.R., “Extensional and flexural waves in a thin-walled graphite/epoxy tube”, *Journal of Composite Materials*, Vol. 26, 1992, pp. 2016-2027.
- 118.** Prosser W.H., Jackson K.E., Kellas S., “Detection and location of transverse matrix cracks in cross-ply Gr/Ep composites using acoustic emission”, *Proceedings of the 1995 ASNT Spring Conference and 4th Annual Research Symposium*, Las Vegas, 1995.
- 119.** Prosser W.H., Jackson K.E., Kellas S., Smith B.T., McKeon J., Friedmann A., “Advanced waveform-based acoustic emission detection of matrix cracking in composites”, *Material Evaluation*, 1995, pp. 1052-1058.
- 120.** Prosser W.H., “Advanced AE techniques in composite materials research, *Journal of Acoustic Emission*”, Vol. 14, N°3-4, 1996, pp. S1-S11.
- 121.** Prosser W.H., “Applications of advanced, waveform based AE techniques for testing composite materials”, *Proceedings of the SPIE conference on Nondestructive Evaluation Techniques for Aging Infrastructure and Manufacturing: Materials and Composites* Scottsdale, 1996, pp. 146-153.

- 122.** Morscher G.N., “Modal Acoustic Emission source determination in silicon carbide matrix composites”, *Review of Progress in Quantitative Nondestructive Evaluation*, 2000, pp. 383-390.
- 123.** Dunegan H.L., “The use of plate wave analysis in acoustic emission testing to detect and measure crack growth in noisy environments”, *Proceedings of the 1996 Structural Materials Technology NDE Conference*, San Diego, 1996, <http://www.deci.com/platewv.htm>.
- 124.** Dunegan H.L., “Acoustic emission analysis of a graphite/epoxy honeycomb panel”, *DECI Technical Report*, 1997, <http://www.deci.com/jan97.htm>.
- 125.** Dunegan H.L., “Modal analysis of acoustic emission signals”, *DECI Technical Report*, 1997, <http://www.deci.com/oct97.htm>.
- 126.** Downs K.S., Hamstad M.A., “Wave propagation effects relative to AE source distinction of wideband AE signals from a composite pressure vessel”, *Journal of Acoustic Emission*, Vol. 14, N°3-4, 1996, pp. S61-S73.
- 127.** Ziola S.M., Gorman M.R., “Source location in thin plates using cross-correlation”, *Journal of the Acoustical Society of America*, Vol. 90, N°5, 1991, pp. 2551-2556.
- 128.** Jeong H., Jang Y.-S., “Wavelet analysis of plate wave propagation in composite laminates”, *Composite Structures*, Vol. 49, 2000, pp. 443-450.
- 129.** Ruzzante J.E., Serrano E.P., “Estimation of Differences in Event Arrival Times Through Wavelet Transform Techniques”, *Proceedings of the 15th World Conference on Nondestructive Techniques*, www.ndt.net, 2000.
- 130.** Nishino H., Takemoto M., Ono K., “Lamb wave source location of impact on anisotropic plates”, *Proceedings of the 24th European Conference on Acoustic Emission Testing*, Senlis, 2000, pp. 77-83.
- 131.** Ma Y., Gao H., Zhao J.R., Yan X., Yang J.Q., “Application of Wavelet Analysis for processing the arrival time of AE Waves”, *Proceedings of the 15th World Conference on Nondestructive Techniques*, Rome, www.ndt.net, 2000.
- 132.** Hamstad M.A., O’Gallagher A., Gary J., “Examination of the Application of a Wavelet Transform to Acoustic Emission Signals Part 2: source location”, *Journal of Acoustic Emission*, Vol. 20, 2002, pp.62-82.

- 133.** Ding Y., Reuben R.L., Steel J.A., “A new method for waveform analysis for estimating AE wave arrival times using wavelet decomposition”, *NDT & E International*, Vol. 37, N°4, 2004, pp. 279-290.
- 134.** Jiao J., He C., Wu B., Fei R., Wang X., “Application of wavelet transform on modal acoustic emission source location in thin plates with one sensor”, *International Journal of Pressure Vessels and Piping*, Vol. 81, 2004, pp. 427-431.
- 135.** Spall J.C., Maryark J.L., Asher M.S., “Neural network approach to locating acoustic emission sources in nondestructive evaluation”, *Journal of Sound and Vibration*, Vol. 211, N°1, 1998, pp. 133-143.
- 136.** Blahacek M., Preverovsky Z., Krofta J., Chlada M., “Neural Network Localization of noisy AE events in dispersive media”, *Proceedings of the 24th European Conference on Acoustic Emission Testing*, Senlis, France, 2000, pp. 363-368.
- 137.** Černý L., Jirsík V., “Signal source location by means of neural network”, *Proceedings of the 25th European Conference on Acoustic Emission Testing*, Prague, Czech Republic, Vol. II, 2002, pp. 295-302
- 138.** Dunegan H., “Global Flaw Location with One Transducer”, *The DECI Report*, <http://www.deci.com/decireport.9.97.html>, 1997.
- 139.** Surgeon M., Wevers M., “One sensor linear location of acoustic emission events using plate wave theories”, *Materials Science and Engineering*, Vol. A265, 1999, pp. 254-261.
- 140.** Shen h.W., Finlayson R.D., Miller R.K., Carlos M.F., Vahaviolos J.V., “Waveform analysis of simulated transient signals”, *Proceedings of the 24th European Conference on Acoustic Emission Testing*, Senlis, 2000, pp. 369-374.
- 141.** Godinez V., Vahaviolos S.J., Finlayson R.D., Miller R.K., Carlos M.F., “Improved source location methods for pressure vessels”, *Proceedings of the 24th European Conference on Acoustic Emission Testing*, Senlis, 2000, pp. 355-361.
- 142.** Nishino H., Uchida F., Takashina S., Takemoto M., Ono K., “A new method of AE source location in pipes using cylindrical guided waves”, *Proceedings of the 24th European Conference on Acoustic Emission Testing*, Senlis, 2000, pp. 139-144.
- 143.** Ziola S., “Digital signal processing of modal acoustic emission signals”, *Journal of Acoustic Emission*, Vol. 14, N°3-4, 1996, pp. S12-S18.

