A fractal approach for damage detection in concrete and masonry structures by the acoustic emission technique

Une approche fractale pour la détection de dommages aux structures de béton et de maçonnerie par les techniques d'émission acoustique

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Résumé

La contribution des méthodes de recherche non destructives et instrumentales est actuellement mise à profit pour mesurer et vérifier l'évolution de certains phénomènes structuraux défavorables, tels que le dommage et les fissures, et pour prédire leurs développements ultérieurs. Le choix de la technique pour contrôler et surveiller les structures en béton armé et en maçonnerie est strictement corrélé avec le type de structure à analyser et avec les données à extraire [1]. Parmi ces méthodes, la méthodologie non destructive basée sur l'émission acoustique (AE) s'avère très efficace [2 - 5].
Au moyen de la technique d'AE, nous avons analysé [6] l'évolution des dommages dans deux piliers soutenant un viaduc le long d'une autoroute italienne construite dans les années 50 (figure 1). Le procédé de surveillance consiste à enregistrer les signaux d'AE résultant des phénomènes de fissure se produisant dans les deux piliers, désignés sous le nom de P1 et de P2 (figure 1). Un avantage évident apporté par cette méthode est qu'elle rend possible de surveiller l'évolution des dommages, même si les fissures ne sont pas apparentes, ou sont largement réparties sur la surface d'un élément de structure. Les capteurs, en fait, peuvent détecter des défauts ou des anomalies dans un rayon de 10 m du point d'application [4]. Les ondes élastiques produites pendant le processus de fissure sont transmises avec une atténuation extrêmement faible dans une structure constituée par un matériau élastique et de forme élancée, telle qu'une colonne de béton. Ces ondes peuvent être détectées par les capteurs à une fréquence d'environ 50 kHz, c'est-à-dire à la plus basse fréquence perçue par les sondes, jusqu'à une distance d'approximativement 10 m de la zone de génération du signal. Cette technique de surveillance originale rend possible d'estimer la quantité d'énergie libérée pendant le processus de rupture, et d'obtenir de l'information sur la criticité du processus en cours.
L'énergie détectée par AE est strictement reliée à celle dissipée par la structure surveillée. L'énergie dissipée pendant la formation de fissures dans les structures constituée de matériaux quasi-fragiles joue un rôle fondamental dans le comportement de ces structures durant toute leur vie. On observe clairement des effets de forte ampleur sur la densité d'énergie dissipée durant la fragmentation. Récemment, un processus de dissipation d'énergie multi-échelle a été montré comme ayant lieu dans la fragmentation, d'un point de vue théorique et fractal [7, 8, 9]. Fondée sur l'hypothèse de Griffith d'une dissipation locale d'énergie proportionnelle à la superficie de fissure nouvellement créée, la théorie fractale montre que l'énergie sera globalement dissipée dans un domaine fractal compris entre une surface et un volume euclidiens. Conformément aux concepts fractals, une théorie ad-hoc est ici employée, pour détecter et surveiller des structures de béton et de maçonnerie au moyen de la technique d'AE. Cette théorie fractale originale tient compte du caractère multi-échelle de la dissipation d'énergie et de ses effets de grande ampleur. Ceci permet d'introduire un paramètre énergétique de dommages utile pour une évaluation des structures basée sur la corrélation entre l'activité d'AE dans une structure et l'activité correspondante enregistrée sur un petit échantillon extrait de la structure et testé jusqu'à sa défaillance [10].
Enfin, en appliquant des critères fractals et d'AE, la sûreté des structures subissant des processus de dommage et de dégradation peut être efficacement évaluée in situ.

Abstract

The Acoustic Emission (AE) technique, a non-destructive and instrumental investigation method, is herein applied to measure and check the evolution of damage in concrete and masonry structures. This method of analysis makes it possible to estimate the energy released by the monitored structure and to obtain information on the criticality of an ongoing process. Based on fractal concepts, which take into account the multiscale character of the energy dissipation in heterogeneous materials, an ad hoc energy parameter to evaluate the damage level of a structure is proposed.

Introduction

The contribution of non-destructive and instrumental investigation methods is currently exploited to measure and check the evolution of some negative structural phenomena, such as damage and cracking, and to predict their subsequent developments. The choice of the technique for controlling and monitoring reinforced concrete and masonry structures is strictly correlated to the kind of the structure to be analysed and on the data to be extracted [1]. Among these methods, the non-destructive methodology based on Acoustic Emission (AE) proves to be very effective [2-4]. This technique makes it possible to estimate the amount of energy released during the fracture process and to obtain information on the criticality of the process underway.
Strictly connected to the energy detected by AE is that dissipated by the monitored structure. The energy

dissipated during crack formation in structures made of quasi-brittle materials plays a fundamental role in the behaviour of a structure throughout its life. Strong size effects are clearly observed on energy density dissipated during fragmentation. Recently, a multiscale energy dissipation process has been shown to take place in fragmentation, from a theoretical and fractal viewpoint [5-7]. Based on Griffith's assumption, of local energy dissipation being proportional to the newly created crack surface area, the fractal theory shows that the energy will be globally dissipated in a fractal domain comprised between an Euclidean surface and volume. According to the fractal concepts, an *ad hoc* theory is herein employed to detect and monitor concrete and masonry structures by means of the AE technique. The fractal theory takes into account the multiscale character of energy dissipation and its strong size effects. This makes it possible to introduce a useful energetic damage parameter for structural assessment based on a correlation between AE activity in a structure and the corresponding activity recorded on a small specimen obtained from the structure and tested to failure [8]. Moreover, by applying Fractal and AE criteria, the safety of structures undergoing damage and degradation processes can be efficiently evaluated.

