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# Characterization of damage in concrete beams under bending with Acoustic Emission Technique (AET)

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## HIGHLIGHTS

- Cyclic loading was applied on two concrete beams under flexion and Damage variable was calculated.
- An empirical law was found between normalized Acoustic Emission activity and damage variable.
- A correlation between Damage variable and Index Damage calculated from Acoustic Emission was proposed.
- Temporal-domain and Frequency-domain analysis were performed on signals originated from specific events.

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ABSTRACT

This paper aims to improve knowledge on the degradation mechanisms of concrete beams subjected to flexural loading by using the Acoustic Emission Technique (AET). A strong correlation between damage evolution and acoustic emission activities was highlighted. Damage severity was also assessed by means of the Calm and Load ratio classification and the results obtained were in good agreement with those of mechanical testing. Empirical laws describing the relationship between damage evolution and acoustic emission activities were proposed in order to predict the degradation state of the material from AE activities and it seems that these laws depend only on the type of material tested. Finally, an analysis of the waveforms associated with one event (namely the same source) was carried out. The results show the difficulty of identifying a specific source from the AE signature.



## 1. Introduction

During recent decades, AET is among of the Non-Destructive Testing (NDT) methods usually implemented to examine civil engineering facilities (bridges, dams, nuclear power plants ...). The objective is to inform in real time the owners and the users about the actual state of existing structures. AET can act as an accurate and cost-efficiently method to assess damages in building structures under corrosion, cracking in concrete members... It can localize the position of developing cracks and determine the damage severity in the existing structures without affecting their service functions and integrity.

The aim of this paper is to contribute knowledge on the degradation mechanisms of concrete beams subjected to mechanical loading by using AET. For that purpose, three point bending tests controlled with Crack Mouth Opening Displacement (CMOD) were conducted on two notched concrete beams assumed to be similar as they were produced from the same batch and had the same shape and dimensions. The aim of these tests was to establish a correlation between a mechanical damage variable [1] obtained during a cyclic loading and AE activities. In addition, the damage severity in every loading cycle was also assessed by means of the Calm ratio and Load ratio.

Finally, crack mode identification is a major concern in civil engineering with regards to the durability of concrete structures (bridges, nuclear power plants, etc.). After localization of the AE events at different stages of loading, some events were selected and AE signals associated with these events were analysed in both

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the time and frequency domains in order to check the possibility of identifying a potential AE source by means of the AE signature.

## 2. Literature review of AET and its applications to damage characterization

An AE signal recorded by a sensor is called a hit and is characterized by a typical shape [2], with a rapid increase before reaching peak amplitude, followed by a slower decrease. First of all, a threshold level in amplitude should be defined prior to any measurement, in order to increase the signal/noise ratio. A hit is the part of the obtained signal that exceeds a threshold fixed by the user. Some parameters can directly be extracted from one signal, such as the Count, the Amplitude, the Duration, the Rise-Time, etc. These are called primary parameters. Other parameters can be deduced from the previous ones, such as the Average Frequency, the Initial Frequency, the Energy, etc. These are called secondary parameters. Finally, frequency-domain features, such as the frequency centroid or the peak frequency, can also be obtained by means of a Fast Fourier Transform (FFT).

Generally, there are two main approaches in AE data processing: the parameter-based (or classical) and the signal-based (or quantitative) approaches. In the parameter-based approach, a signal is reduced to a few sets of parameters and the evolution of these parameters with time or with external parameters (for instance the load or the mid-span displacement) is investigated. This approach also deals with establishing correlation between the AE parameters. Additionally, crack type (or crack mode) can be identified, so cracks can be classified into mode I (or tensile crack) and mode II (or shear crack). The RA method (see Fig. 1) listed in RILEM Recommendation TC 212-ACD [3–5] is one of the crack classification methods based on the fact that each crack mode is associated with a type of waveform. According to [3], mode I cracks should result in waveforms with a short Rise-Time (RT) and high Average Frequency (AF), whereas mode II cracks should result in waveforms with a longer RT and lower AF. The RT and the maximum Amplitude are used to calculate the RA value, while the Average Frequency (AF) value is obtained from the Count and the Duration [3].

