



# Short Review of the Use of Acoustic Emissions for Detection and Monitoring of Cracks

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## Abstract

Proper detection and monitoring of cracks are crucial when evaluating the health of equipment and structures because of the catastrophic failures that can occur if they evolve without control. Among the group of nondestructive tests (NDT), acoustic emissions (AE) emerge as the most used technique for this purpose. This is due to its high sensitivity to low-energy events, which allows the incipient detection of cracks. In this paper, a short review is presented concerning some practical and research activities on crack detection and monitoring in structures using AE. It is shown that AE is a versatile technique for crack detection and monitoring, with applications in a broad range of materials such as concrete, composites, rocks, metals, and wood and in different types of civil and industrial applications.

**Keywords** Acoustic emission · Crack · Structure health monitoring

## 1 Introduction

One of the main concerns in structure health monitoring (SHM) is the detection of cracks and the monitoring of their evolution in time. Different nondestructive tests (NDT) are used for the inspection of structures and materials in search of possible cracks that might appear, or for the monitoring of the evolution of existing cracks. Among this group of techniques, acoustic emission (AE) is probably the most used tool for crack detection and monitoring, this being due to its high sensitivity to low-energy and transient events such as the waves generated when cracks appear or grow.

In some applications such as wind turbine blades, the acoustic emissions technique is the most widely used, since it shows good prospects in early warnings before damage develops [1]. Similarly, in pressurized tanks, the AE is a technique that allows saving costs, since it allows the inspection of the complete structure, including the welds and the base during pressurization [2].

This short review paper briefly addresses the main aspects of AE focused on the subject of cracks and then presents different applications of the AE technique to crack detection and monitoring on structures and materials.

## 2 General Aspects of AE

When a solid material is subjected to working conditions exceeding its mechanical resistance capacity, its internal structure suffers dislocations and fractures that release a certain amount of energy. This energy propagates in the form of mechanical waves in the medium, known as acoustic emissions (AEs).

AE refers essentially to the propagation of high-frequency stress waves that generate nonpermanent deformations in the medium and whose amplitude rapidly decays, meaning they have a transient nature. Some examples of AE sources include friction contact, impacts, thermal deformations able to produce structural changes, and the formation and growth of cracks in isotropic and orthotropic materials.

AE waves in materials can be of four types. Two of them occur in the internal structure of the material (longitudinal P-waves and shear S-waves), and the other two are surface waves (Rayleigh waves and Love waves), as in Fig. 1. One AE source can produce one or more of these waves, which can coexist and interact. For example, internal P-waves can

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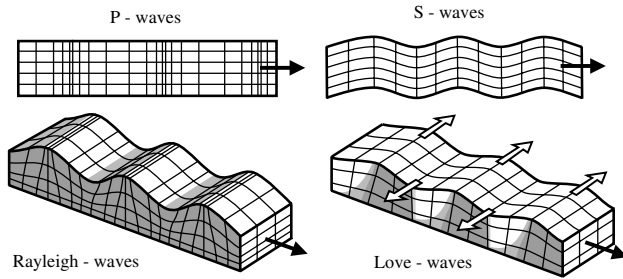


Fig. 1 Propagation of acoustic emissions—wave types

produce Rayleigh waves when reaching the surface of the material.

The typical arrangement for AE measurement involves the placement of a sensing element in direct contact with the surface. Most AE sensors are based on the piezoelectric effect, which consists of the property of some materials to generate a voltage when they are subjected to mechanical stress. There are two groups of piezoelectric AE sensors [3]: BAW sensors (bulk acoustic waves), which measure all types of AE waves (Fig. 1), e.g., the resonant type, which is based on the natural frequency of the piezoelectric sensor; and SAW sensors (surface acoustic waves), which measure surface Rayleigh waves, the most widely used. The measured AE signals are usually pre-amplified and then sampled (ideally above 1 MHz) using high-speed A/D converters.

