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# DAMAGE DIAGNOSTIC IN CONCRETE AND MASONRY STRUCTURES BY ACOUSTIC EMISSION TECHNIQUE

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**Abstract**. *The damage diagnostic of reinforced concrete structures or masonry buildings represents a complex task. Therefore, monitoring techniques are assuming an increasing importance in the evaluation of structural conditions and reliability. Heterogeneous materials like concrete or masonry, when subjected to increasing stresses, provide a typical power-law relation between the energy released by microcracks, detected by Acoustic Emission (AE) technique, and the frequency of AE events. This Technique permits to estimate the amount of energy released during the fracture process and to obtain information on the criticality of ongoing process. Moreover, by applying Fracture Mechanics criteria, the safety of structures undergoing damage and degradation process can be efficiently evaluated in situ.*

## 1. INTRODUCTION

Fracture in concrete and masonry structures develops as smeared microcracking or single macrocracks. Both phenomena, occurring for instance in the inelastic hinging regions of concrete beams or frames, cause the moment-curvature diagram to exhibit post peak softening. Thus, plastic limit analysis is invalidated because the capacity for energy absorption is reduced, leading to poor inelastic moment redistribution. The evaluation of safety and reliability of aged structures represents a complex problem. Therefore, monitoring techniques are progressively assuming greater importance in the field of structural engineering [1].

A non-destructive technique, originally applied to industrial steel elements and nowadays commonly adopted to identify defects and damage in heterogeneous elements, is based on the Acoustic Emission (AE). By means of this technique, a particular methodology has been put forward to monitoring crack propagation, and assess its stability, in structural elements under service conditions. The highest frequency of AE events, in fact, occurs at a stress level corresponding to about 80% of the ultimate load. Thus, the AE technique becomes particularly effective when coupled with Fracture Mechanics argu-

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ments. It is possible, in fact, to evaluate the relations between diffused micro-cracking, coalescence of defects at the mesoscale, and macroscopic crack propagation leading to collapse.

When deling with highly heterogeneous materials like concrete or masonry, subjected to constant or increasing stress fields, experimental tests provide a typical power-law relation between the amplitude of AE events (which is related to the released energy) and their frequency. Similar analyses are commonly employed, af different scales in seismology, where it was proved that a larger number of emissions correspond to the smaller amplitudes, whereas the larger amplitudes are restricted to few events [2].

In this paper, by means of this technique, we have analysed the evolution of cracks and estimated the released strain energy during their propagation in structural members. With this procedure, masonty historical buildings and reinforced concrete structures under service have been investigated to evaluate damage process and the efficiency of the reinstatement interventions.

## 2. FUNDAMENTALS OF THE TEHNIQUE

By monitoring a structure by means of the AE technique, it is possible to detect the occurrence and evolution of stress-induced cracks. Cracking is, in fact, accompanied by emission of elastic waves which propagate within material bulk. These waves can be eceived and recorded by transducers applied on the surface of the structural element [4]. A signal detector analyses the waves captured by the instruments and counts the oscillations whose amplitude is larger than a certain threshold (measured in Volts). In this way, it is possible to race the cumulative curves of the number of counts during the whole test period or over limited time intervals, see Fig. 1a. This method is called Ring-Down Counting and is widely used for defect analysis [5,6,7]. As a firs approximation, in fact, the number of counts (NT) can be compared with the amount of energy released during the loading process, assuming that both quantities grow proportionally to the extent of damage.

Another methodology for analysing EA records is based on the damping characteristics of the transducer. It is possible, in principle, to consider all the oscillations produced by a single EA signal as belonging to a single event. In this way, the so-called Event-Counting can be used in place of the Ring-Down-Counting (Fig.1b). During AE testing, the peak amplitude of the oscillations can span various orders of magnitude. Thereby, in the presence of a proper detector apparatus (e.g., able to detect the actual shape of the signal), the intensity of damage can be directly related to the peak amplitude of the oscillations. To this purpose, we introduce two quantities to characterize the distribution of peak amplitudes. These are, respectivaly, the differential distribution $n(v_p)$, defined so that the product $n(v_p)dv_p$ represents the number of signals with peak amplitude comprised between $v_p$ and $v_p + dv_p$, and the cumulative distribution $N(v)$, defined by the following integral:

$$N(v) = \int_{v}^{\infty} n(v) dv_p$$

which represents the number $N(v)$ of recorded signals with peak amplitude larger than v.Eq. (1) can be expressed, with a good approximation, according to the following equation [2]:

$$\log N(v) = c - av$$

By means of the above equation, the cumulative distribution can be easily described through the constants *a* and *c*. In order to obtain a quantitative comparison between two different distributions and to evaluate the magnitude of a certain AE phenomenon, we can introduce the power of the emission, $E(t)$, measured in *J/s*, whose expression is the following:

$$E(t) = \int_{v}^{\infty} v_p^2 n(v_p) dv_p$$

where $n(v_p)dv_p$ is the number of signals with peak amplitude comprised between $v_p$ and $v_p + dv_p$. The integral (3) permits to weigh the AE events with different amplitudes by means of the squared amplitude. In this way, when evaluating the criticality associated to a certain propagating crack, few emissions characterised by large amplitudes play a more significant role with respect to many low-amplitude emissions. Clearly, the total energy can be obtained by multiplying eq. (3) by the time interval of measurement.

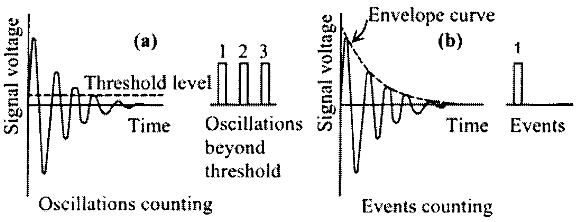


Fig. 1. Detected signals by AE technique

The apparatus consits of four piezo-electric transducers (PZT), calibrated in the frequency range between 100 and 400 kHz, and of four data acquisition systems [9]. The threshold level of the signal is set equal to 100 μV and is amplified up to 100 mV. The amplification gain can be related to the ratio between the output and the input voltage (*Eu/Ei*) according to the formula $dB = 20 log10\ Eu/Ei$. In our case, the increment is equal to 60 *dB*. According to the literature, this represents the typical value used for AE measurements in concrete [8]. The oscillation counting capacity has been set equal to 255 counts in 120 seconds, i.e., a single "event" is the result of 2 ecorded minutes. By means of this system, the intensity of a single event is calculated assuming that the amplitude *v* of the signals is proportional to the number of counts NT recorded in the time interval (Event Counting). Clearly, this hypothesis is fully justified in the presence of slow-crack growth.

## 3. DAMAGE DIAGNOSTIC OF CONCRETE FRAMES

The AE methodology has been applied to two buildings, with reinforced concrete structure. The first building, built in the city of Moncalieri (Torino), around 1960, is located in the proximity of a bridge with high traffic density. It showed the formation of a network of microcracks in the internal walls (both within the apartments and around the stairs), and the occurrence of wide cracks on the external walls. Not significant crack has been detected in the concrete foundations nor on the concrete structure. Indeed, vibrations due to the heavy traffic are felt in the apartments at the top floors. In order to assess the stability of the structure, two column-beam joints located in the central part of the building, at the lower floor, have been monitored (Fig. 2).

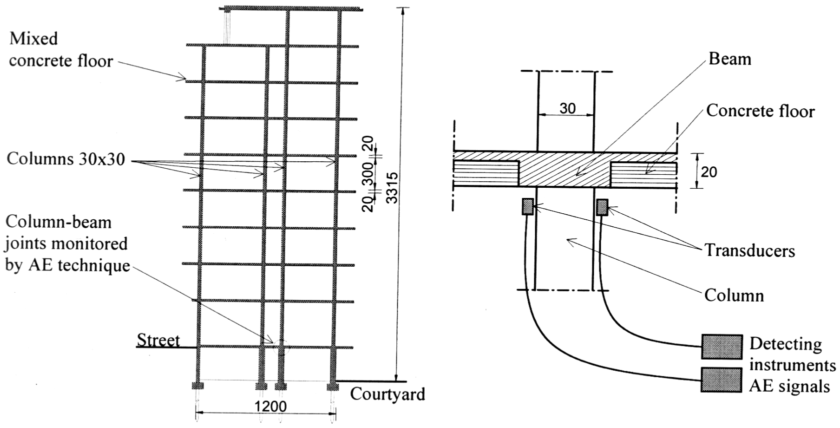


Fig. 2. Building in Moncalieri. Structural section of the building and location of transducers on column-beam joints