Acoustic emission monitoring

Monitoring a structure by means of the AE technique, it proves possible to detect the occurrence and evolution of stress-induced cracks. Cracking, in fact, is accompanied by the emission of elastic waves which propagate within the bulk of the material. These waves can be received and recorded by transducers applied to the surface of the structural elements.

This technique, originally used to detect cracks and plastic deformations in metals, has been extended to studies and research in the field of rocks and can be used for diagnosing structural damage phenomena [9]. In AE monitoring, piezoelectric (PZT) sensors are generally used, thereby exploiting the capabilities of certain crystals to produce electric signals every time they are subjected to a mechanical stress. As a rule, the amplitude of the elastic pressure waves, which varies from one material to another also in terms of order of magnitude, is very weak and up to 10^{-6} times lower than that of atmospheric pressure. As a result, the electric signal from the transducer requires very high amplification (10^4 or 10^5 times) before it can be correctly elaborated (Fig.1).

Analysis of AE signals

The signal picked up by a transducer is preamplified and transformed into electric voltage; it is then filtered to eliminate unwanted frequencies, such as the vibration arising from the mechanical instrumentation, which is generally lower than 100 kHz. Up to this point the signal can be represented as a damped oscillation. The signal is therefore analysed by a measuring system counting the emissions that exceed a certain voltage threshold (measured in volts (V)).

This method of analysis is called Ring-Down Counting and is broadly used in the AE technique for the identification of defects (Fig. 1). As a first approximation, the number of counts *N* can be compared with the quantity of energy released during the loading process and we may assume that the corresponding increments grow proportionally to the widening of the crack faces. This technique also considers other procedures. For instance, by keeping track of the characteristics of the transducer used, and particularly of its damping, it is possible to consider all the oscillations produced by a single AE signal as a unique event and to replace the Ring-Down Counting with the Counting of Events method [10,11].

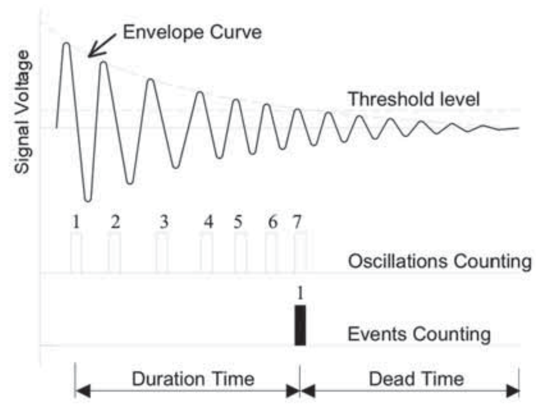


Fig. 1 : Signal identified by the transducer and counting methods in AE technique

AE data acquisition system

The AE monitoring equipment adopted by the authors consists of PZT transducers fitted with a preamplifier and calibrated on inclusive frequencies of between 100 and 400kHz. The transducers are connected to switchboards equipped with an amplifier and a pass-band filter, one threshold level measuring system, a recorder and an oscillation counter. The threshold level of the signal recorded by the system, fixed at 100μV, is amplified to up to 100mV. The amplification gain, determined as the ratio between the voltage at output E_u and that at input E_i according to the formula $dB = 20 \log_{10} E_u/E_i$, turns out to be 60 dB.

This signal amplification value is the one commonly adopted in the assessment of AE events in concrete. Oscillation counting capacity is assigned a limit of 255 every 120 seconds of signal recording. In this manner, a single *event* is the result of 2 recorded minutes [4].

From the literature [12] we find that the maximum amplitude of the direct non-amplified signal is of the order of 100μV, neglecting the attenuation phenomena due to the distance of signal generation; hence, it can be assumed that the measurement system has the ability to detect only the most significant AE events of material cracking. By means of this system, the intensity of a single event is by definition proportional to the number of counts *N* recorded in the time interval (Event Counting). Clearly, this hypothesis is fully justified only in the case of slow crack growth [13].

Damage detection on a concrete structure

By means of the AE technique, we have analysed [8] the evolution of damage in two piers supporting a viaduct along an Italian highway built in the 1950s (Fig. 2). The monitoring process consists of recording the AE signals arising from the cracking phenomena occurring in two piers, referred to as P_1 and P_2 (Fig. 3).