Two types of AE are distinguished in the measured signals: continuous-type AE and burst-type AE. The former is a noise-like signal caused by continuous interaction sources such as fluid leaks and asperity contact resulting from friction. Burst-type AE is of short duration and results from the occurrence of sudden singular events such as impacts and crack formation and growth, as in Fig. 2.

The processing of AE is oriented to the detection, distinction, and assessment of the continuous and burst types of AE. One approach for this bases on the analysis of the raw AE signal where tools are used such as the envelope spectrum for detecting possible pseudo-periodic patterns in the burst generation process [4] and the wavelet transform for evaluating the wave frequency of the bursts [5]. A different approach focuses on the burst-type AE and is

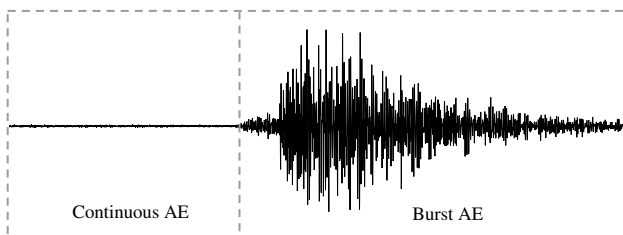


Fig. 2 Continuous and burst AE

based on the calculation of indicators and the evaluation of their trends. The indicators include (Fig. 3), where “y” is the amplitude vector of the burst.

- Peak amplitude (A):

$$A = \max(|y|) \tag{1}$$

- Rise time (RT): from burst start to peak amplitude, where the start is defined by crossing up a set threshold.
- Downtime (DT): from the peak amplitude to the burst end, where the end is defined by crossing down the set threshold.
- Duration (D) of the burst:

$$D = RT + DT \tag{2}$$

- Counts: number of times that the burst wave crosses the threshold in one direction.
- Average frequency (AF):

$$AF = \frac{\text{Counts}}{D} \tag{3}$$

- MARSE energy: measured area under the rectified signal envelope

$$\text{MARSE} = \int_0^D e(t)dt \tag{4}$$

where  $e(t)$  is the envelope of the AE signal.

- True energy: area under the squared signal envelope

$$\text{True Energy} = \int_0^D e^2(t)dt \tag{5}$$

- RMS value:

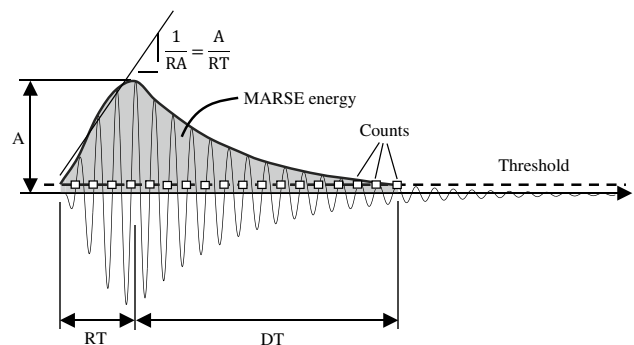


Fig. 3 AE indicators

$$\text{RMS} = \sqrt{\frac{\sum_{i=1}^n (y_i)^2}{n}} \tag{6}$$

– RA, quotient between rise time and peak amplitude:

$$\text{RA} = \frac{\text{RT}}{A} \tag{7}$$

– b value

The b value was first proposed by Gutenberg Richter in the field of seismology and is used to characterize earthquakes. In the field of AE, this indicator is used to analyze fracture process and is defined as in Eq. (8) [6].

$$\log_{10} N = a + b \frac{A_{\text{dB}}}{20} \tag{8}$$

where  $A_{\text{dB}}$  is the burst peak amplitude in dB,  $N$  is the number of bursts with peak amplitude greater than  $A_{\text{dB}}$ , and  $a$  and  $b$  are constant coefficients. From this definition, a low b value points out that the specimen is approaching imminent failure.

