Damage analysis of concrete structures by means of acoustic emissions technique.

Domenico Luca Carnì[1], Carmelo Scuro[2], Francesco Lamonaca[3], Renato Sante Olivito[2], Domenico Grimaldi[1]

[1]*Dept. of Informatics, Modelling, Electronics and System Engineering - University of Calabria, 87036 Rende – CS, Italy*

[2]*Dept. of Civil Engineering - University of Calabria, 87036 Rende – CS, Italy*

[3]*Dept. of Engineering - University of Sannio, 82100 Benevento – BN, Italy*

Abstract

Aim of this work is the evaluation of the damage of concrete structure by analysis of Acoustic Emission (AE) signal. In order to reduce the loss of AE signals and the waste of storage memory, multi-triggering and adaptive acquisition time interval proposed in previous papers are used. The analysis of the AE signal is based on the Gutenberg–Richter law (GBR), that expresses the relationship between magnitude and total number of earthquake events in defined region and time interval. On the basis of the GBR law the AE signals identifying critical damages are selected. Moreover, the analysis of the event frequency of these critical AE signals that satisfy specific requirements of the GBR law permits to identify the relationship between the AE signals and specimen stress. The proposed procedure is experimentally validated through compression tests carried out on the concrete cubic specimens.

Keywords: Damage mechanics; Acoustic emission; Non-destructive testing; Process monitoring.

1. Introduction

In order to realize non-invasive and continuous structural health monitoring system, the Acoustic Emission (AE) signals are widely used [1]–[8]. The AE signals are generated by the localized internal energy releasing during the damage of the sample. The analysis of the AE signals permits to characterize the cracks, and then to assess the material condition [9], [10] and prevent large-scale failure. Moreover, it is possible to monitor the evolution of the damage on the structure in service [3], [4], [6], [7], [9], [11]–[19].

The damage modality is unpredictable and then alteration of AE signal due to propagation and attenuation cannot be known a priory. This can provoke that AE signal reaches the transducer with low amplitude and the system don't identify the signal because it is corrupted by noise.

Propagation can attenuate the signal below the trigger level causing signal loss, while the occurrence of multiple AE events can cause the loss or partial acquisition of signal due to the unpredictability of the Acquisition Time Interval.

In order to reduce the probability of losing or partial acquisition due to the unpredictability of the transducer that firstly detects the AE signal and to reduce the amount of acquired data in continuous monitoring, in [17] the multi-triggered acquisition modality is proposed. This is implemented in hardware by the Logic Flat Amplifier and Trigger (L-FAT) generator block.

Once acquired the AE signals, it needs to define the relationship with the damage of the structure.

In the paper is proposed to evaluate the damage of the concrete material by analysing AE signals on the basis of the Gutenberg–Richter law (GBR). The GBR law [20] defines the relationship between the magnitude and total number of earthquake events recognized in a region during a pre-established time period.

The b-value parameter, defined in the framework of the GBR law, is used to select the AE signals that identify critical damage events. In particular, the critical AE signals are selected under the condition that the b-value has value in the neighbour of 1. In fact, in this neighbour, the AE signals have highest amplitude and are generated by the most important damage events. The information arising from the event frequency of the critical AE signals can be related to the specimen stress, also.

The advantage of the proposed method is that it furnishes the criterion to establish the healthy state of the structure in concrete under uniaxial compression state.

The paper is organized as it follows. In Section 2, information about the L-FAT and the experimental setup are provided. In Section 3, the GBR law is analysed. In Section 4, the correspondence between the critical AE signals selected on the basis of GBR law and specimen stress is synthetized. In Sections 5, the experimental results are presented. Finally, in Section 6 the conclusions are drawn.

2. Experimental setup of AE signal acquisition system

The AE signals generated in the concrete specimen are characterized by frequency band in the range [15–64] kHz [4]. Therefore, the data acquisition system has band pass equal to 1 MHz, 12 bit ADC amplitude resolution, and sampling frequency equal to 5 MHz.

The effect of the propagation attenuation in the concrete can cause (i) the increasing of the probability to lose AE signals, (ii) the decreasing of the capability of the monitoring system to detect a damage, and (iii) the wrong evaluation of the health of the structure under examination [15].

The solution based on multiple transducer has the drawback that AE signals could be partially acquired or loss by some transducer. To overcome this problem a multi triggering system is used that starts the acquisition when one transducers detects the AE signal. Moreover, the band of the transducer requires high sampling frequency. The use of high sampling frequency and multiple transducer causes the extensive memory occupation. To overcome these inconvenient in [7], [17] a multi triggering hardware is pointed out and a proper post processing procedure to reduce the storage memory is proposed. The hardware is the L-FAT block shown in the left part of Fig.1, the post processing procedure [17] is schematized in the right part of Fig.1.