- 144.** Narisawa I., Oba H., “An evaluation of acoustic emission from fibre-reinforced composites, Part 1 Acoustic Emission interpretation of epoxy matrix and model composites containing glass beads, carbon and glass fibre”, *Journal of Materials Science*, Vol. 19, 1984, pp. 1777-1786.
- 145.** Netravali A.N., Henstenburg R.B., Phoenix S.L., Schwartz P., “Interfacial Shear Strength Studies Using the Single-Filament-Composite Test. I: Experiments on Graphite Fibers in Epoxy”, *Polymer Composites*, Vol. 10, N°4, 1989, pp. 226-241.
- 146.** Jacques D., “Transfert de charge entre fibre et matrice dans les composites carbone-résine. Comportement en traction d’un composite model monofilamentaire”, PhD. Thesis, Institut National Polytechnique de Lorraine, France, 1989.
- 147.** Petry M., “Mechanical, superficial and interfacial characterisation of Carbon fibre/VEUH composites”, Diploma thesis, University of Kaiserslautern, Germany, 2000.
- 148.** da Fonseca S.B.C., “Caracterização de interfaces em compósitos de matriz termoplástica reforçada com fibras de vidro longas”, MSc Thesis, Universidade do Minho, 2001.
- 149.** Pickering K.L., Bader M.G., Kimber A.C., “Damage accumulation during the failure of uniaxial carbon fibre composites”, *Composites Part A*, 29A, 1998, pp. 435-441.
- 150.** Galiotis C., “Interfacial studies in model composites by Laser Raman Spectroscopy”, *Composites Science & Technology*, Vol. 42, 1991, pp. 124-136.
- 151.** de Lange P.J., Mäder E., Mai K., Young R.J., Ahmad I., “Characterization and micromechanical testing of the interphase of aramid-reinforced epoxy composites”, *Composites Part A*, Vol. 32, 2001, pp. 331-342.
- 152.** Zhao F.M., Zhang S.J., Hayes S., Patterson E.A., Jones R., “Measurements of matrix deformation near fibre ends by means of photo-elastic technology”, *Proceedings of the 13th International Conference on Composite Materials*, Beijing, China, 2001.
- 153.** Smith G.E., Spencer A.J.M., “Interfacial Traction in a Fibre-Reinforced Elastic Composite Material”, *J. Mech. Phys. Solids*, Vol. 18, 1970, pp. 81-100.
- 154.** Whitney J.W., Drzal L.T., “Axisymmetric Stress Distribution Around an Isolated Fiber Fragment, Toughened Composites”, ASTM 937, edited by N.J. Johnson, ASTM, Philadelphia, 1987, pp. 179-196.

- 155.** Cox H.L., “The elasticity and strength of paper and other fibrous materials”, *British Journal of Applying Physics*, Vol. 3, 1952, pp. 72-79.
- 156.** Kelly A., Tyson W.R., “Tensile properties of fiber reinforced metals: copper/tungsten and copper/molybdenum”, *Journal of Mechanical and Physics of Solids*, Vol. 13, 1965, pp. 329-350.
- 157.** Piggott M.R., “Micromechanics of fibre-polymer interfaces”, *Proceedings of the 2nd International Conference – Interfacial phenomena in composite materials’91*, 17-19 September, Leuven, Belgium, 1991.
- 158.** Jinen E., Ni Q.-Q., “Fracture behavior and acoustic emission of optical fiber SFC material”, *Nippon Kikai Gakkai Ronbunshu, A Hen/Transactions of the Japan Society of Mechanical Engineers, Part A* Vol. 62, N°599, July 1996, pp. 1582-1589.
- 159.** Giordano M., Calabro A., Esposito C., “Acoustic-emission characterization of the failure modes in polymer-composite materials”, *Composites Science and Technology*, Vol. 58, N°12, 1998, pp. 1923-1928.
- 160.** Morscher G.N., Martinez-Fernandez J., Purdy M.J., “Determination of interfacial properties using a single-fiber microcomposite test”, *Journal of the American Ceramic Society*, Vol. 79, N°4, 1996, pp. 1083-1091.
- 161.** Sachse W., Netravali A.N., Baker A.R., “An enhanced acoustic emission-based single-fiber-composite test”, *Journal of Nondestructive Evaluation*, Vol. 11, N°3-4, 1992, pp. 251-261.
- 162.** Sachse W., Netravali A.N., “Enhanced, acoustic emission-based, single-fiber-composite test”, *American Society of Mechanical Engineers, Applied Mechanics Division, AMD, Proceedings of the ASME Winter Annual Meeting*, 28 November - 3 December 1993, pp. 21-32.
- 163.** Manor A., Clough R.B., “In-situ determination of fiber strength and segment length in composites by means of acoustic emission”, *Composites Science and Technology*, Vol. 45, N°1, 1992, pp. 73-81.
- 164.** Netravali A.N., Sachse W., Wu H.F., “Determination of fibre/matrix interfacial shear strength by an acoustic emission technique”, *Journal of Materials Science*, Vol.26, 1991, pp. 6631-6638.

- 165.** Netravali A.N., Topoleski L.T.T., Sachse W., Phoenix S.L., “An Acoustic Emission Technique for Measuring Fiber Fragment Length Distributions in Single-Fiber Composite Test”, *Composite Science and Technology*, Vol. 35, 1989, pp. 13-29.
- 166.** Haselbach W., Lauke B., “Acoustic emission of debonding between fibre and matrix to evaluate local adhesion”, *Composites Science and Technology*, 2003, Vol. 63, pp. 2155–2162.
- 167.** Bohse J., “Acoustic emission characteristics of micro-failure processes in polymer blends and composites”, *Composites Science and Technology*, 2000, Vol. 60, pp. 1213-1226.
- 168.** Mäder E., Moos E., Karger-Kocsis J., “Role of film formers in glass fibre reinforced polypropylene-new insights and relation to mechanical properties”, *Composites Part A*, Vol. 32, 2001, pp. 631-639.
- 169.** Ni Q.-Q., Jinen E., “Acoustic emission and fracture of carbon fiber reinforced thermosoftening plastic (CFRTP) materials under monotonous tensile loading”, *Engineering Fracture Mechanics*, Vol. 45, 1993, pp. 611–25.
- 170.** Ni Q.-Q., Iwamoto M., “Wavelet transform of acoustic emission signals in failure of model composites”, *Engineering Fracture Mechanics*, 2002, Vol. 69, pp. 717-728.
- 171.** Huguet S., “Application de classificateurs aux données d’émission acoustique. Identification de la signature acoustique des mécanismes d’endommagement dans les composites à matrice polymère”, PhD. Thesis Institut National des Sciences Appliquées, Lyon, France, 2002.
- 172.** Park J.-M., Shin W.-G., Yoon D.-J., “A study of interfacial aspects of epoxy-based composites reinforced with dual basalt and SiC fibres by means of the fragmentation and acoustic emission techniques”, *Composites Science and Technology*, Vol. 59, 1999, pp. 355-370.
- 173.** Park J.-M., Kim J.-W., Yoon D.-J., “Interfacial evaluation and microfailure mechanisms of single carbon fiber/bismaleimide (BMI) composites by tensile and compressive fragmentation tests and acoustic emission”, *Composites Science and Technology*, Vol. 62, N°6, 2002, pp. 743-756.