This second, indicator-based approach, which is more extended in practical applications for SHM, requires a proper detection and separation of the bursts contained in the signal. This is a key aspect for which several methods have been developed [7] (summarized in Table 1), being the most extended:

- *Fixed threshold method* [8]: It consists of detecting the AE samples exceeding a fixed preset threshold value
- *Window power variation* [9]: It is based on the evaluation of changes in the moving RMS
- *Edge detection* [9]: It consists of obtaining the envelope using a lowpass filter on the rectified signal and then subtracting from it a delayed version of itself. The detection is then performed on the resulting signal using a fixed threshold value.

The fixed threshold method is by far the most widely used for burst detection. However, it presents strong difficulties when the AE signal contains bursts with large amplitude variations, or when several bursts occur in a short period.

In these cases, the method can fail in separating individual bursts and takes them as a single large burst, thus affecting the indicators and their trends, as shown in Fig. 4. A summary of the main advantages and disadvantages of burst detection methods is presented in Table 1.

Based on the importance of proper burst detection, authors have proposed different approaches to overcome this inconvenience. In [10] Unnthorsson suggests that detection can be performed from a triangular envelope obtained from the simplification of the AE signal by applying a series of local thresholds, with which the individual bursts can be detected and properly separated. Recently, in [11], Duong et al. propose an improved CFAR (constant false alarm rate) based on an adaptive threshold considering the noise of the AE (i.e., continuous-type AE). These methods allow obtaining indicator trends that more accurately represent the progression of the AE signal and thus the evolution of the AE source.

Another important application is the localization of the source generating the AE bursts. The most used technique for this is the time of arrival (TOA) [12], which considers the distance between sensors, the speed of propagation of the AE wave in the medium, and the difference in the time of arrival of the burst at the surrounding sensors.

One last important point in the context of crack and AE is the existence of the Kaiser effect, which can be understood as the absence of AE activity if the stress levels in the material do not exceed the maximum stress level previously reached [13]. This effect assumes that the energy release is irreversible. However, if a sufficient period for *recovery* is allowed, the material can again produce AE activity under the application of stresses below the maximum stress ever reached. This disappearance of the Kaiser effect is known as the Felicity effect [14].