The structure has been continuously monitored for 40 days, corresponding to 960 hours. During this period of time, a rehabilitation activity was carried out on the roof and on the facade of the building. The oscillation count registered at the end of each day is plotted in Fig. 3. Notice that Acoustic Emission have not been revelaed during the stops of the intervention, whereas transducers perceived significant signals during the working days.

The AE analysis permits to assert that the structural behaviour is stable, since the AE activity was practically absent during normal situatins (implying that no energy was released under service loads, i.e. damage was not propagating). In this specific case, the absence of AE activity shows that the traffic vibrations, although perceptible in the building, are efficiently absorbed by the structure damping capacity and do not result in cracking phenomena. On the other hand, the crack networks revealed on the vertical walls of the building can be ascribed to significant deformability and creep of the concrete floors.

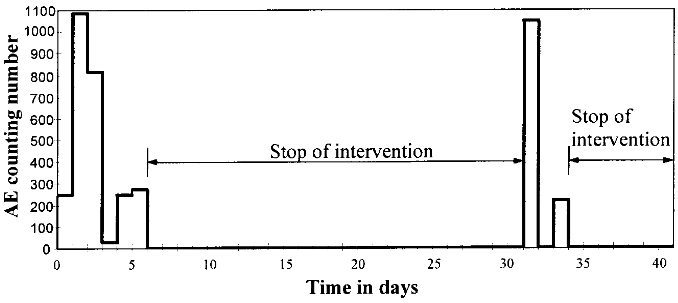


Fig. 3. Column-beam joint. AE counting number per each day of detection

The second building that has been monitored is located in Cascine Vica (Torino). In this case, four important macro-cracks have appeared on a retaining wall made of not reinforced concrete situated at the bottom of the structure. Cracks started from the foundations of the wall, and propagated vertically, extending throughout the width, stopping only before a steel-reinforced beam put just below the concrete colums, see Fig. 4. The average crack opening was equal to 2 mm at the bottom and to almost 0.2 mm at the top of the wall.

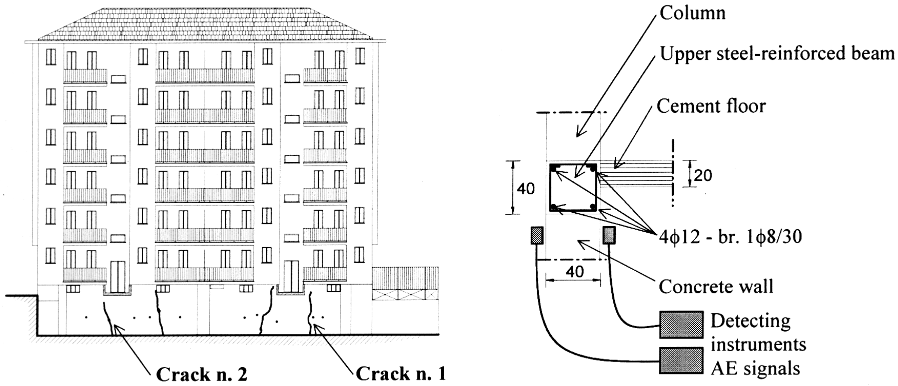


Fig. 4. Building in Cascine Vica. Cracking framework and location of transducers on the concrete wall