- 174.** Park J.-M., Lee S.-I., Kim J.-W., Yoon D.-J., “Interfacial and Microfailure Evaluation of Modified Single Fiber–Brittle Cement Matrix Composites Using an Electro-Micromechanical Technique and Acoustic Emission”, *Journal of Colloid and Interface Science*, Vol. 244, 2001, pp. 410–422.
- 175.** Park J.-M., Kim D.-S., Kim S.-R., “Improvement of interfacial adhesion and nondestructive damage evaluation for plasma-treated PBO and Kevlar fibers/epoxy composites using micromechanical techniques and surface wettability”, *Journal of Colloid and Interface Science*, Vol. 264, 2003, pp. 431–445.
- 176.** Park J.-M., Kim D.-S., Kim S.-R., “Interfacial properties and microfailure degradation mechanisms of bioabsorbable fibers/poly-L-lactide composites using micromechanical test and nondestructive acoustic emission”, *Composites Science and Technology*, Vol. 63, 2003, pp. 403–419.
- 177.** Bunsell A.R., Hagege R., “Testing Methods for Single Fibres”, *Composite Materials Science*, Elsevier, Chapter 10, 1986, pp. 479-515.
- 178.** Gao Z., “Strength Prediction and Optimisation of Composites with Statistical Fibre Flaw Distributions”, *Journal of Composite Materials*, Vol. 26, N°11, 1992, pp. 1678-1705.
- 179.** American National Standard, ASTM D3379: 1989, “Standard test method for tensile strength and Young’s modulus for high-modulus single-filament materials”, American Society for Testing and Materials, 5 p.
- 180.** Weibull W., “A Statistical Distribution Function of Wide Applicability”, *Journal of Applied Mechanics*, 1951, pp. 292-295.
- 181.** Stoner E.G., “The effect of shape on the tensile strength of pitch-based carbon fibres”, PhD. Thesis, Clemson University, USA, 1998.
- 182.** Padgett W.J., Durham S.D., Mason A.M., “Weibull Analysis of the Strength of Carbon Fibres Using Linear and Power Law Models for the Length Effect”, *Journal of Composite Materials*, Vol. 29, N°14, 1995, pp. 1873-1884.
- 183.** Hoecker F., “Grenzflächeneffekte in Hochleistungsfaserverbundwerkstoffen mit polymeren Matrices“, PhD. Thesis, University of Kaiserslautern, 1996.

- 184.** Waseem S.F., Gardner S.D., He G., Wenbo Jiang, U. Pittman Jr., “Adhesion and surface analysis of carbon fibres electrochemically oxidised in aqueous potassium nitrate”, *Journal of Materials Science*, Vol. 33, 1998, pp. 3151-3162.
- 185.** Munz D., Fett T., “Streuung der mechanischen Eigenschaften Mechanisches Verhalten keramischer Werkstoffe”, *Werkstoff-Forschung und -Technik Bd.8*, Hrsg. B.Ilschner, Springer, 1984, pp. 83-95.
- 186.** Van der Zwaag S., “The Concept of Filament Strength and the Weibull Modulus”, *Journal of Testing and Evaluation*, Vol. 17, N°5, Sept. 1989, pp. 292-298.
- 187.** EN 59:1977 standard, “Glass reinforced plastics - Measurement of hardness by means of a Barcol impressor”, European Comity of Normalisation, 1977.
- 188.** ISO 527-1: 1993, “Plastics -- Determination of tensile properties - Part 1: General principles”, 1993.
- 189.** Bensouda M., “Contribution à l’analyse par émission acoustique de l’endommagement dans le béton”, PhD Thesis, Le Mans University, France, 1987.
- 190.** Envirocoustics, “Noesis 4.0: Advanced Acoustic Emission Data Analysis Pattern Recognition & Neural Networks Software”, [www.envirocoustics.gr/pdf_files/Noesis 4.0 Brochure.pdf](http://www.envirocoustics.gr/pdf_files/Noesis_4.0_Brochure.pdf), 2004.
- 191.** Vallen-System GmbH, “Vallen Visual Class™: The AE tool for recognizing waveform similarities”, <http://www.vallen.de/software/visualclass.htm>.
- 192.** Duda R.O., Hart P.E., Stork D.G., “Pattern Classification”, John Wiley & Sons Inc., 2nd Ed, ISBN 0-471-05669-3, 2001.
- 193.** Ono K., Huang Q., “Pattern recognition analysis of acoustic emission signals”, *Progress in Acoustic Emission VII*, T. Kishi & al Ed., Japanese Society for NDI, Tokyo, 1994, pp. 69-78.
- 194.** Anastassopoulos A.A., Philippidis T.P., “Clustering methodology for the evaluation of acoustic emission from composites”, *Journal of Acoustic Emission*, Vol. 13, N°1/2, 1995, pp. 11-22.
- 195.** Dubes R., Jain A.K., “Clustering techniques: the user’s dilemma”, *Pattern Recognition*, 1976, Vol. 8, pp. 247-260.