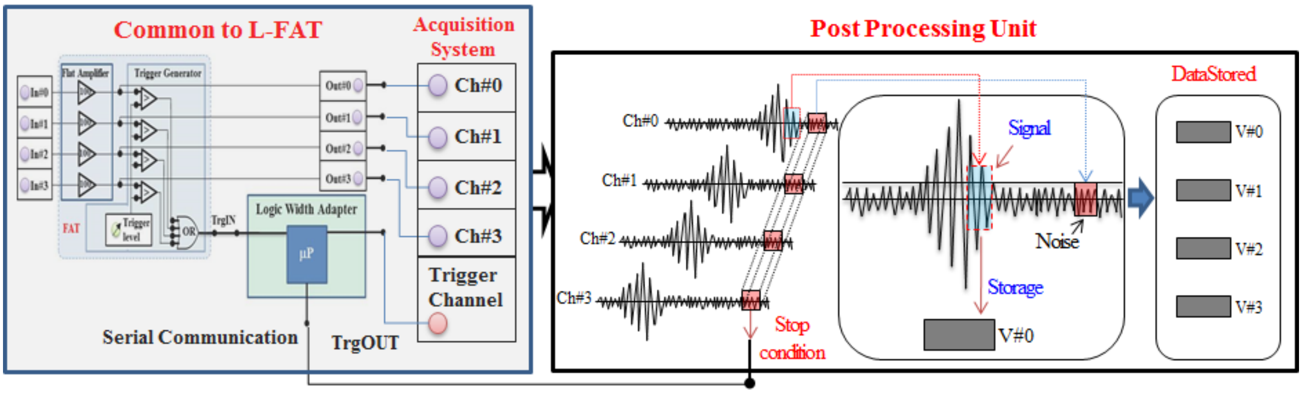


Fig.1 Acquisition system of the AE signals and post processing procedure.

The AE transducers connected to the input channel of the L-FAT are the R15α, characterized by:

- peak sensitivity 69V/(m/s),
- resonant frequency 150 kHz,
- directionality ±1.5 dB;

On the centre of each surface [1] of the specimen is attached the AE transducer (S1-S4 of Fig.2) by silicone adhesive bonding agent.

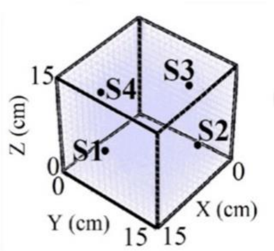


Fig.2 AE transducers on the concrete specimen.

During the compression tests the L-FAT detects if the voltage signal to its input channels is higher than a pre-established threshold set according to the noise floor, as defined in EN 13477-2 [21].

Fig.3 shows the AE signal in which specific characteristic parameters are highlighted such as the maximum amplitude A_{dm}, the threshold for the detection of the AE signal event, and the hits. These parameters are used to characterize the fracture generating the AE signals and to assess the damage in concrete sample [8].

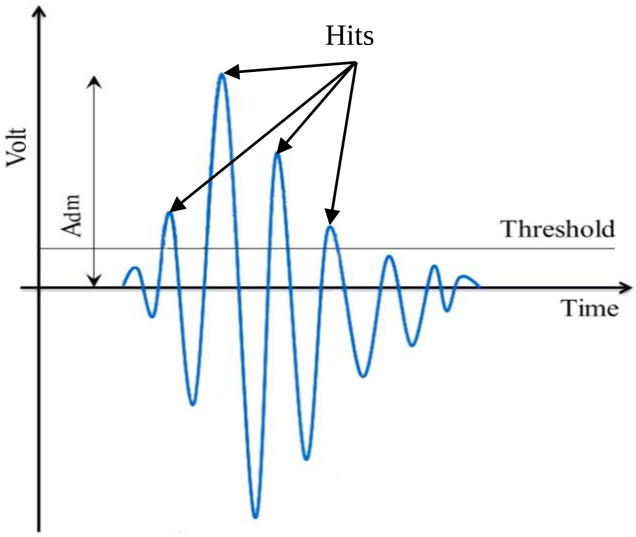


Fig.3 Characteristic parameters of AE signal.

3. GBR LAW.

The AE signals are analyzed on the basis of the GBR law. This law was used typically in seismology to analyze the relationship between the magnitude and total number of earthquakes in the pre-established region and time interval. The relationship of the GBR law [22] is the following:

$$Log(N) = a - b \cdot M \tag{1}$$

where N is the number of the hits in the observation time interval, M is the magnitude of the events, “a” and “b”, so called b-value, are two constants. The constant "a" depends on the seismicity rate which varies greatly from region to region, whereas the b-value is related to the properties of the material.

A first proposal for a law that linked the magnitude of a seismic event and the period occurred in the 1936, when Charles Francis Richter and Beno Gutenberg released a paper with these topics [20]. The GBR law shows that the probability of occurrence of a low magnitude event is higher than events characterized by very high magnitude. As an example, Fig.4 shows the event magnitude distribution and the magnitude histogram for the earthquake occurred in Tocopilla (northern Chile) on 17 November 2007 [23].

