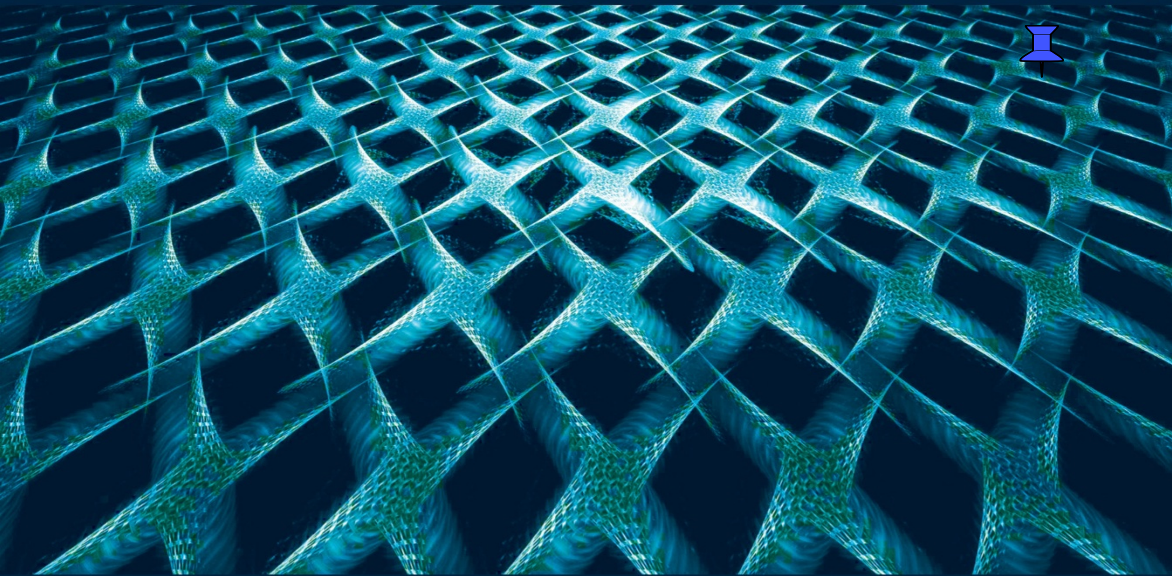
MATERIALS SCIENCE SERIES

DURABILITY AND AGEING OF ORGANIC COMPOSITE MATERIALS SET



Volume 3

Acoustic Emission and Durability of Composite Materials

Nathalie Godin, Pascal Reynaud and Gilbert Fantozzi

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coordinated by
Marco Gigliotti

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First published 2018 in Great Britain and the United States by ISTE Ltd and John Wiley & Sons, Inc.

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Hoboken, NJ 07030
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Library of Congress Control Number: 2017963070

British Library Cataloguing-in-Publication Data
A CIP record for this book is available from the British Library
ISBN 978-1-78630-019-5

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Introduction

The weight reduction of structures is still a challenge for reducing fuel consumption. For example, in the automotive sector, EU regulations on CO_2 emissions from passenger cars set a threshold of 130 g/km and lowered the threshold to 95 g/km by 2020. Vehicle weight reduction with the introduction of composite materials is one of the areas of improvement necessary for achieving this objective. For aircraft manufacturers, the current challenge is also to reduce the fuel consumption of aircrafts and/or increase their efficiency, either by increasing the temperature of the engines or by reducing the weight of the parts. Metallic superalloys, currently used in commercial aircraft engines, have a high density, which penalizes the weight/power ratio. In the field of aeronautics, composite materials have been used since the 1970s for secondary parts and are now increasingly used for primary parts. Organic matrix composites (OMCs) reinforced with glass or carbon fibers are now widely used. For example, in the latest generation of commercial aircraft, they are the most used type of material (50% for the Boeing 787 Dreamliner and 52% for the Airbus A350). Thanks to the realized weight gain, the fuel consumption was reduced by about 20%. SAFRAN has developed blades and a fan casing made of 3D woven composite material produced by the RTM (Resin Transfer Molding) process for the LEAP engine. These blades allow a significant weight benefit. In addition, as part of the ARCOCE program, an A320 airbus has been flown with a CFM-56-5B engine equipped with the ARCOCE plug (rear ceramic composite bodies), an ejection nozzle produced entirely in ceramic matrix composites (CMCs).