- 196.** Kouroussis D., Anastassopoulos A.A., Vionis P., Kolovos V., “Unsupervised Pattern recognition of acoustic emission from full scale testing of a wind turbine blade”, Proceedings of the 24th European Conference on Acoustic Emission Testing, Senlis, 2000, ISBN 2-85400-496-5, pp 291-297.
- 197.** Anastassopoulos A.A., Kouroussis D.A., Nikolaidis V.N., Proust A., Dutton A.G., Blanch M.J., Jones L.E., Vionis P., Lekou D.J., van Delft D.R.V., Joosse P.A., Philippidis T.P., Kossivas T., Fernando G., “Structural integrity evaluation of wind turbine blades using pattern recognition analysis on acoustic emission data”, Proceedings of the 25th European Conference on Acoustic Emission Testing, Prague, Czech Republic, 11-13 September 2002, ISBN 80-214-2174-6, Vol. I, pp. 21-28.
- 198.** Blanch M.J., Kouroussis D.A., Anastassopoulos A.A., Nikolaidis V.N., Proust A., Dutton A.G., Jones L.E., Vionis P., Lekou D.J., van Delft D.R.V., Joosse P.A., Philippidis T.P., Kossivas T., Fernando G.F. “Damage classification of acoustic emission using AEGIS pattern recognition software from ten small wind turbine blade tests”, Proceedings of the Global Windpower, Paris, France, 2-5 April 2002.
- 199.** Anastassopoulos A.A., Kouroussis D.A., Tsimogannis A., “Unsupervised Classification of Acoustic Emission Sources from Aerial Man Lift Structural integrity evaluation of wind turbine blades using pattern recognition analysis on acoustic emission data”, Proceedings of the 25th European Conference on Acoustic Emission Testing, Prague, Czech Republic, 11-13 September 2002, ISBN 80-214-2174-6, Vol. I, pp. 21-28.
- 200.** Pappas Y.Z., Markopoulos Y.P., Kostopoulos V., “Failure mechanisms analysis of 2D carbon/carbon using acoustic emission monitoring”, NDT&E International, Vol. 31, N°3, 1998, pp 157-163.
- 201.** Pappas Y.Z., Kostopoulos V., “Toughness characterization and acoustic emission monitoring of a 2D carbon/carbon”, Engineering fracture mechanics, Vol. 68, 2001, pp. 1557-1573.
- 202.** Loutas T.H., Kontsos A., Sotiriadis G., Pappas Y.Z., Kostopoulos V., “On the identification of the damage mechanisms in oxide/oxide composites using acoustic emission”, Proceedings of the 25th European Conference on Acoustic Emission Testing, Prague, 11-13 September 2002, ISBN 80-214-2174-6, Vol. II, pp 15-24.

- 203.** Kostopoulos V., Loutas T.H., Kontsos A., Sotiriadis G., Pappas Y.Z., “On the identification of the failure mechanisms in oxide/oxide composites using acoustic emission”, *NDT&E International*, Vol. 36, 2003, pp. 571–580.
- 204.** Johnson M., “Waveform based clustering and classification of AE transients in composites laminates using PCA”, *NDT&E International*, 35, 2002, pp 367-376.
- 205.** Godin N., Huguet S., Gaertner R., Salmon L., “Clustering of acoustic emission signals detected during tensile tests on unidirectional glass/polyester composite using supervised and unsupervised classifiers”, *NDT & E International*, Vol. 37, N°4, 2004, pp. 253-264.
- 206.** Grabec I., Kuljanic E., “Characterization of manufacturing processes based upon acoustic emission analysis by neural networks”, *CIRP Annals*, Vol. 43, N°1, 1994, Bern, Switzerland, pp. 77-80.
- 207.** Leem C.S, Dreyfus S.E., “Learning input feature selection for sensor fusion in tool wear monitoring”, *Proceedings of the 1992 Artificial Neural Networks in Engineering*, 15-18 November 1992, Vol. 2, St. Louis, pp. 815-820.
- 208.** Niu Y.M., Wong Y.S., Hong G.S., “Intelligent sensor system approach for reliable tool flank wear recognition” *International Journal of Advanced Manufacturing Technology*, Vol. 14, N°2, 1998, pp. 77-84.
- 209.** Wakuda M., Inasaki I., Ogawa K., Takahara M., “Monitoring of the grinding process with an AE sensor integrated CBN wheel”, *Journal of the Japan Society of Precision Engineering*, Vol. 59, N°2, 1993, pp. 275-280.
- 210.** Kuo R.J., Cohen P.H., “Intelligent tool wear estimation system through artificial neural network and fuzzy modelling”, *Artificial Intelligence in Engineering*, Vol. 12, 1998, pp. 229-242.
- 211.** Chungchoo C., Saini D., “A computer algorithm for flank and crater wear estimation in CNC turning operations”, *International Journal of Machine Tools & Manufacture*, 42, 2002, pp. 1465-1477.
- 212.** Wang Z., Willet P., De Aguiar P.R., Webster J., “Neural network detection of grinding burn from acoustic emission”, *International Journal of Machine Tools & Manufacturing*, Vol. 41, 2001, pp. 283-309.

- 213.** Yao Y., Li X., Yuan Z., “Tool wear detection with fuzzy classification and wavelet fuzzy neural network”, *International Journal of Machine Tools and Manufacture*, Vol. 39, 1999, pp. 1525-1538.
- 214.** Wilkinson P., Reuben R.L., Jones J.D.C., Barton J.S., Hand D.P., Carolan T.A., Kidd S.R., “Tool wear prediction from acoustic emission and surface characteristics via an artificial neural network”, *Mechanical Systems and Signal Processing*, Vol. 13, N°6, 1999, pp. 955-966.
- 215.** Levy N., Zhou M.C., Quan Y., “Real-Time wear identification using sensor integration with neural networks”, *IEEE, Proceedings of the 33rd Conference on Decision and Control*, Florida, 1994, pp. 1050-1051.
- 216.** Dolinsek S., Kopac J., Viharos Zs.J., Monostori L., “An intelligent AE sensor for the monitoring of finish machining process”, *The Second International Conference on Intelligent Processing and Manufacturing of Materials*, 10-15 July 1999, Honolulu, Hawaii, pp. 847-853.
- 217.** Žižka J., Prukner V., Ogawa D., Sumiya H., Shiraishi M., “Neural network for tool wear monitoring on the acoustic emission signal basis”, *Proceedings of the 25th European Conference on Acoustic Emission Testing*, Prague, Czech Republic, 11-13 September 2002, Vol. II, 2002, pp. 295-302.
- 218.** Li X., “A brief review: acoustic emission method for tool wear monitoring during turning”, *International Journal of Machine Tools & Manufacture*, Vol. 42, 2002, pp. 157-165.
- 219.** Lansing M.D., Walker J.L., Russell S.S., “Residual strength prediction of impact-damaged composite structures by optical and acoustical computer sensing with neural network techniques”, *Proceedings of the 7th Symposium on Composite Materials: Fatigue and Fracture*, 7-8 May 1997, N°1330, 1999, St. Louis, United-States of America, pp. 285-297.
- 220.** Teti R., Caprino G., “Evaluation of impacted composite laminate residual strength through neural networks”, *Applications of Artificial Intelligence in Engineering Proceedings of the 10th International Conference on Applications of Artificial Intelligence in Engineering*, AIENG'95, July 1995, Udine, Italy, pp. 411-418.