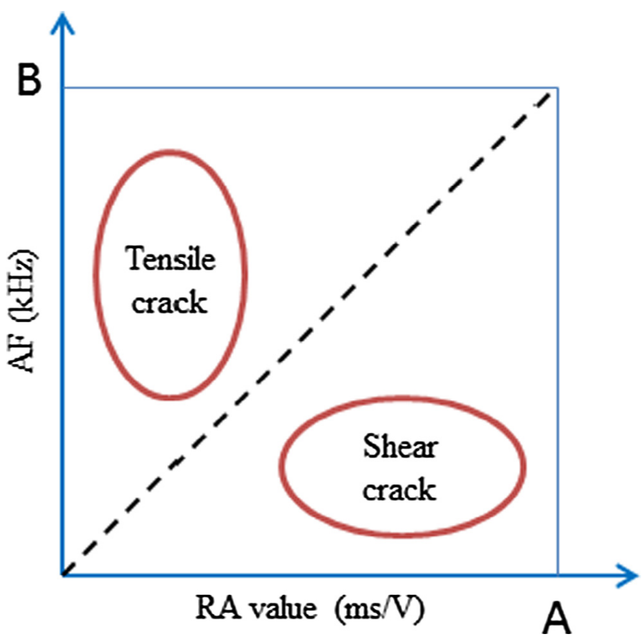


**Fig. 1.** Principle of RA method classification with the floating dash-line that depends on A and B values.

However, as indicated in [6], no specific rule to determine the typical RA value and the AF associated with each crack type is given by standards (NDIS 2421, for instance). In other words, the slope of this diagonal line will be fixed from the user's experience, which limits the usefulness of this method for classifying cracks in specific modes. In Fig. 1, if A corresponds to the maximum RA value and B is the maximum value of AF, the ratio K = A/B (ms/V $\times$ kHz$^{-1}$) represents the slope of the diagonal line, the value of which depends on the type of material, the geometry of the specimens and the type of load. Some values of K ratio obtained by different authors on different types of concrete subjected to four-point bending tests and for different types of application are reported in Table 1.

In addition, the RILEM TC212-ACD recommends the users to calculate RA and AF from the moving average of at least 50 continuous hits. The aim is to find the variation trends of both RA and AF values. The rising of RA associated with the downshift of AF could be associated with the occurrence of shear mode, especially at the end of the tests in which the specimens completely failed [7–13]. This phenomenon was recently found during bending tests in concrete and RC specimens. On the other hand, as shown by [14–18], the increase of RA value at the final period also depends on the distance from the source to the sensors. According to these studies, sensors having large distances from the AE source will produce signals with low Amplitude and then high RA values. Consequently, users might be misled as the increase of RA corresponds to the shear mode.

In order to assess the damage severity of structures under cyclic loading, one criterion based on the Kaiser effect is proposed in the recommended practice recently published in [3]. New AE parameters, namely the Load ratio and Calm ratio have been defined to qualify the damage severity. The Load ratio (LR) is defined as the load at the onset of AE activity in the subsequent loading, divided by the previous maximum load. The Calm ratio (CR) is the ratio between cumulative AE activities during the unloading process

**Table 1**
Example of K values obtained on concrete-based specimens under four-point-bending tests.

| Authors | Type of specimen | Dimensions (mm) | Loading type | RA (ms/V) | AF (kHz) | K (ms/V/kHz) |
|---|---|---|---|---|---|---|
| Soulioti et al. [21] | Steel Fibre concrete specimen, | 100 $\times$ 100 $\times$ 400 | Monotonic | 6 | 65 | 0.09 |
| Calabrese et al. [22] | Plain concrete specimen. | 140 $\times$ 140 $\times$ 500 | Cyclic | 7 | 350 | 0.02 |
| Aggelis [23] | Plain concrete specimen. | 100 $\times$ 100 $\times$ 400 | Monotonic | 15 | 550 | 0.027 |
| Shahidan et al. [24] | Reinforced concrete specimen. | 150 $\times$ 250 $\times$ 1900 | Cyclic | 150 | 150 | 1 |
| Aldahdooh et al. [25] | Reinforced concrete specimen. | 1500 mm in length, and various dimensions for the cross-section | Monotonic | 5 | 400 | 0.0125 |
| Shahidan et al. [26] | Reinforced concrete specimen | 150 $\times$ 250 $\times$ 1900 | Cyclic | 200<br>40 | 160<br>40 | 1.25<br>1 |
| Behnia et al. [10] | RC, SFRC, PFRC beam specimen | 200 $\times$ 250 $\times$ 2500 | Cyclic | 5 $\times$ 10$^{-3}$ | 400 | 12.5 $\times$ 10$^{-6}$ |
| Prem et al. [27] | Reinforced concrete specimen. | 100 $\times$ 200 $\times$ 1500 | Monotonic | 200 | 200 | 1 |