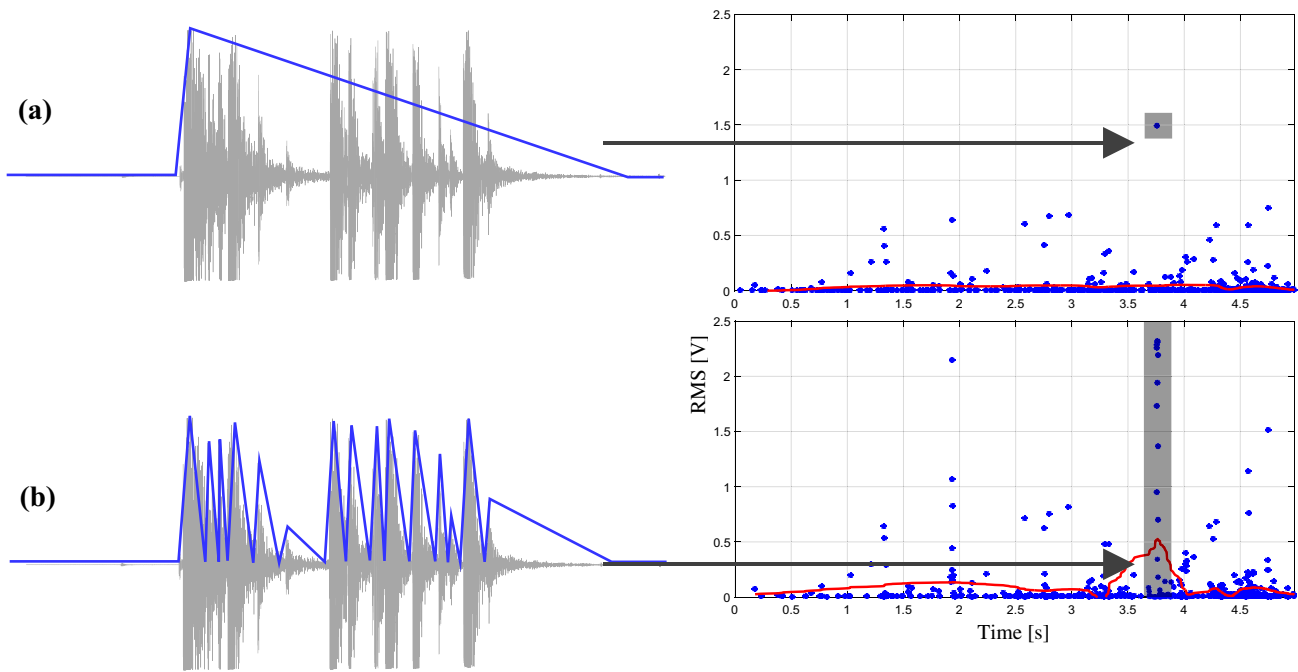
### 3 Research Studies and Applications

Different investigations have been carried out to study the behavior of the AE generated during crack progression. These studies are oriented to gain detailed knowledge about crack growth as the AE source.

In [15], Pascoe et al. use the AE technique to investigate the behavior of crack growth during a single fatigue cycle. It

**Table 1** Advantages and disadvantages of burst detection methods

	Advantages	Disadvantages
Fixed threshold	Lowest computational cost Good detection rate	Amplitude variations and bursts in a short time make detection difficult
Window power	Low computational cost	Low detection rate
Edge detection	Good detection rate	High computational cost



**Fig. 4** Burst detection and RMS curve. **a** Fixed threshold method. **b** Triangular envelope method [10]

is concluded that crack growth can occur if the strain energy release rate is above a crack growth threshold, which can occur both in loading and unloading during the test.

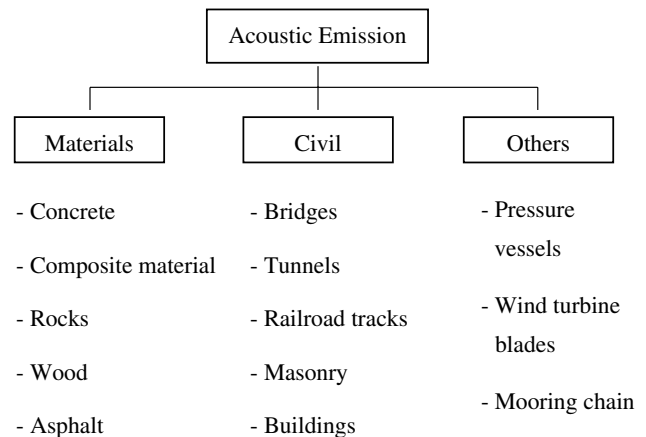
In [16], Vshivkov et al. investigate the propagation of cracks in metal under fatigue loads. The authors found a correlation between energy dissipation due to plastic deformation at the tip of the crack and the energy of AE signals. AEs are used to study cracks according to the most common fracture modes; these are tensile mode, shear mode, and mixed mode [17, 18]. In addition, in [19], Aggelis et al. investigate the different modes of fracture in concrete, finding that the AE indicators AF, RA, and MARSE exhibit a strong sensitivity to the fracture mode.

In [20], Berezovski et al. present the results from a numerical model and simulation of the AE generated during the crack propagation in a three-point bending test. The authors observed that the model produced AE waveforms similar to those measured in experiments depending mainly on the crack tip velocity and crack growth criterion used in the simulations.

Other researchers focus more on the application of AE than on the understanding of the AE source during crack growth. Some of these studies (Fig. 5) are presented in the next sections.