- 221.** Walker J.L., Russell S.S., Workman G.L., Hills E.V.K., “Neural network/acoustic emission burst pressure prediction for impact damaged composite pressure vessels”, *Materials Evaluation*, American Soc for Nondestructive Testing Columbus, United-States of America, Vol. 55, N°8, 1997, pp. 903-907.
- 222.** Fisher M.E., Hill E.V.K., “Neural network burst pressure prediction in fiberglass epoxy pressure vessels using acoustic emission”, *Materials Evaluation*, American Society for Nondestructive Testing Columbus, Vol. 56, N°12, 1998, pp. 1395-1401.
- 223.** Kosel T., Grabec I., Muzič P., “Location of acoustic emission sources generated by air flow”, *Ultrasonics*, 38, 2000, pp 824-826.
- 224.** Schindler P.M., May R.G., Claus R.O., “Location of impacts on composite panels by embedded fiber optic sensors and neural network processing”, *Proceedings of SPIE Smart structures and materials: Smart Sensing, Processing, and instrumentation*, San Diego, California, 27 February-1 March 1995, Vol. 2444, pp. 481-489.
- 225.** Pollock A.A., Almeida A.F., Miller R.K., “The Use of Neural Networks to Discriminate Defect Signals from Noise”, *Proceedings of the 40th Regular Meeting of the Acoustic Emission Working Group*, 9-13 June 1997.
- 226.** Hironobu Y., Kyoji H., “Estimation of acoustic emission source waveform of fracture using a neural network”, *NDT & E International*, Vol. 29, N°1, 1996, pp. 21-25.
- 227.** Philippidis T., Nikolaidis V., Anastassopoulos A., “Damage characterisation of carbon/carbon laminates using neural network techniques on AE signals”, *NDT&E International*, Vol. 31, N°5, 1998, pp. 329-340.
- 228.** Huguet S., Godin N., Gaertner R., Salmon L., Villard D., “Use of acoustic emission to identify damages modes in glass fibre reinforced polyester”, *Composites Science and Technology*, 62, 2002, pp 1433-1444.
- 229.** Bhat C., Bhat M.R., Murthy C.R.L., “Acoustic emission characterization of failure modes in composites with ANN”, *Composite Structures*, Vol. 61, 2003, pp. 213-220.
- 230.** Bar H.N., Bhat M.R., Murthy C.R.L., “Identification of failure modes in GFRP using PVDF sensors: ANN approach”, *Composite Structures*, Vol. 65, 2004, pp. 231-237.
- 231.** Philippidis T.P., Nikolaidis V.N., Kolaxis J.G., “Unsupervised pattern recognition techniques for the prediction of composite failure”, *Journal of Acoustic Emission*, Vol. 17, N°1/2, 1999, pp. 69-81.

- 232.** Vesanto J., Alhoniemi, E., "Clustering of the Self-Organizing Map", IEEE Transactions on Neuronal Network, Vol. 11, N°3, 2000, pp. 586-600.
- 233.** Kohonen T., "Self-Organizing Maps", Springer, Third Extended Edition, ISBN 3-540-67921-9, 2001.
- 234.** Haykin S., "Neural Networks: a comprehensive foundation", Prentice Hall, 1999.
- 235.** Vesanto J., "Data Exploration Process Based on the Self-Organizing Map", PhD Thesis, Helsinki University of Technology, Espoo, Finland, 2002.
- 236.** Ultsch A., Siemon H.P., "Kohonen's self organizing feature maps for exploratory data analysis," Proceedings of the International Neural Network Conference, Dordrecht, The Netherlands, 1990, pp. 305–308.
- 237.** Kraaijveld M. A., Mao J., Jain A. K., "A nonlinear projection method based on Kohonen's topology preserving maps," IEEE Transactions on Neural Networks, Vol. 6, 1995, pp. 548–559.
- 238.** MacQueen J.B., "Some Methods for classification and Analysis of Multivariate Observations", Proceedings of 5th Berkeley Symposium on Mathematical Statistics and Probability", Berkeley, University of California Press, 1967, Vol. 1, pp. 281-297.
- 239.** Davies D.L., Bouldin D.W., "A cluster separation measure," IEEE Transactions on Pattern Analysis and Machine Intelligence, Vol. PAMI-1, 1979, pp. 224–227.
- 240.** Pazdera L., "Wigner Spectrum as Powerful Tool for Description of Acoustic Emission Hit Generated from Ceramic Structures upon Bend Load", Proceedings of the 15th World Conference on Nondestructive Techniques, Rome, 2000, www.ndt.net.
- 241.** Pazdera L., Smutný J., "Identification and Analysis of Acoustic Emission Signals by Cohen's Class of Time Frequency Distribution", Proceedings of the 15th World Conference on Nondestructive Techniques, Rome, 2000, www.ndt.net.
- 242.** Prosser W.H., Seale M.D., Smith B.T., "Application of the Pseudo Wigner-Ville distribution to the measurement of the dispersion of Lamb modes in graphite/epoxy plates", Proceedings of the 8th International Symposium on Nondestructive Characterization of Materials, 15-20 June 1997, <http://techreports.larc.nasa.gov/ltrs/PDF/1997/mtg/NASA-97-8snm-whp.pdf>.

- 243.** Prosser W.H., Seale M.D., Smith B.T., “Time-frequency analysis of the dispersion of Lamb modes”, *Journal of the Acoustical Society of America*, Vol. 105, N°5, 1999, pp. 2669-2676.
- 244.** Holland S., Kosel T., Weaver R., Sachse W., “Determination of plate source, detector separation from one signal”, *Ultrasonics*, Vol. 38, 2001, pp 620-623.
- 245.** Niethammer M., Eisenhardt C., Jacobs L.J., Jarzynski J., Qu J., “Application of the short-time Fourier transform to interpret ultrasonic signals”, *Review of Progress in Quantitative Nondestructive Evaluation*, American Institute of Physics, 2000, pp. 703-708.
- 246.** Niethammer M., Jacobs L.J., Qu J., Jarzynski J., “Time-frequency representation of Lamb waves using the reassigned spectrogram”, *Journal of the Acoustical Society of America*, 2000, Vol. 107, N°5, pp. L19-L24.
- 247.** Niethammer M., Jacobs L.J., Qu J., Jarzynski J., “Time-frequency representation of Lamb waves”, *Journal of the Acoustical Society of America*, May 2001, Vol. 109, N°5, pp. 1841-1847.
- 248.** Graps A., “An introduction to wavelets”, *IEEE Computational Science and Engineering*, Vol. 2, N°2, 1995.
- 249.** Qi G., Barhorst A.A., “On predicting the fracture behavior of CFR and GFR composites using wavelet-based AE technique”, *Engineering Fracture Mechanics*, Vol. 58, N°4, 1997, pp. 363-385.
- 250.** Zhao J.R., Ma Y., Gao H., Yang J.Q., “Denoising Method of AE Signal by Using Wavelet Transform”, *Proceedings of the 15th World Conference on Nondestructive Techniques*, Rome, www.ndt.net, 2000.
- 251.** Grosse C.U., Reinhardt H.W., Motz M., Kröplin B.H., “Signal conditioning in acoustic emission analysis using wavelets”, *The e-Journal of Nondestructive Testing*, ISSN 1435-4934, www.ndt.net, Vol. 7, N°9, September 2002.
- 252.** Grosse C.U., Finck F., Kurz J.H., Reinhardt H.W., “Improvements of AE technique using wavelet algorithms, coherence functions and automatic data analysis”, *Construction and Building Materials*, Vol. 18, 2004, pp. 203-213.
- 253.** Gaul L., Hurlebaus S., “Identification of the impact location on a plate using wavelets”, *Mechanical Systems and Signal Processing*, Vol. 12, N°6, 1998, pp. 783-795.