In this context, damage of structural composite materials is a key factor in mastering the durability and reliability of parts in service. It is necessary not only to quantify the damage but also to identify the different mechanisms responsible for it. It is therefore essential to characterize the composite materials, define the most suitable damage indicators and use or develop models to estimate the remaining lifetime from analysis of precursor events resulting from damage. To address this issue, acoustic emission (AE) is a well-adapted technique. Indeed, the damage mechanisms are accompanied by energy release in the form of acoustic waves. Sensors on the surface of the structure allow the recording of AE signals. Acoustic emission refers to a non-destructive technique that allows the detection of material damage in real time. This technique has the advantage of being totally passive and therefore having no influence on the observed damage.

In 1964, the control of the casings of the Polaris rocket gave rise to the industrial applications of AE. In 1982, AE received its first administrative recognition with the publication of CARP (Committee on Acoustic Emission from Reinforced Plastics) codes [CAR 93]. Since the rise in the use of the method in the 1980s, its applications on structures in composite materials have been constantly increasing. An example of an industrial application is the control of glass fiber reinforced storage tanks according to ASTM E1067 [AST 11]. AE and composite material characterization have been the most active fields since the 1990s, especially for OMCs, accounting for more than 50% of publications.

One of the stakes in structural health monitoring is the early detection of damage before the latter leads to disaster. The classical integrated health monitoring process is based on the characterization of the damage and the prognosis of the remaining useful life. A diagnosis phase and a prognostic phase can thus be distinguished. The diagnosis phase must be able to detect the damage, locate it, identify it and assess its severity. The prognosis phase, based on the results of the diagnosis and on models, makes it possible to evaluate the residual lifetime. Acoustic emission allows this objective to be met, as this technique allows the health of an entire structure regardless of its size to be monitored while reducing maintenance costs.

The analysis of the collected data can be used to discriminate the sources of damage (matrix cracks, fiber breaks, fiber/matrix decohesion, delamination, etc.) and to measure the kinetics of the various degradation mechanisms. In addition, an estimate of the composite material's remaining lifetime can be considered based on a real-time tracking of the damage recorded by AE. Indeed, the initial damage is often diffused and uncorrelated before it becomes organized. The events occurring at the beginning of the commissioning of the part strongly influence the lifetime; they can be described as precursor events. Knowledge of the latter is then indispensable to the evaluation of the remaining lifetime. The greater the heterogeneity, the greater the number of precursor events. This leads to a somewhat paradoxical conclusion: the more complex the system, the easier the prediction.

These two aspects will be discussed in this book. Two approaches based on two complementary analyses of acoustic activity are presented:

1) an individual analysis of the signals: the objective of this analysis is to associate each AE signal with the damage mechanism that generated it. This allows, in real time, identifying the type of damage that occurs and having an idea of its severity;

2) a collective and cooperative analysis of all the collected signals. The idea is to predict the lifetime of a part in service by analyzing its behavior by monitoring the acoustic emission during the load. The rupture can then be predicted by looking at the cooperative aspect, synthesizing all the information contained in the events in a global way.

Chapter 1 presents acoustic emission and its main characteristics. Chapter 2 is devoted to the identification of the acoustic signature of the various damage mechanisms occurring in OMCs and also in CMCs. The contributions of this approach as well as its main difficulties and limitations are presented. Chapter 3 is devoted to lifetime prediction using AE for long-term tests.

1

Acoustic Emission: Definition and Overview

1.1. Overview

The European standard NF EN 1330-9 [NF 17], defines acoustic emission as "transient elastic waves generated by the release of energy in a material or by a process". The ASTM (American Society for Testing of Materials) standard [AST 17] states that acoustic emission is "the set of phenomena in which transient elastic waves are generated by dissipation of energy from sources located within a material". All the frequencies of the concerned waves are in the ultrasonic range between 50 kHz and 1.5 MHz. A material subjected to deformation dissipates energy by creating material micro-displacements, a fraction of which is in the form of elastic waves [BEA 83, EIT 84, SCO 91]. The waves thus released, of different natures and frequencies, propagate in the material and may undergo modifications before reaching the surface of the studied sample. The surface vibration is generally detected by a piezoelectric sensor which translates it in the form of an electrical signal. This acoustic emission signal is then amplified and digitized by acquisition software (Figure 1.1). The term acoustic emission is also used to designate the measurement technique. It is a volumetric method, in which the whole of a structure can be followed by AE regardless of its size. The information obtained has both a local character (thanks to localization) and a global character (monitoring the whole structure).