### 3.1 Acoustic Emissions Used for Material Testing

Material testing is one active field in which AE is typically used as a tool for the evaluation of the material resistance



**Fig. 5** Some applications of AE

during tests, which has mostly to do with the appearance and growth of cracks.

#### 3.1.1 Concrete

Concrete is composed of a binder medium with aggregate particles (e.g., sand, rocks, etc.) embedded [21]. It is the most used material for the construction of civil or industrial structures, e.g., foundations, columns, bridges, dams, streets, breakwaters, etc.

The standard ISO 1920 [22] explains in general the procedures for manufacturing and testing concrete specimens;

whereas the standard ISO 16,836 [23] deals specifically with the use of AE as NDT tool for evaluation in concrete.

In [24], Kocáb et al. test three concrete specimens with a different modulus of elasticity ( $E$ ). Results from AE measurements showed that more AE events occurred in specimens with lower  $E$ , which was attributed to the higher level of porosity and impurities in contrast to specimens with higher  $E$ . In [25], Aggelis et al. use AE to characterize the types of failure in hybrid concrete, a highly heterogeneous material. It is obtained that the matrix failures of the material generate high-frequency bursts, whereas delamination failures produce bursts with lower frequencies. In [26], El Kadi et al. test three beams of different health conditions (intact, cracked, and self-cured with textile reinforcement). It is obtained that the cracking increases the RA index and that the cured specimens show partially restored AE parameters compared to the intact specimen.

### 3.1.2 Composite Materials

Composite materials consist of a reinforcing material, on which the mechanical properties mainly depend, and a matrix, which makes the material a monolithic structure [27]. Anisotropy is one of the main characteristics of these materials, allowing the pieces to be designed so that they are optimally adapted to the function they must perform.

The standard ASTM D3039/D3039M [28] is used to perform tensile tests on specimens, standard ASTM D5528 [29] explains how to induce delamination in unidirectional fiber composite materials, and standard ISO 18,249 standard [30] focuses on the methodology for testing specimens using AE.

In [31], Michalcová et al. induce delamination in beams of epoxy matrix with carbon fiber reinforcement according to ASTM D5528. The tests are carried out in a climatic chamber at two different temperatures ( $-55\text{ }^{\circ}\text{C}$  and  $80\text{ }^{\circ}\text{C}$ ). The results showed a decrease in AE energy at  $80\text{ }^{\circ}\text{C}$ , thus showing the influence of temperature in the AE activity. In [32] Oz et al. study the hypothesis that high-frequency AE bursts can be related to faults in the fiber reinforcement. However, they concluded that a failure in the matrix can also generate a burst with this feature. In [33], Yilmaz et al. correlate the decrease in the Poisson's ratio in reinforced polymer fibers to the development of microcracks generated during the breaking process. AEs are measured during static tensile tests and the bursts are grouped according to their average frequency and correlated with the fracture modes (transverse fracture, delamination, or fiber breakage). With this, authors were able to evaluate which fracture modes have more influence on the reduction of the Poisson's ratio.

### 3.1.3 Rocks

Rocks are the solid materials that build the earth's crust and are composed of one or more minerals [34]. Because rocks are formed by natural processes, their structural composition is not homogeneous (due to cracks and pores) and, therefore, their properties will depend on the selected sample and will usually have an anisotropic behavior.

There are no standards for measuring AE in rock; however, standards for concrete may be applicable to rock specimens.

In [35], Yang et al. use three multiparametric indicators to evaluate the evolution of the crack in sandstone specimens. Trends are established that would indicate the eventual fracture of the material. In [36], Du et al. carry out four types of fracture tests (each to induce a particular type of failure) in granite, marble, and sandstone. The change in AE indicators is analyzed to evaluate the different modes of fracture in rocks. In [37], Manthei et al. use a method for detecting clusters of AE events based on the fractal dimension  $D$ , this applied in the tensile test of a rock salt specimen. The objective is to analyze the geometry of the fracture (flat or not) and the spatial position of the clusters.