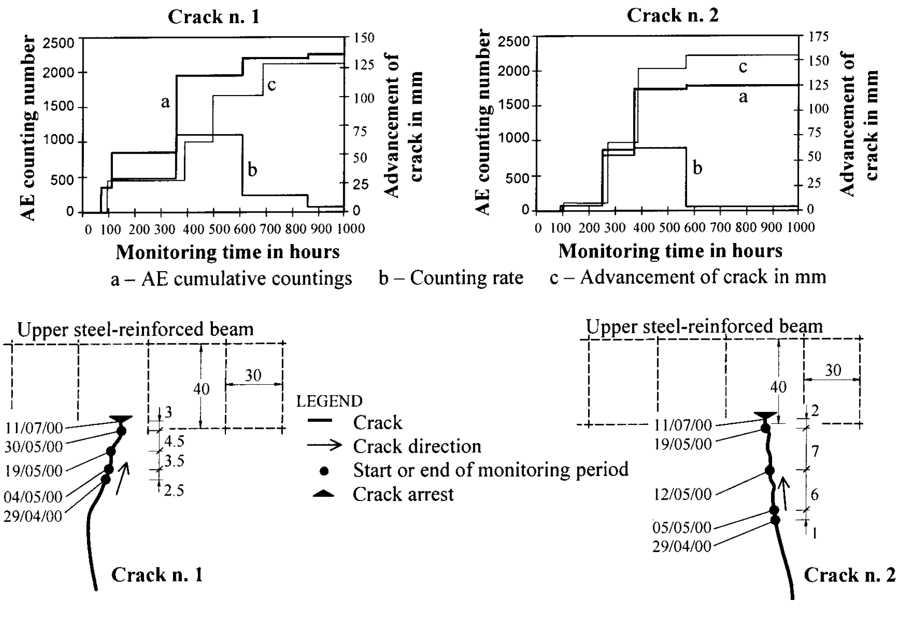


Fig. 5. Results of monitoring with the AE technique

We have chosen to monitor two main cracks which had not already reached the upper beam. We have tried to evaluate the speed of propagation of these cracks and to predict their future development based on the cumulative count of AE. The advancement has been monitored, in the case of both cracks, for almost 1000 hours, starting on April 29, 2000, an ending on July 11, 2000. In Fig. 5 the cumulative counts of emissions and the advancement of the cracks are reported and compared. Notice that, at any stage of the test, the oscillation count is proportional to crack propagation and that a reduction of AE density is directly related to crack arrest in the proximity of the upper beam (where a significantly larger toughness is attained due to steel reinforcement). Since the highest number of AE counts detected during the test corresponds to the maximum velocity of propagation, we can deduce that the local maxima of the AE distribution function correspond to the most critical stages of propagation.

## 4. Damage diagnostic of masonry buildings

Two masounry buildings have been monitored. The first one, called "Casa Capello", is located in the historical area of Rivoli, and it has been, constructed upon pre-existing ruines, dated XIV century, Fig. 6. This edifice has recently been object of complex interventions of functional extension and restoration. The AE methodology has been applied on certain walls of this building, in order to evaluate the status of the cracks spreaded out after the collapse of a breast-wall [9]. In particular, the monitoring has involved two cracks which appeared inside the internal surface of the sustaining structure, at the ground floor level. Crack n. 1, monitored for about 900 hours, has been developed on a masonry wall reinforced with an external concrete surface. Crack n. 2 has been identified in a part of a wall, entirely builty by bricks, and monitored for about 800 hours.

Fig. 6. "Casa Capello" in Rivoli. On the background the bell tower of the Collegiata, on the foreground the breast wall that collapsed during the restoration works

Two transducers have been used to detect the AE released by the cracks. They were applied approximately 3 cm far from the top of fissures, to minimise signal attenuation. The dates of the first application of the transducers and their final removal are represented in Fig. 7. The graphs, obtained by the monitoring data, exhibit how the behaviour of the countings is proportional to the advancing of the cracks and whow as the exhaustion of the ring-down counting cleraly reveal the arrest of the cracks advancement.

Furthermore diagrams remark that the maximum conting of AE happens during the highest velocity of the fissure advancing process. Following this event, both the counting than the crack advancement tend to decrease rapidly, until complete cancellation. We can therefore assume how the peak data of distribution of AE does correspond to the most critical period of advancing of the crack, which then reaches a condition of stability, proceeeding towards more compressed zones of masonry. Diagrams relative to time-advancing of fissures show a stable behaviour, as well as the diagrams that relate the time to the cumulative counting of AE.