Acoustic Emission and Durability of Composite Materials, First Edition.
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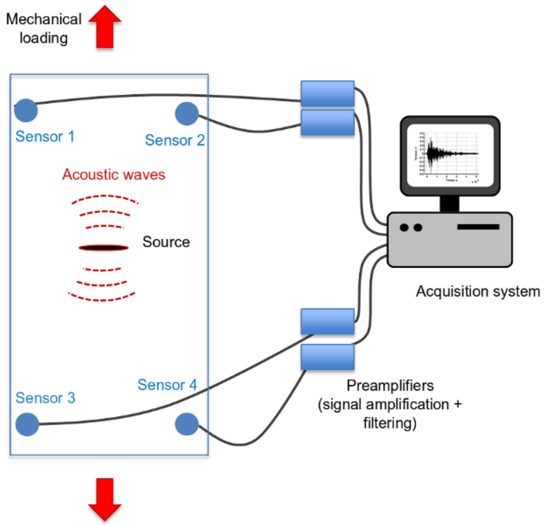

Figure 1.1. *AE diagram of the acoustic emission chain, from the generation of the acoustic wave during a mechanical test to the visualization of the AE signal*

The earliest known phenomenon of acoustic emission is probably "tin cry". The alchemist of the 8th Century Jabir ibn Haya (Geber) noted that "Jupiter (tin) produces a rough sound, a crack and that Mars (iron) is very sonorous during forging" [DRO 96, DRO 87]. This noise emitted by iron is probably due to the formation of martensite during cooling. "Tin cry" was attributed to twinning in 1916 by Czochralski [CZO 16]. In France, Portevin [POR 23] and Le Chatelier mentioned, in 1923, a "little dry noise" during the formation of slip bands in aluminum alloys. Another source of acoustic emission which has probably been used industrially for a very long time is the cracking of the woodworking in mines which indicates the imminence of a collapse. Other observations of audible acoustic emission have been collected by Drouillard [DRO 96, DRO 87].

The source mechanisms expected during the mechanical stress of fibrous composite materials are mainly: matrix cracking, interfacial decohesion, fiber breaks and delamination (Figure 1.2). We can recall that many physical phenomena are at the origin of AE:

– plastic deformation, dislocation movement, twinning, grain boundaries slipping, formation of Piobert–Lüders bands, rupture of inclusions or intermetallic compounds and phase transformation (e.g. martensitic);

– the initiation and propagation of cracks (static stress, fatigue, corrosion under stress, etc.);

– hydrogen embrittlement;

– cavernous or pitting corrosion;

– friction;

– mechanical impacts;

– leaks (liquid and gas), cavitation and boiling.

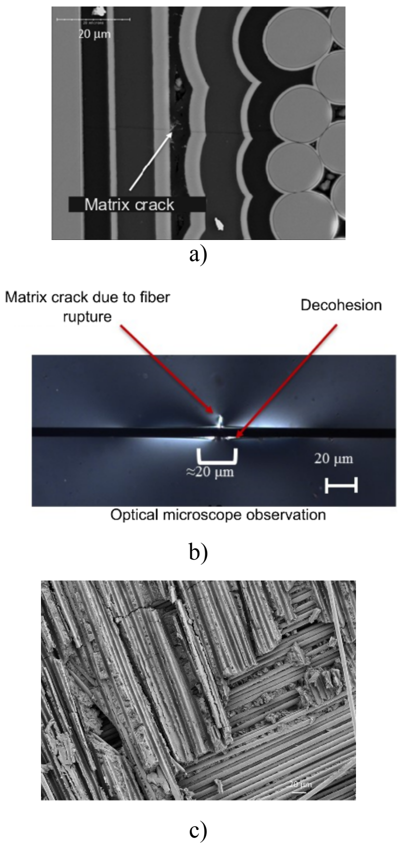

Figure 1.2. *Acoustic emission sources in composite materials: a) matrix cracking in a SiC_f/SiC ceramic matrix composite; b) rupture of a carbon fiber in an epoxy resin with fiber/matrix decohesion [LUT 14]; c) damage of a composite with polyamide matrix PA12, carbon fibers [– / + 45 °] subjected to tensile stress after aging in water for 45 days at 110°C. For a color version of this figure, see www.iste.co.uk/godin/acoustic.zip*

Table 1.1 summarizes the possibilities offered by different non-destructive techniques to identify the damage in composite materials [WEV 97, COR 16]. In addition to the high-resolution X-ray technique, the acoustic emission technique is the only one that detects all types of damage. It allows following the initiation, the propagation and the interactions of damage mechanisms, *in situ*, in real time and in a non-destructive way. It can also be applied to all types of composite materials (organic matrix, metallic or ceramic matrix and whatever the material constituting the reinforcement) and, unlike ultrasonic or X-ray methods, does not require a special environment.