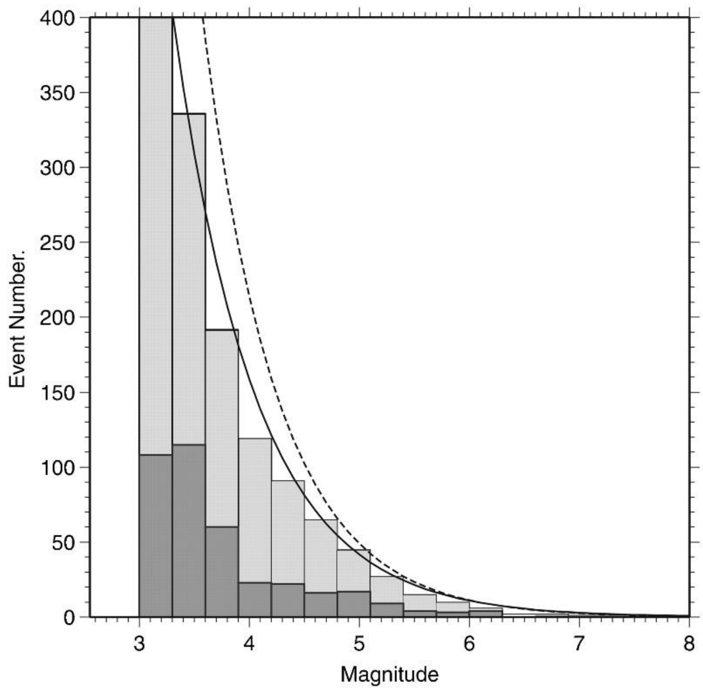


Fig.4. Distribution of the earthquake magnitude (dark grey) and histogram of the number of events per magnitude bin (light grey). The black line is the Gutenberg–Richter law evaluated [23].

The relationship between event number and magnitude is common to different seismic events, although the values of “a” and “b” may vary significantly from region to region and in the time.

Today there are many opposing views on the causes that may lead to a change in the b-value. Scholz [24] supposes that b is related to the rock type and the state of stress, and it increases with the ductility of the rock. Mogi [25] argues that b increases with the non-uniformity of the ground. In addition to what said before, it is known that the b-value tends to decrease in the case the earthquakes have higher magnitude [20].

4. GBR law for AE signals

The aim of this work is to use the relationship of GBR in AE signals filed, also. The earthquakes generate waves very similar to AE signals acquired during the tests. They are oscillating damped waves characterized by amplitude decreasing in the time, going to noise threshold, Fig.3. On the basis of this consideration, the AE signals can be analyzed by the (1), modified as:

$$Log(N) = a - b \cdot A_{dm} \quad (2)$$

where N is the number of the hits higher than the noise threshold, A_{dm} is the maximum amplitude of AE signal, and “a” and “b” are two constants. The constant "a" can be obtained for each test carried out, by the following relation:

$$a = Log(N) + b \cdot A_{dm} \quad (3)$$

In the seismic wave analysis, the b-value tends to decrease with increasing the magnitude of the seismic event. When the earthquake is characterized by higher magnitude for the specific region, the b-value tends to 1.

In the analysis of the AE signals generated in the concrete, it is assumed that each fracture is constituted by the sum of many micro cracks that join to compose a greater fracture. The most important crack will be characterized by the maximum amplitude of the AE signal. By using the L-FAT, the maximum value of the AE signals, that can be acquired, is equal to the full scale of the acquisition system equal to 12 V. As for the earthquakes, it is assumed that the b-value is tending to the unit value for maximum amplitude of the AE signal. Fig.5 shows the trend of the *Log(N)* experimentally evaluated and the “a” value estimated by (3). The maximum value of “a” is equal to 14.45. This value will be used in the following.

For each AE signal stored during the compression test the b-value was calculated according to (2).

Different types of cracks generate AE signals with different number of hits and amplitudes characteristics. The micro-cracks generate a large number of weak AE signals, which leads to a relatively high b-value evaluated by (2), while macro-cracking leads to a low b-values near to the unit, since they generate a large number of high amplitude AE signals [6].

The application of AE signals based b-value to understand the fracture behavior in concrete is used in a variety of structures [2], [5], [12]–[14], [26]–[28]. However, the analysis of AE signals based b-value to understand stress condition in the concrete has not been made. In this work, attempt has been made to understand the stress trend in the concrete by the b-value analysis.