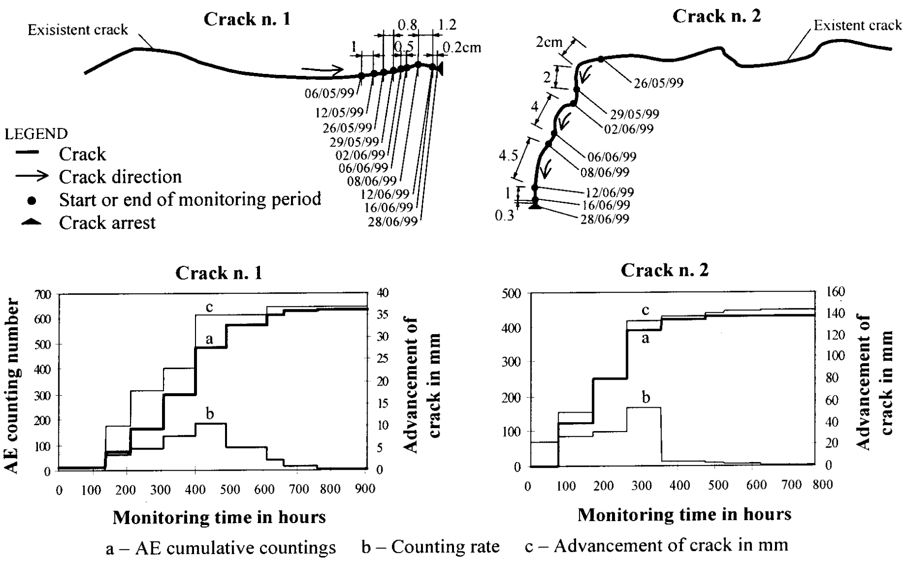


Fig. 7. Crack n. 1 and 2. Development and AE monitoring results

Correlation diagrams are represented in Fig. 8, independent of the time, between the crack advancement and the number of AE events. This graph puts synthetically in comparison the behavior of the two masonries during the cracking process. We indeed note how, the ectension being the same, crack n 2 released much less energy than crack n. 1, showing a higher toughness of the material where it developed. For crack n. 2, the correlation values between crack advancement and number of AE events are more distant from the average line than those referring to crack n. 1. The larger dispersion chows how the material crossed by crack n. 2 (the bricks masonry) is more heterogeneous and therefore tougher than the material crossed by crack n. 1 (the little wall in concrete).

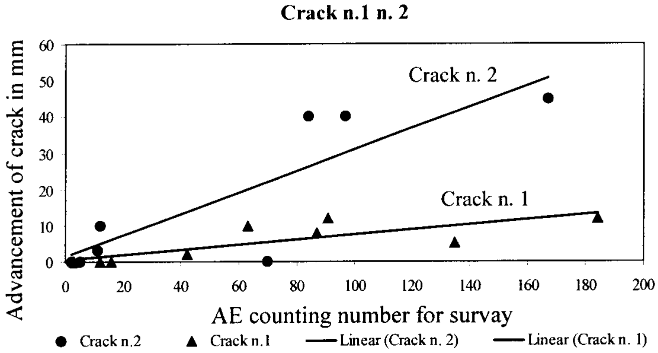


Fig. 8. Diagrams of correlation between the number of AE events and the crack advancement

The second masonry building, called "Torre Sineo", dated XIII century, is the tallest and most mighty of the medieval towers preserved in the town of Alba. The structure squared planned, with size measured in 5,9 × 5,9 m, is about 39 meter high and is leaning to the north side. The foundations lie below 3,5 m from the surface of the street level. The walls are variably thick between 2 and 0,8 m. The sustaining wall is "a sacco" with the external bricks joined with one centimeter thick mortar. The internal filling is composed by a mesheval of remainders and bricks tied by a poor morter. The tower is incorporated for 15 m in a later dated building. Regarding the incorporated part, the floors have been realized through masonry vaults, while in the upper part of the tower the floors are made with wooden structures, Fig. 9.

The cracking framework can be observed both on the internal then external overview. The most significant crack are inside the tower, mainly located between the 6th and 8th floors. On the external side we can observed minor cracks, mainly near the windows, more specifically between the 6th and 7th floors.