	Acoustic emission	C-scan ultrasound	X-ray	Microscopy	Matrix dissolution or pyrolysis	High-resolution X-ray
Fiber rupture	Possible	No	Possible	Non-destructive or destructive	Yes	Possible
Delamination	Possible	Yes	Yes	On the edge or destructive	Yes	Possible
Matrix cracking	Possible	No	Yes	On the edge or destructive	-	Possible
Decohesion	Possible	No	No	Non-destructive or destructive	-	Possible

Table 1.1. *The main techniques used for the identification of damage in composites [JAC 00]*

The acoustic emission technique differs fundamentally from the ultrasonic technique. Indeed, ultrasound used in non-destructive testing produced by a transmitter device is controlled by the operator. In the case of acoustic emission, the operator does not have control over the characteristics of the waves he is trying to detect because they are produced within a material under the effect of an external stress. This aspect represents the full potential of the AE technique and also all the difficulty of analysis. The interpretation of the information contained in AE data requires a careful analysis of material damage and the collected signals. In summary, AE differs from other acoustic techniques for several reasons:

– the material itself generates the signal to be analyzed;

– an AE signal can only be obtained if the structure is stressed (chemically, mechanically, thermally, etc.). Under these conditions, only active or scalable defects can be detected. This technique does not make it possible to obtain mapping of the existing defects in a given structure;

– AE can reveal the presence of an evolutionary defect, even give its position and sometimes if the reference data are sufficient, measure its harmfulness. However, it is difficult or impossible to characterize the geometry of the defect (depth, width, length, shape, etc.);

– a large structure can be controlled by AE in a single operation using a limited number of sensors;

– the amplitude of AE signals depends on the rate of change in the size of the defect and not just on the total defect size (Figure 1.3). AE is very sensitive to a length increment of a crack in a brittle material with a high propagation rate but much less sensitive to large displacements in a ductile material with a slower displacement rate.

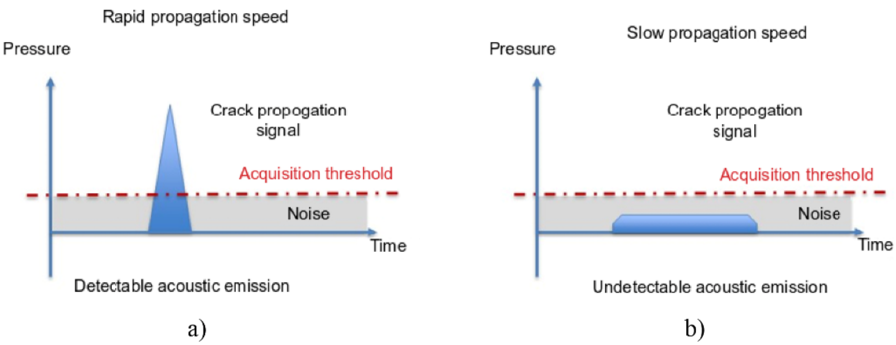

Figure 1.3. *An acoustic emission signal produced by a crack growth of the same length in a) a brittle material and b) a ductile material*

Generally, continuous acoustic emission is distinguished from discrete acoustic emission or by bursts:

– discrete emission (Figure 1.4(a)) is in the form of damped or sine waves (resonant sensors) or very short pulses (broadband sensors). It is often associated with damage phenomena such as crack initiation and propagation, stress corrosion and fiber ruptures;

– continuous emission (Figure 1.4(b)) is in the form of an amplified noise signal of which a measurable characteristic is the mean amplitude. When the bursts are so frequent that they overlap, the acoustic emission signal translates into an apparent increase in background noise. It is often associated with the movement of dislocations during the plastic deformation of metallic materials.