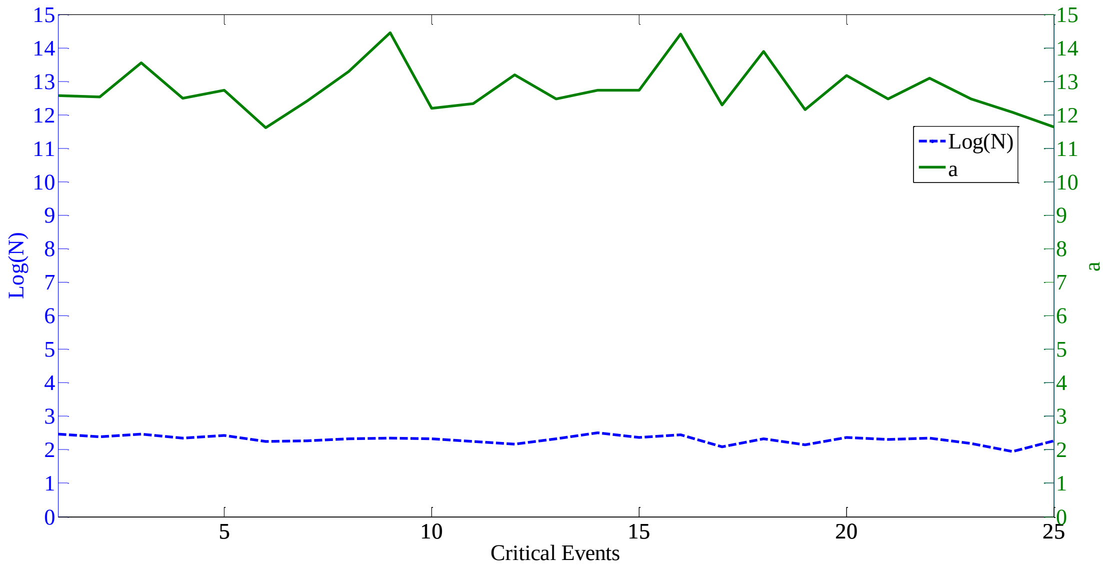


Fig. 5. Experimental value of the Log(N) evaluated for critical AE and “a” value.

5. Experimental results

The specimen under test is the concrete cubic with no steel reinforcement, with size $15x15x15cm^3$. According to EN12390-3 the samples are cured 28 days at a temperature 20 ± 2 °C and relative humidity equal to 95%.

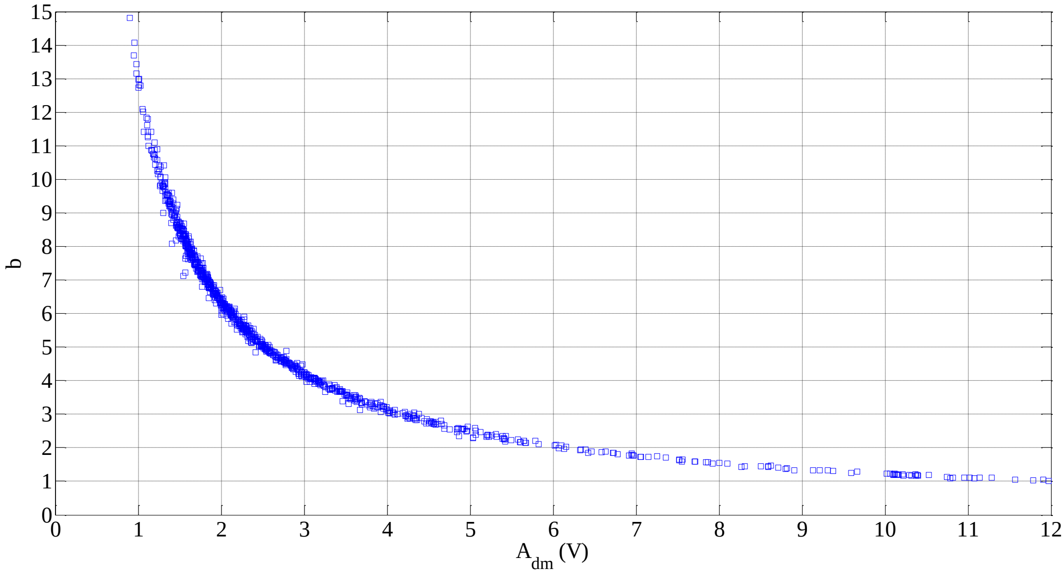
The compression test of the specimen is realized by hydraulic press with a closed loop governing system with 3000 kN and accuracy class 0.5%. The hydraulic press permits to record and obtain the load-displacement and the load-time diagrams. The press is used to implement a controlled uniaxial compression of the specimen by pushing from the top to the bottom with a constant displacement rate of 0.1 mm/min until failure. The control of the displacement is realized by feedback process that adapts the standard force.

Preliminary tests are devoted to highlight the correspondence among A_{dm} and the formation of cracks in the material by the analysis of the b-value.