- 254.** Jeong H., Jang Y.-S., “Fracture source location in thin plates using the wavelet transform of dispersive waves”, *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency control*, Vol. 47, N°3, 2000, pp. 612-619.
- 255.** Jeong H., “Analysis of plate wave propagation in anisotropic laminates using a wavelet transform”, *NDT&E International*, 34, 2001, pp. 185-190.
- 256.** Mizutani Y., K. Nagashima K., Takemoto M., Ono K., “Fracture mechanism characterization of cross-ply carbon-fiber composites using acoustic emission analysis”, *NDT&E International*, Vol. 33, 2000, pp. 101-110.
- 257.** Sung D.-U., Kim C.-G., Huong C.-S., “Monitoring of impact damages in composite laminates using wavelet transform”, *Composites Part B*, 2002, Vol. 33, pp. 35-43.
- 258.** Hamstad M.A., O’Gallagher A., Gary J., “Examination of the Application of a Wavelet Transform to Acoustic Emission Signals Part 1. Source identification”, *Journal of Acoustic Emission*, 2002, Vol. 20, pp. 39-61.
- 259.** Mallat S., “A wavelet tour signal processing”, Academic Press, ISBN 0-12-466606-X, 1999.
- 260.** Chui, C.K., “An introduction to Wavelets”, Academic Press, ISBN 0-12-174584-8, 1992.
- 261.** Rao R.M., Bopardikar A.S., “Wavelet transforms: introduction to theory and applications”, Hardcover, ISBN 0-201-63463-5, 1999.
- 262.** Misiti M., Misiti Y., Oppenheim G., Poggi J.-M., “Wavelet toolbox user’s guide”, The MathWorks, Inc, 2000.
- 263.** Berthelot J.-M., Leblond P., El Mahi A., Le Corre J.-F., “Transverse cracking of cross-ply laminates: Part 1. Analysis”, *Composites Part A*, Vol. 27A, 1996, pp. 989-1001.
- 264.** Berthelot J.-M., El Mahi A., Leblond P., “Transverse cracking of cross-ply laminates: Part 2. Progressive widthwise cracking”, *Composites Part A*, Vol. 27A, 1996, pp. 1003-1010.
- 265.** Berthelot J.-M., Le Corre J.-F., “A model for transverse cracking and delamination in cross-ply laminates”, *Composites Science and Technology*, Vol. 60, 2000, pp. 1055-1066.

- 266.** Berthelot J.-M., Le Corre J.-F., “Statistical analysis of the progression of transverse cracking and delamination in cross-ply laminates”, *Composites Science and Technology*, Vol. 60, 2000, pp. 2659-2669.
- 267.** Berthelot J.-M., “Transverse cracking and delamination in cross-ply laminates. Static and fatigue loading”, *Applied Mechanics Reviews*, Vol. 56, 2003, pp. 111-147.
- 268.** Favre J.-P.; Laizet J.-C., “Acoustic emission analysis of the accumulation of cracks in CFRP cross- ply laminates under tensile loading”, *Journal of Acoustic Emission*, Vol. 9, N°2, 1990, pp. 97- 102.
- 269.** Surgeon M., Vanswijghoven E., Wevers M., Van DerBiest O., “Acoustic emission during tensile testing of SiC-fibre-reinforced BMAS glass-ceramic composites”, *Composites Part A*, Vol. 28A, 1997, pp. 473-480.
- 270.** Morscher G.N., “Stress-dependent matrix cracking in 2D woven SiC-fiber reinforced melt-infiltrated SiC matrix composites”, *Composites Science and Technology*, Vol. 64, 2004, pp. 1311–1319.
- 271.** Dzenis Y.A., Qian J., “Analysis of microdamage evolution histories in composites”, *International Journal of Solids and Structures*, Vol. 38, 2001, pp. 1831-1854.
- 272.** Surgeon M., Wevers M., “Modal analysis of acoustic emission signals from CFRP laminates”, *NDT&E International*, Vol. 32, 1999, pp. 311-322.
- 273.** Johnson M., Gudmundson P., “Broad-band transient recording and characterization of acoustic emission events in composite laminates”, *Composites Science and Technology*, Vol. 60, 2000, pp. 2803-2818.
- 274.** Johnson M., Gudmundson P., “Transient recording and analysis of acoustic emission events resulting from damage evolution in composite laminates”, *Proceedings of 15th World Conference on NDT*, <http://www.ndt.net/article/wcndt00/>, Rome, 2000.
- 275.** Toyama N., Okabe T., Takeda N., “Lamb wave evaluation and localization of transverse cracks in cross-ply laminates”, *Journal of Materials Science*, Vol. 38, 2003, pp. 1765-1771.
- 276.** Vesanto J., Himberg J., Alhoniemi E., Parhankangas J., “SOM Toolbox for MATLAB 5”, <http://www.cis.hut.fi/projects/somtoolbox/>
- 277.** Udd E., “Fibre Optic Smart Structure Technology”, In *Fibre Optic Smart Structures*, John Wiley & Sons, Inc., ISBN 0-471-55448-0, 1995, pp. 5-21.