### 3.1.4 Wood

Wood is an organic material obtained mainly from tree trunks; its mechanical properties depend on the species analyzed. Wood is composed of fibers and thus it exhibits an anisotropic behavior. There are no standards for measuring AE in wood.

In [38], Perrin et al. use AE to characterize the failure mechanisms of different types of wood. It is also obtained that each species of wood has a different acoustic signature. In [39], Diakhate et al. explore the use of AE for monitoring crack growth in wood. For this purpose, double cantilever beam samples with variable inertia are used. The results obtained showed the technique is useful for monitoring crack propagation. In [40], Sousa et al. subject beams of two types of wood with artificial cracks to three-point bending tests. It is found that the Kaiser effect is also observed in wood. Also, AE event counting was used to monitor crack growth, observing a strong increase of this indicator close to the failure. In [41], Fernández et al. test samples of raw bamboo in monotonic tension. The study is based on the use of the center of gravity of the frequency spectrum to classify the bursts according to the source that generated them. The results are compared with microscopic images, obtaining a good correlation between the behavior of the fracture and the AE measured.

### 3.1.5 Other Materials

Asphalt, unlike concrete, is obtained from the distillation of crude oil. In [42], Wei et al. use AE to analyze the process of formation and growth of cracks in an asphalt beam subjected to three-point bending, under low-temperature conditions ( $-10\text{ }^{\circ}\text{C}$ ). The spatial positioning of the bursts and the calculation of indicators (counts, peak amplitude) are carried out. It is concluded that AE can detect cracks in asphalt pavements in cold regions.

Refractories are materials capable of resisting high temperatures and are used mainly in furnaces and petrochemical applications. In [43], De Smedt et al. study the effectiveness of the AE parameters (counts,  $b$  value, and AF/RA) to analyze the brittleness and the formation of cracks in refractory bricks with different levels of hardness. It is concluded that the AF/RA indicator is the one that best achieves this objective.

### 3.2 Civil Structures

In civil engineering applications of SHM, the AE technique has been widely used due to its ability to obtain information on the existence and location of cracks without interrupting the regular operation of the structure [44]. Some applications are presented in the following.

In [45], Manuello et al. monitor an arched concrete tunnel for a period of 100 days. During this period, changes in the cumulative event (burst) counting,  $b$  value, and the  $\beta_i$  exponent indicators were noticed. Using the triangulation technique, it was possible to locate the AE source, which was coincident with the propagation of a visible crack when inspected. In [46], Bayane et al. use AE sensors in combination with strain gauges to monitor a bridge during a period of 1 year under normal operating conditions. They conclude that by analyzing the  $b$  value and cracking mode classification, under consideration of known loading and thermal variations, it was possible to locate a crack in the concrete and monitor its evolution. In [47], Qu et al. use AE to predict the breaking of seven-strand wires of high-strength steel used in suspension bridges. The cross-sectional area in the center of the cable is artificially and progressively reduced from 0 to 90% in 10% steps. The cable is subjected to tension, and AEs are measured at each end with two sensors. AE indicators MARSE and counts were monitored, showing slight changes for damages up to 80% followed by a sudden increase when the area was reduced to 90%. Also, by using the two sensors, it was possible to locate the damaged zone. In [48], Li et al. obtain that AE true energy cumulative can accurately describe the evolution of fatigue damage of corroded bridge cables. Additionally, they propose the margin index as an indicator to effectively monitor the damage evolution and the time of occurrence of the fracture. AEs measured for

the monitoring of railroad tracks are characterized by a low signal-to-noise ratio, which requires using further signal processing methods. In [49], Li et al. classify waves using a combination of the synchrosqueezed wavelet transform and a multibranch convolutional neural network. In [50], Wang et al. propose a method based on the restricted independent component analysis and ensemble empirical mode decomposition. Both methodologies were validated in real applications.