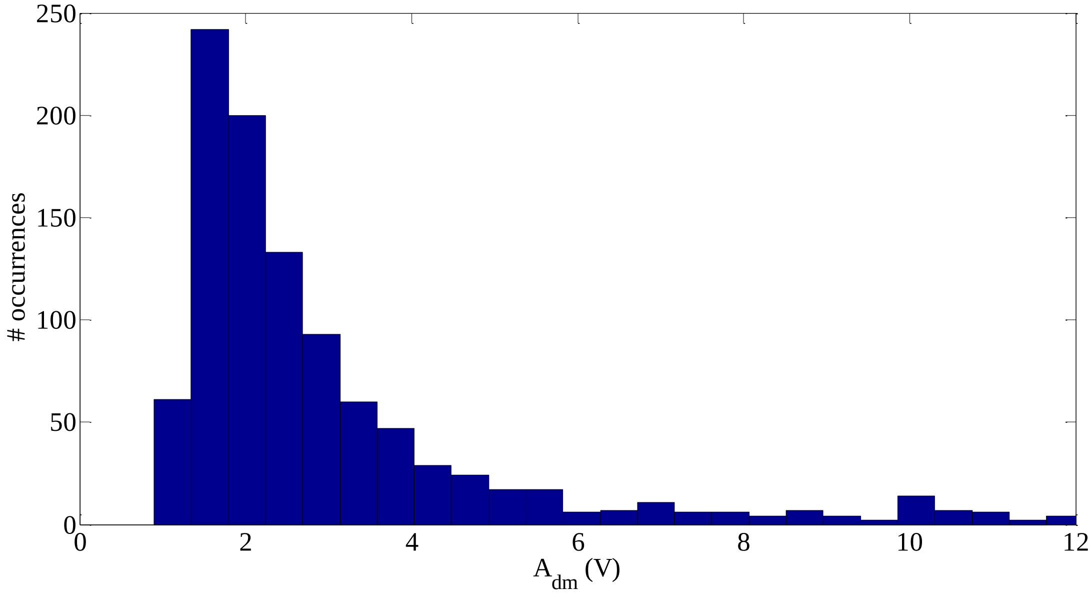
Fig.6a shows the trend of the b-value experimentally evaluated by (2). The Fig.6b shows the occurrence histogram of the amplitudes of the AE signals. It can be noted that the distribution of the amplitudes characterized by high b-value can be assumed concentrated in the range [1, 4] V, because it includes 80% of the occurrences. The critical values of the AE signals, characterized by b tending to 1, can be assumed concentrated in the range [9, 12] V, as shown in Fig.6a and Fig.6b.

To correlate the damage with the b value, the event frequency of AE signals is taken into examination. In particular, the event frequency of the AE signals taken into analysis are referred to critical AE signals characterized by b-value in the neighbour of 1 recognized in an established time interval. The time interval is determined by the sliding observation window with size equal to 60 s, and shifted at step of 1 s. For each step the number of critical AE events occurring in the observation window is determined.

Fig.7 shows the trend versus the time of the superposition of the stress, and of the cumulative number of critical AE signals characterized by the b-value equal to 1. Increasing the stress, the frequency of the important fractures increases. In fact, the event frequency of critical AE signals (with b equal to 1) is increasing. This can be argued by the increasing of the slope of the trend of the cumulative AE signal events.

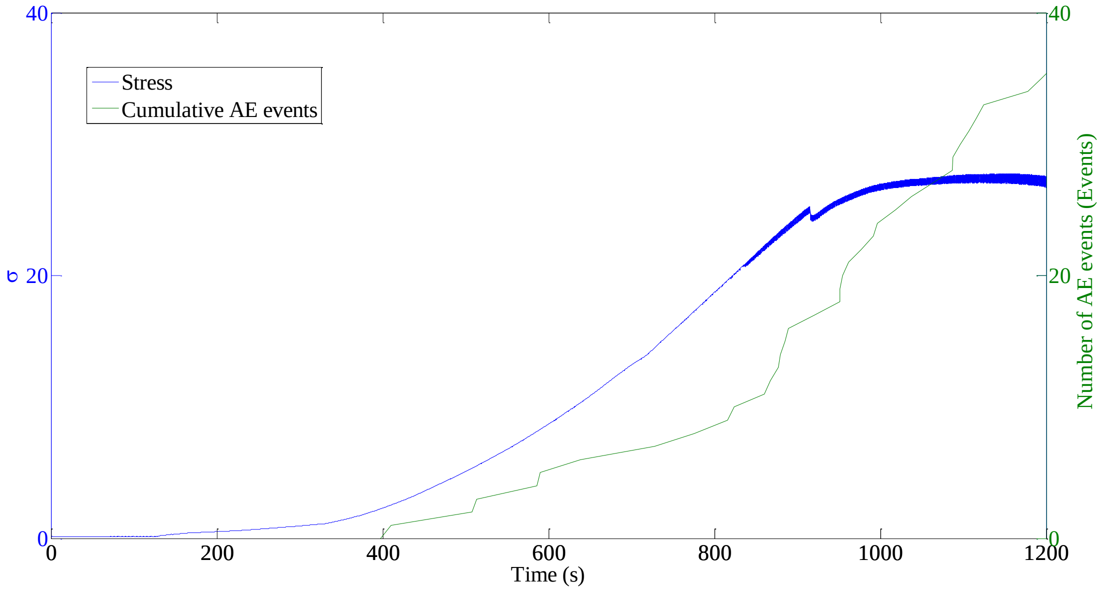


a)