- 278.** Dakin J., Culshaw B., “Optical fibre sensors: Principles and components”, Artech House, ISBN 0-89006-317-6, 1988.
- 279.** Krohn D.A., “Fibre Optic Sensors: Fundamentals and Applications”, Instrument Society of America, third edition, ISBN 1-55617-714-3, 2000.
- 280.** Keiser G., “Optical Fibre Communications”, McGraw-Hill International Editions, third edition, ISBN 0-07-116468-5, 2000.
- 281.** Carman G.P., Sendekyj G.P., “Review of the mechanics of embedded optical sensors”, Journal of Composites Technology & Research, Vol. 17, N°3, 1995, pp. 183-193.
- 282.** Sirkis J.S., Dasgupta A., “Optical Fibre/Composite Interaction Mechanics”, In Fibre Optic Smart Structures, John Wiley & Sons, Inc., ISBN 0-471-55448-0, 1995, pp. 61-107.
- 283.** Jensen D.W., Sirkis J.S., “Integrity of composite structures with embedded optical fibres”, In Fibre Optic Smart Structures, John Wiley & Sons, Inc., ISBN 0-471-55448-0, 1995, pp. 109-120.
- 284.** Carman G.P., Averill R.C., Reifsnider K.L., Reddy J.L., “Optimization of Coatings to Minimize Micromechanical Stress Concentrations in Composites”, Journal of Composite Materials, Vol. 27, N°6, 1993, pp. 589-613.
- 285.** Czarnek R., Guo Y.F., Bennett K.D., Claus R.O., “Interferometric Measurements of Strain Concentrations Induced by an Optical Fibre Embedded in a Fibre Reinforced Composite”, Proceedings of the Fibre Optic Smart Structures and Skins Conference, SPIE, Vol. 986, 1989, pp. 43-54.
- 286.** Singh H., Sirkis J.S., Dasgupta A., “Micro-Interaction of Optical Fibres Embedded in Laminated Composites”, Proceedings of the Fibre Optic Smart Structures and Skins IV Conference, SPIE, Vol. 1588, 1991, pp. 76-85.
- 287.** Salehi A., Tay A., Wilson D., Smith D., “Strain Concentrations Around Embedded Optical Fibres by FEM and Moiré Interferometry”, Proceedings of the 5th Annual ASM/ESD Advance Composite Conference/Exposition, Dearborn, MI, 1989, pp. 11-19.
- 288.** Dasgupta A., Wan Y., Sirkis J.S., Singh H., “Micro-Mechanical Investigation of an Optical Fibre Embedded in a Laminated Composite”, Proceedings of the Fibre Optic Smart Structures and Skins III Conference, SPIE, Vol. 1370, 1990, pp. 119-128.

- 289.** Tay A., Wilson D.A., Wood L., “Strain Analysis of Optical Fibres Embedded in Composite Materials Using Finite Element Modeling”, Proceedings of SPIE, Vol. 1170, 1990, pp. 521-533.
- 290.** Dickmanm O., Kowalska M., Savage S.J., “Intelligent material systems and structures: The interface”, Proceedings of the Advanced Composites’93 Conference, pp. 669-673.
- 291.** Seo D.C., Lee J.J., “Effect of embedded optical fibre sensors on transverse crack spacing of smart composite structures”, Proceedings of the 8th International Conference on Composite Structures, September 1995, Vol. 32, N°1-4.
- 292.** Measures R.M., “Structural monitoring with fibre optic technology”, Academic Press, ISBN 0-12-487430-4, 2001.
- 293.** Leblanc M., “Interaction Mechanics of Single-Ended Fibre Sensors Using Novel In-Situ Measurement Techniques”, Ph.D. Thesis, University of Toronto, 1998.
- 294.** Skontorp A., “Effect of embedded optical fibre on the structural integrity of composites”, Proceedings of the 12th International Conference on Composite Materials, Paris, 1999.
- 295.** Davidson R., Roberts S.S.J., “Do embedded Sensors Degrade Mechanical performance of Host Composites?”, Proceedings of the Active Materials and Adaptive Structures Conference, Alexandria, VA, 1991, pp. 109-114.
- 296.** Surgeon M., Wevers M., “Static and dynamic testing of a quasi-isotropic composite with embedded optical fibres”, Composite A, Vol. 30, 1999, pp. 245-251.
- 297.** Badcock R.A., Fernando G.F., “An intensity-based optical fibre sensor for fatigue damage detection in advanced fibre-reinforced composites”, Smart Material structures, Vol. 4, 1995, pp. 223-230.
- 298.** Silva J.M.A., Ferreira J.A.M., Devezas T.C., “Fatigue Behaviour of Carbon-Epoxy Laminates”, Proceedings of the 8as Jornadas de Fractura, Vila Real, Portugal, 2002, pp. 371-378.
- 299.** Cheol C., Cheol S.D., Jung Ju L., Jang-Kyo K., “Effect of embedded optical fibres on the interlaminar fracture toughness of composite laminates”, Composite Interfaces, Vol. 5, N°3, 1998, pp. 225-240.

- 300.** Udd E., “Fibre Optic Sensor Overview”, In *Fibre Optic Smart Structures*, John Wiley & Sons, Inc., ISBN 0-471-55448-0, 1995, pp. 155-170.
- 301.** Zhou G., Sim L.M., “Damage detection and assessment in fibre-reinforced composite structures with embedded fibre optic sensors-review”, *Smart Material Structures*, Vol. 11, 2002, pp. 925-939.
- 302.** Le Blanc M., Measures R.M., “Fibre Optic Damage Assessment”, In *Fibre Optic Smart Structures*, John Wiley & Sons, Inc., ISBN 0-471-55448-0, 1995, pp. 518-613.
- 303.** Crane R.M., Macander A.B., Gagoric J., “Fibre Optics for a Damage Assessment System for Fibre Reinforced Plastic Composite Structures”, *Review of Progress in Quantitative Nondestructive Evaluation*, Vol. 2B, 1982, pp. 1419-1430.
- 304.** Glossop N.D.W., Dubois S., Tsaw W., Leblanc M., Lymer J., Measures R.M., Tennyson R.C., “Optical fibre damage detection for an aircraft composite leading edge”, *Composites*, Vol. 21, N°1, 1990, pp. 71-80.
- 305.** Waite S.R., “Use of embedded optical fibre for early damage detection in composite materials”, *Composites*, Vol. 21, N°2, 1990, pp. 148-154.
- 306.** Waite S.R., “Use of embedded optical fibre for significant fatigue damage detection in composite materials”, *Composites*, Vol. 21, N°3, 1990, pp. 225-231.
- 307.** Sage I., Badcock R., Humberstone L., Geddes N., Kemp M., Bourhill G., “Triboluminescent damage sensors”, *Smart Material Structures*, Vol. 8, 1999, pp. 504-510.
- 308.** Takeda N., “Characterization of microscopic damage in composite laminates and real-time monitoring by embedded optical fiber sensors”, *International Journal of Fatigue*, Vol. 24, 2002, pp. 281-289.
- 309.** Okabe Y., Yashiro S., Kosaka T., Takeda N., “Detection of transverse cracks in CFRP composites using embedded fiber Bragg grating sensors”, *Smart Material Structures*, Vol. 9, N°6, 2000, pp. 832-840.
- 310.** Takeda S. Okabe Y., Takeda N., “Delamination detection in CFRP laminates with embedded small-diameter fiber Bragg grating sensors”, *Composite Part A*, Vol. 33, 2002, pp. 971-980.