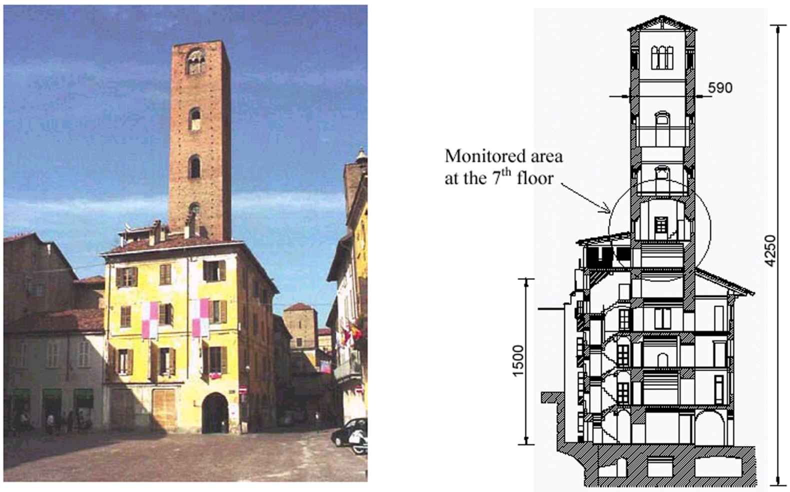


Fig. 9. Sineo Tower in Alba

Through the monitoring of AE two cracks have been detected in the internal surface of masonry on the 7th floor, Fig. 10: one located by a window, and the other one nearly. The monitoring has reported a continuos damaging process, characterized by a slow spread of cracks inside the brick walls. In the most damaged zone, we detected and arrest of the damaging progress, since the cracks have arhieved a new condition of stability, leading towards compressed zones of masonry.

In this particular case it could be observe how each appreciable advancing of the cracks, in the monitoring zone, is often correlated by a seismic event. In the diagram of Fig. 10, we have overlaid the cumulative AE function, of the monitored area, with the seismic occurrences and their intensity, happened in Alba region in the same period of time. The seismic events data have been provided by the National Institute for Geophisics and Volcanology in Rome. This detection might prove how the tower behaves stable when is only subject to vertical loads. The structure, in fact, doesn't have the capacity to respond elastically when it is subject to horizontal or waving actions.

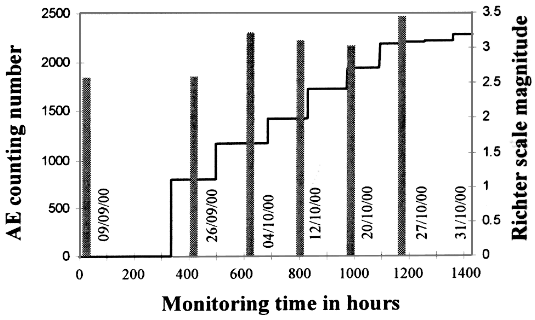


Fig. 10. Sineo Tower monitoring

## CONCLUSIONS

In this work we have meant to describe the application of the AE technique to monitoring concrete and masonry buildings. In particular we have proposed an innovative methodlogy, based on the counting of events, in order to determine the released energy and therefore the conditions of stability or the risk due to the spreading of defects. With this method damage diagnostic of structural elements under service has been performed.

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# DIJAGNOSTIKA OŠTEĆENJA BETONSKIH I ZIDANIH STRUKTURA PUTEM TEHNIKE AKUSTIČNOG EMITOVANJA

**A. Carpinteri, G. Lacidogna**

*Dijagnostika oštećenja ojačanih betonskih struktura ili zidanih gradjevina predstavlja jedan složen posao. Stoga tehnike monitoringa dobijaju sve veći značaj u proceni strukturalnih uslova i pouzdanosti. Heterogeni materijali poput betona ili ozida, kada se podvrgnu rastućim naponima, pružaju tipičan odnos po zakonu snage izmedju energije koju oslobadjaju mikroprsline, a koja se pronalazi tehnikom akustičnog emitovanja (AE), i frekvencije AE dogadjaja. Ova tehnika dopušta procenu količine energije koja se oslobodi tokom procesa loma, i dobijanje podataka o kritičnosti procesa koji je u toku. Štaviše, primenom kriterijuma mehanike loma, bezbednost struktura koje podležu procesu oštećenja i propadanja se na efikasan način može oceniti in situ.*