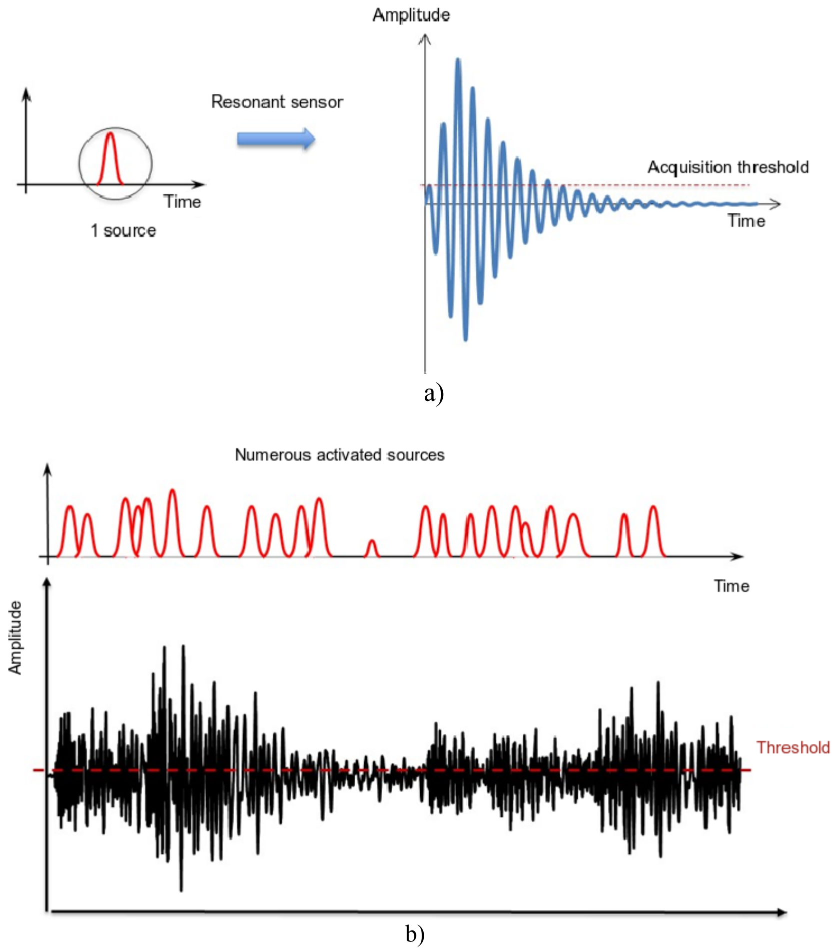

Figure 1.4. *Acoustic emission signal type: a) discrete and b) continuous*

Acoustic emission sources are generally related to irreversible phenomena. A classic characteristic of the AE response of certain materials is the Kaiser effect [KAI 50]. When subjected to monotonic stress up to a load F_1, a material activates acoustic waves if it enters its plastic domain (Figure 1.5). During a second load increase, the AE appears only for a load

F_2 greater than or equal to F_1, i.e. a load greater than the maximum load of the preceding load. It is then said that the material respects the Kaiser effect. Often observed in metals, it represents the manifestation in AE of the irreversible nature of the deformations. If the structure is damaged (fatigue, corrosion), AE appears for a load $F_2 < F_1$ (Figure 1.5(b)). The Felicity ratio R_F is then defined by equation [1.1]. The Kaiser effect is used to determine the health of metallic equipment. The Felicity ratio is used to assess the health of composite structures:

$$R_F = \frac{F_2}{F_1} \qquad [1.1]$$

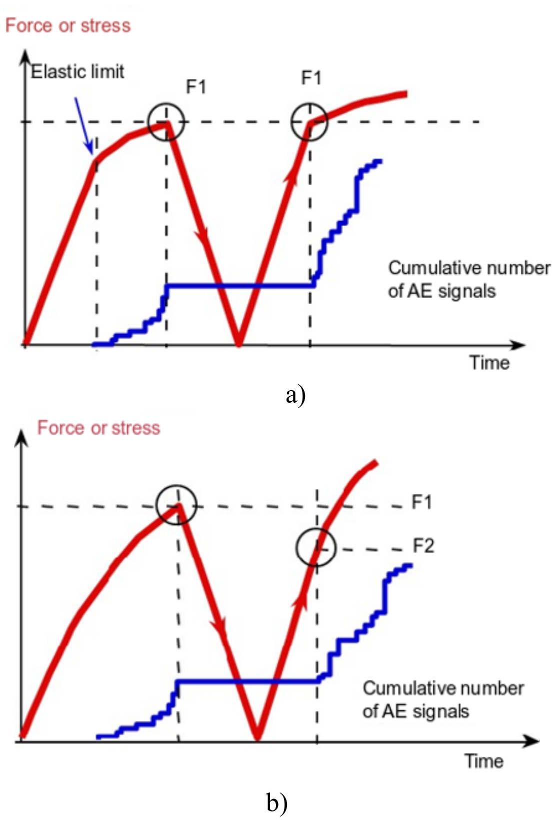

Figure 1.5. *a) The Kaiser effect and b) the Felicity ratio. For a color version of this figure, see www.iste.co.uk/godin/acoustic.zip*