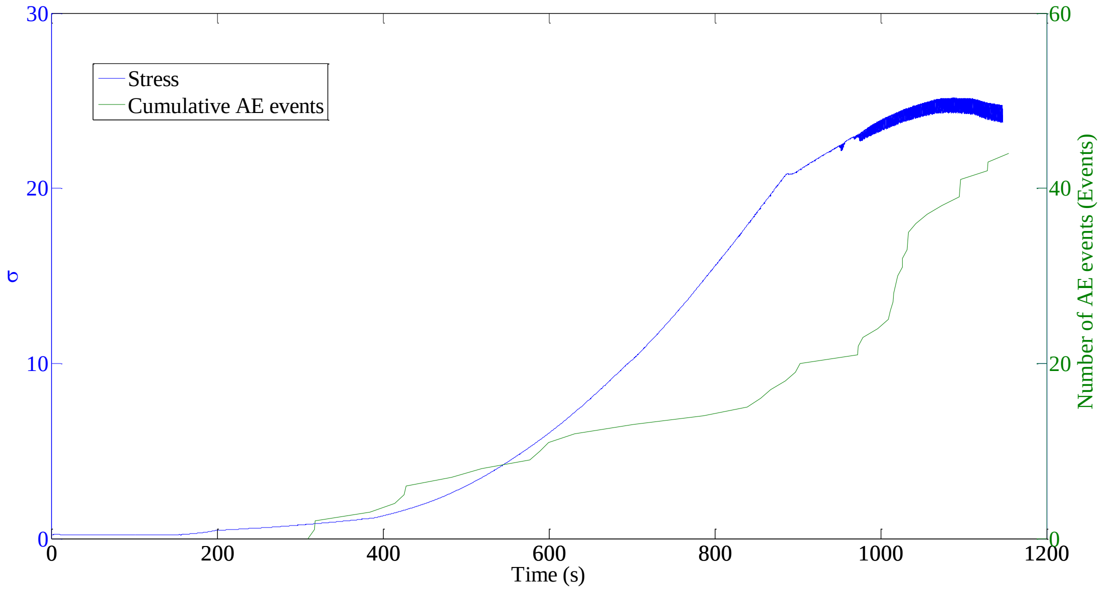
b)

Fig. 6. a) Trend of the b-value versus the A_{dm} in the experimental data, and b) histogram of the maximum amplitude of the detected AE signals.



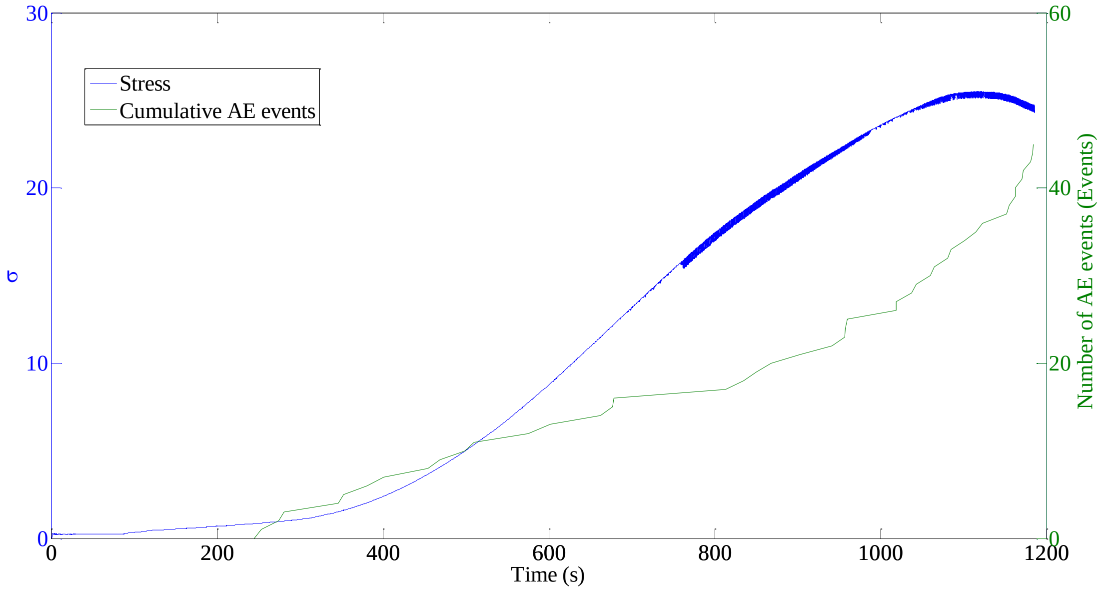
40
20
0
σ
Stress
Cumulative AE events
0
200
400
600
800
1000
1200
Time (s)
Number of AE events (Events)

a)



30
20
10
0
σ
Stress
Cumulative AE events
60
40
20
0
200
400
600
800
1000
1200
Time (s)
Number of AE events (Events)

b)



c)

Fig.7. Trend of the stress versus time and the cumulative number of critical AE signals detected (with b=1) versus time for three specimens.

The specimen is characterized by irregularities on the surfaces subjected to compression, that cause AE signals characterized by b-value in the neighbour of 1. These irregularities cause concentrated loads that create important cracks that propagate in a short time until settling of the test.