- 311.** Okabe Y., Tsuji R., Takeda N., “Application of chirped fiber Bragg grating sensors for identification of crack locations in composites”, *Composites: Part A*, Vol. 35, 2004, pp. 59-65.
- 312.** Measures R.M., “Fibre Optic Strain Sensing”, In *Fibre Optic Smart Structures*, John Wiley & Sons, Inc., ISBN 0-471-55448-0, 1995, pp. 171-247.
- 313.** Liu K., Ferguson S.M., Measures R.M., “Damage detection in composites with embedded fibre optic interferometric sensors”, *Proceedings of the Fibre Optic Smart Structures and Skins II Conference*, SPIE, Vol. 1170, 1990, pp. 205-210.
- 314.** Liu K., Ferguson S.M., McEwen K., Tapanes E., Measures R.M., “Acoustic emission detection for composite damage assessment using embedded ordinary single-mode fibre-optic interferometric sensors”, *Proceedings of the Fibre Optic Smart Structures and Skins III Conference*, SPIE, Vol. 1370, 1991, pp. 316-323.
- 315.** Glossop N.D.W., Tsaw W., Measures R.M., Tennyson R.C., “Image-Enhanced Backlighting: A New Method of NDE Translucent Composites”, *Journal of Nondestructive Evaluation*, Vol. 8, N°3, 1989, pp. 181-193.
- 316.** Maslouhi A., Proulx D., Roy C., Liu K., McEwen K., Measures R.M., Zimcik D.G., “Use of embedded optical fibre sensors for acoustic emission detection within composite materials”, *Proceedings of the 36th International SAMPE Symposium and Exhibition*, Vol. 36, 15-18 April 1991, pp. 259-271.
- 317.** Tsuda H., “Response of Michelson interferometric fibre-optic sensors to simulated acoustic emission”, *Journal of the Japan Institute of Metals*, Vol. 65, N°9, 2001, pp. 831-834.
- 318.** Gong J., Jin W., Liao Y., MacAlpine J.M.K., “Amplitude-multiplexing of Mach-Zehnder interferometer array and its application of locating acoustic emission”, *Proceedings of the Advanced Photonic Sensors and Applications II Conference*, Singapore, 27-30 November 2001.
- 319.** Baillie P.W.R., Hale K.F., Fernando G.F., Jones B.E., “Optical fibre sensing of acoustic emission in fibre reinforced composites”, *Proceedings of the 7th Conference on Sensors and Their Applications*, Dublin, 1995, pp. 125-130.

- 320.** Greene J.A., Tran T.A., Bhatia V., Gunther M.F., Wang A., Murphy K.A., Claus R.O., “Optical fiber sensing technique for impact detection and location in composite materials and metal specimens”, *Smart Material Structures*, Vol. 4, 1995, pp.93-98.
- 321.** Dorigi J.F., Krishnaswamy S., Achenbach J.D., “Stabilization of an Embedded Fibre Optic Fabry-Pérot Sensor for Ultrasound Detection”, *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, Vol. 52, N°5, September 1995.
- 322.** Hong C.-S., Bang H.-J., Kang H.-K., Kim C.-G., “Real-time damage detection for smart composite materials using optical fiber sensors”, *Proceedings of the 13th International Conference on Composite Materials*, Beijing, 2001.
- 323.** Borinski J.W., Boyd C.D., Dietz A., Duke J.C., Horne M.R., “Fibre optic sensors for predictive health monitoring”, *IEEE*, ISBN 0-7803-7094-5, 2001, pp 250-262.
- 324.** Read I., Foote P., Murray S., “Optical fibre acoustic emission sensor for damage detection in carbon fibre composite structures”, *Measurement Science and Technology*, Vol. 13, N5-N9, 2002.
- 325.** Kim D.-H., Koo B.-Y., Kim C.-G., Hong C.-S., “Damage detection of composite structures using a stabilized extrinsic Fabry-Perot interferometric sensor system”, *Smart Material Structures*, Vol. 13, 2004, pp. 593-598.
- 326.** Yuana L., Zhou L.-m., Jin W., “Detection of acoustic emission in structure using Sagnac-like fiber-loop interferometer”, *Sensors and Actuators A*, 2004, in press, www.sciencedirect.com
- 327.** Rippert L., Wevers M., Van Huffel S., “Optical and acoustic damage detection in laminated CFRP composite materials”, *Composites Science and Technology*, Vol. 60, 2000, pp 2713-2724.
- 328.** Perez I., Cui H.-L., Udd E., “Acoustic emission detection using fiber Bragg gratings”, *Proceedings of the Smart Structures and Materials 2001 - Sensory Phenomena and Measurement Instrumentation for Smart Structures and Materials*, Newport Beach, CA, United States, 5-6 March 2001, SPIE, Vol. 4328, pp. 209-215.
- 329.** Ohsawa I., Kageyama K., Tsuchida Y., Kanai M., “Development of a novel optical fiber sensor for AE detection in composites”, *Journal of Acoustic Emission*, Vol. 21, 2003, pp. 176-186.

- 330.** Badcock R.A., Krishnamurthy S., Fernando G.F., Butler T., Chen R., Tetlow J., “Health Monitoring of Composite Structures Using a Novel Fibre Optic Acoustic Emission Sensors”, Proceedings of the 11th European Conference on Composite Materials, Rhodes, Greece, 31 May-3 June 2004, pp. 51-52.
- 331.** Chen R., Fernando G.F., Butler T., Badcock R.A., “A novel ultrasound fibre optic sensor based on a fused-tapered optical fibre coupler”, Measurement Science Technology, Vol. 15, 2004, pp. 1490-1495.
- 332.** Hecht E., “Optics”, Addison Wesley edition, second edition, ISBN 0-201-11611-1, 1987.
- 333.** Tran T.A., Miller W.V. III, Murphy K.A., Vengsarkar A.M., Claus R.O., “Stabilized Extrinsic Fiber-Optic Fizeau Sensor for Surface Acoustic Wave Detection”, Journal of Lightwave Technology, Vol. 10, N°10, 1992, pp. 1499-1505.
- 334.** Dahlem M., Santos J.L., Ferreira L.A., Araújo F.M., “Passive Interrogation of Low-Finesse Fabry-Pérot Cavities Using Fiber Bragg Gratings”, IEEE Photonics Technology Letters, Vol. 13, pp. 990-992, 2001.