In masonry, [51], Alexakis et al. indicate that an analysis based on the characteristics of the AE in combination with the  $b$  value can help to identify different stages of structural damage. In [52], Xu et al. point out that traditional localization methods cannot be used directly because of the heterogeneous quality of masonry. The authors propose a modified localization method considering a delay in the propagation of the waves to reduce the effect of this material feature. In reinforced concrete buildings, in [53] Carpinteri et al. conclude that cumulative event counting allows rapid and efficient on-site assessment of ongoing damage phenomena of full-scale structures. Also, they showed a relationship between the crack propagation velocity and the behavior of the  $b$  value.

Another important application of AE is the detection and location of cracks in running pipes. The difficulty, in this case, is the high level of continuous-type AE produced by the flow inside the pipe, which can strongly mask the AE bursts stemming from a crack. In [54], Quy et al. use time–frequency analysis to locate events, which were then classified according to its amplitude, frequency, and AE wave type. In [55], Shamsudin et al. perform a Bayesian estimation of effective coefficients derived from the cross-correlation of AE signal from different sensors. Both works reported satisfactory results in this application.

### 3.3 Other Applications

In industry, the AE technique has become a standard NDT tool for pressure vessel health monitoring [56]. For measurements, an overpressure of 5%–10% of the maximum load applied to the vessel in the last 12 months is required due to the Kaiser effect [2]. An application is presented in [57], where Hasan et al. proposes using traditional AE indicators in combination with a genetic algorithm and classification by  $k$ -NN method for the monitoring of a spherical vessel, obtaining an average 99.8% of accuracy in the health state classification of the vessel.

In the monitoring of wind turbine blades, in [58] Bo et al. use a blind deconvolution separation approach based on the idea that AE signals are usually a mixture of signals from multiple sources. With this method, it was possible to distinguish the different fatigue damage states of a wind turbine blade. In [59], Tang et al. identify three types of

damage in a wind turbine blade: matrix cracking, delamination, and debonding. Each type of damage is associated with different values in the AE indicators such as peak frequency, average frequency, peak amplitude, and MARSE.

In [60], Rivera et al. study the formation of cracks in a link of a mooring chain. These are used in anchors and docks and therefore are exposed to wear and corrosion. The link is immersed in a pond with a saline solution (simulating seawater) and subjected to a constant load increasing in steps over a period of 3.7 months. It is obtained that all the AE indicators used including peak amplitude and MARSE energy have the potential to discriminate between the different stages in stress corrosion cracks in chains.

## 4 Conclusions

The AE technique allows detecting the low amounts of energy released in solid materials when cracks and dislocations occur. This feature makes AE a versatile technique, oriented to the detection of incipient stages of damage, and, thus, finds several applications for health monitoring in a variety of systems and different materials. It is also a common choice for the evaluation of the material behavior during tests in the development of new materials.

From the reviewed papers, it is possible to group the following AE indicators according to their use:

- Amplitude, energy, b value, duration, and event counting are used to monitor crack growth, because these indicators are related to the energy released during the fracture process.
- Average frequency, RA, and rise time allow classifying the bursts according to the fracture mode in solid materials, while in composite material they allow determination of the crack source (matrix or fiber).

One challenging aspect when using AE is the high data amount generated by AE signals due to the need for sampling rates in the MHz range. This situation can be overcome by calculating indicators such as the mentioned above. It is important to highlight that all of them rely on the correct detection of the bursts present in the signal. Thus, proper burst detection is a fundamental aspect that should be addressed carefully. Even though advances have been made in this regard, the fixed threshold method is still the most widely used. However, this is not the best choice for crack monitoring due to the high number of events occurring in short periods. Efforts in automation and decision-making algorithms for proper burst detections should continue to develop to contribute to this key point.

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