The standard EN 12390-3 [29] indicates that for a stress lower than 40% of its maximum resistance of compression, that in case under consideration is equal to 10 MPa, the macroscopic behaviour of the specimen is linear and elastic, and there aren't important cracks because not inside the specimen. Instead, for stress in the range [40, 85] % of maximum resistance of compression, the macroscopic behaviour of the specimen is not linear and the micro cracks develop with the increasing of the stress.

Consequently, the AE signals detected during the first 600 s, corresponding to the compression of 1 mm of specimen, are discarded. Fig.8 and Fig.9 show that after this time interval, the settling of the specimen is finished, because there is a load stabilization and increasing slope of the stress versus time. This phase is characterized by a significant stop of AE signals due to the stabilization of the specimen which is approaching to the plastic phase of compression. This phase describes the non-reversible deformation changes of shape of the specimen in response to applied stresses.

In particular, Fig.8 shows the trend versus the time of the AE event frequency estimated with the sliding window overimposed to the stress, for the specimen #1. This figure highlights that for the AE event frequency equal to 0.05 events/s the stress is equal to the 67.4% respect to the characteristic cubic compressive strength of concrete (Rck) equal to 25 MPa.

In the compressive test the cracks start from about the 30% of the compressive strength of the concrete and increases until about the 70% of the load. After this strength, the cracks propagate through the cement with accelerated rate. After this strength, the cracks begin to propagate through the cement while not affecting the aggregates, with an accelerated rate and bringing the specimen to imminent collapse [30]. The process damages the specimen until destruction.

On the basis of this analysis, it can be assumed that 3 critical AE signals in the time interval of 60 s indicates (i) increasing of the rate of the event, and (ii) that the strength is in the proximity of the 70 %.

The test is repeated with other two specimens. As shown in Fig.9, the results are similar to that of Fig.8.

Tab.1 reports the event frequency of the critical AE signal in the observation window of 60 s, the stress imposed to the samples related to the beginning of the observation window, and the normalized stress respect to the Rck.

Results of preliminary tests shown in Tab.1 highlight that event frequency of the critical AE signals equal to 0.05 (events/s) is correlated to a normalized stress in the range [64.7, 67.4] % and then can be considerate as a safety limit for the structure under examination.

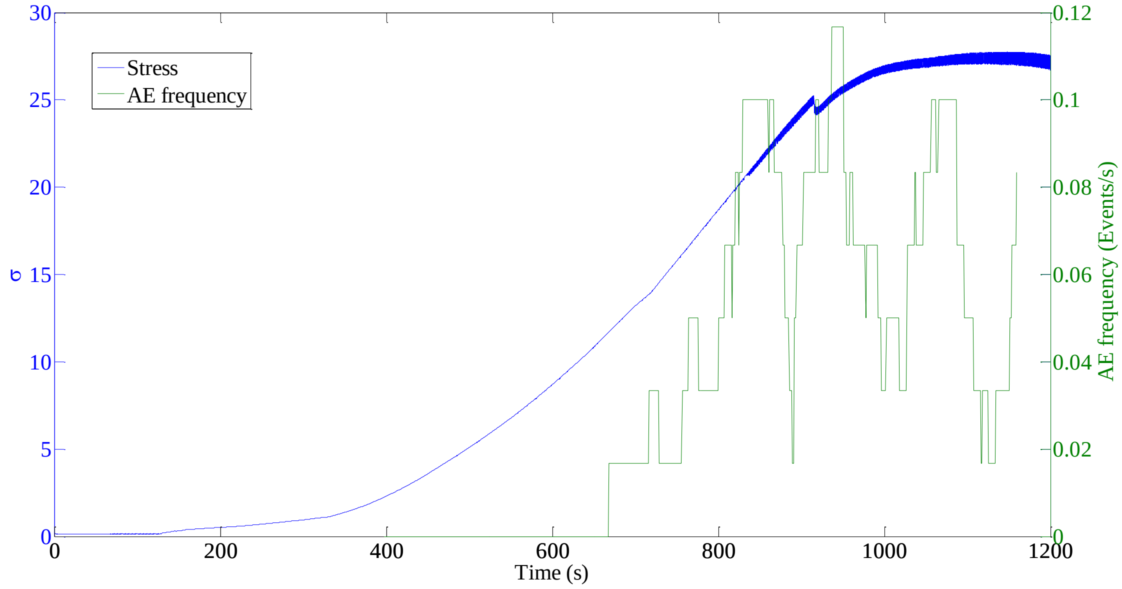
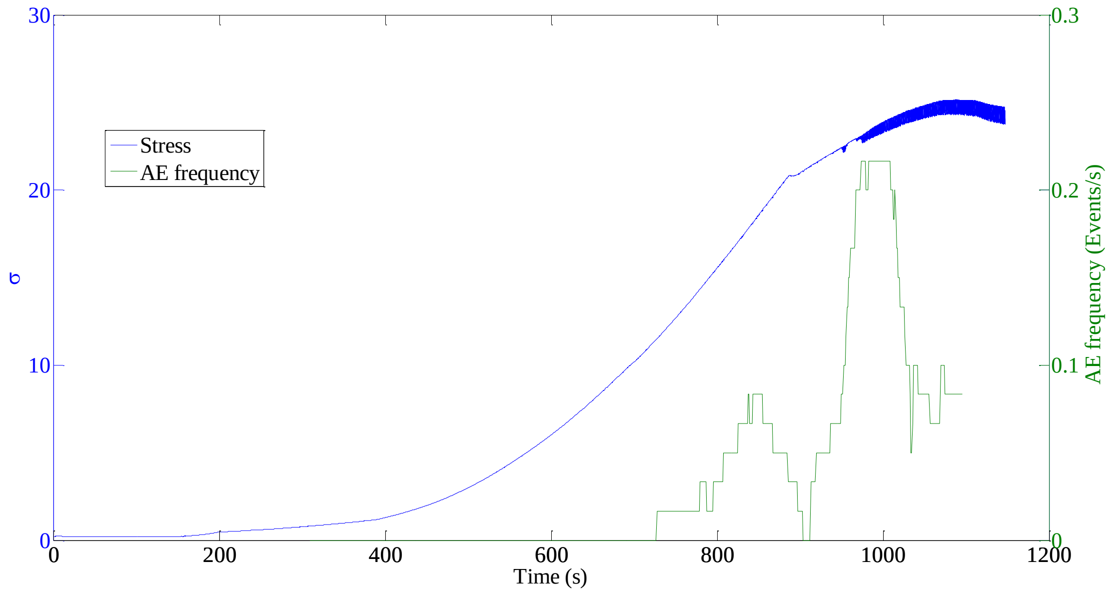
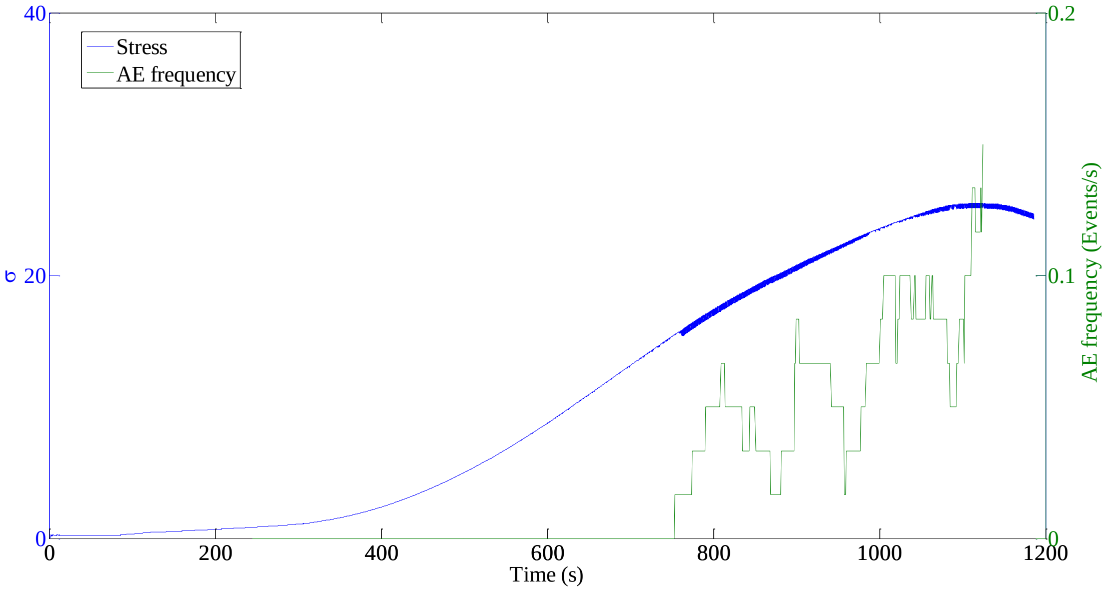


Fig.8. AE event frequency estimated with the sliding window with size equal to 60 s and step equal to 1 s superimposed to the stress versus time, for the specimen #1.



a)



b)

Fig.9. AE event frequency estimated with the sliding window with size equal to 60 s and step equal to 1 s superimposed to the stress versus time, for the specimen #2 (a) and #3 (b).

Tab.1. Event frequency of critical AE signals versus the stress of the specimen.

Samples	**AE events frequency**	**Stress (M Pa)**	**Normalized stress [%]**
1	0.05	16.8	67.4
1	0.10	20.4	81.6
2	0.05	16.2	64.7
2	0.10	22.5	90.2
3	0.05	16.8	67.2
3	0.10	23.7	94.8

Conclusions

In the paper a non-invasive technique for the damage evaluation of concrete structure is proposed. The technique is based on the analysis of Acoustic Emission (AE) signal by the Gutenberg–Richter (GBR) law.

For the acquisition of the AE signals is used the Logic Flat Amplifier and Trigger generator block that implements a multi-triggering acquisition systems.

The GBR law allows to identify the critical damages. Moreover, it permits to highlight the relationship between the critical AE signals and the specimen stress.

The preliminary experimental tests confirm the analysis and show that for the event frequency of the critical AE signals equal to 0.05 events/s the stress is close to the 70 % of the maximum value.

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