Fig. 2 : The monitored viaduct

An obvious advantage afforded by this method is that it proves possible to monitor the evolution of damage even if the cracks are not visible or are widely spread over the surface of a structural member. The transducers, in fact, are able to detect defects or anomalies within a radius of 10 m from the point of application [4]. The elastic waves generated during the cracking process are transmitted with an extremely low attenuation level in a structure consisting of elastic material and having an elongated shape, such as a concrete column. These waves can be picked up by the transducers at a frequency of ca 50kHz, i.e. the lowest frequency perceived by the sensors, over a distance of approx. 10 m from the signal generation zone (Fig. 3).

Monitoring piers P_1 and P_2

Pier P_1 was monitored for ca 4126 hours, corresponding to 172 consecutive days. Figure 4 shows a chart of the differential counts of the oscillations recorded per hour, and a chart of the cumulative counts obtained from the sum of the latter.

In a loading process entailing the opening of cracks in the concrete, AE activity, as quantified on the basis of energy release, can be neglected as long as stress levels do not exceed the levels reached previously (*Kaiser effect* [14]). In this manner, for the piers monitored, it can be assumed that the evolution of damage, i.e., damage occurring after the previous stress levels are exceeded and cracks begin to be formed, is proportional to the AE counts measured over time. From the cumulative count chart shown in Figure 4, it may therefore be seen that pier behaviour is not stable, since damage evolves progressively over time. The differential count chart displays, on an expanded scale, the predominant events, i.e., the emission peaks characterising the critical moments in crack propagation. These events occur at intervals of hundreds of hours. Their occurrence shows that damage is not due to traffic-induced vibrations, whose frequent oscillations remain within the structure's elasticity limits, and it is caused instead by other slow-rate phenomena, such as foundation settlements due to soil creep.

Pier P_2 was also monitored for 172 days running. The charts of differential and cumulative counts are shown in Figure 4. From the cumulative count chart we find that the total number of oscillations for this pier is ca 40% the number recorded for pier P_1. The different count chart also shows that the times at which P_2 cracking events occurred coincide with the times relating to P_1, though the relative frequency and intensity levels are lower.

Accordingly, damage in P_2 is characterised by a slower evolution compared to P_1. The response to the actions on the pier, in fact, in terms of stresses produced in the

Fig. 3 : Cracks in the P_1 pier and the applied sensor (a). Relationship between signal detection distance and signal frequency (b).

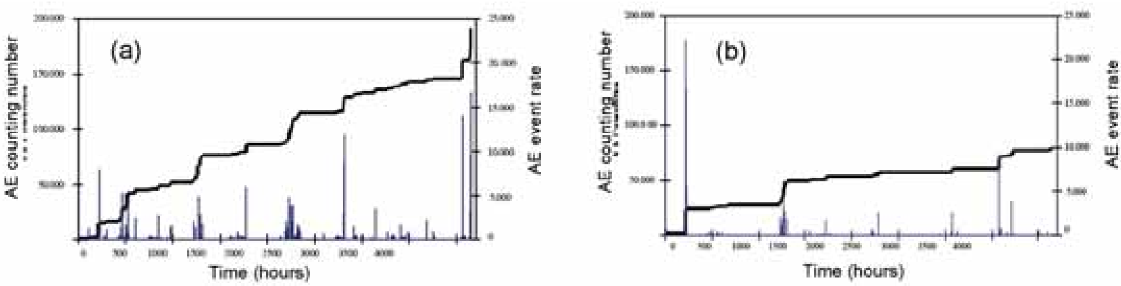


Fig. 4: Piers P_1 (a) and P_2 (b) monitoring data

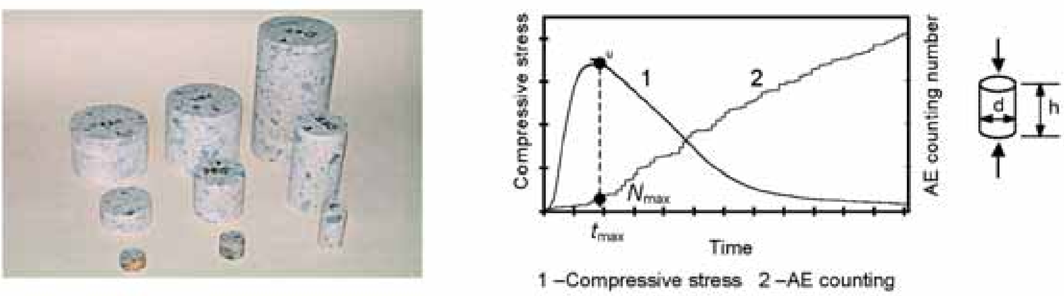
structural member, generally appears confined to within the material's elastic limits, and the rate at which damage is seen to evolve seems to rule out traffic-induced vibration as the cause of damage.

Compression tests on concrete specimens

From the piers we drilled a number of cylindrical concrete specimens in order to detect the mechanical properties of the material under compression and to evaluate scale effects on AE activity, in terms of size and time. The concrete, possessing good mechanical properties, has an apparent specific weight of about 2.22 g/cm^3 and a maximum aggregate size of about 15 mm. For each pier, three different specimen diameters *d* are considered in a maximum scale range of 1:3.4. The specimens had three different slenderness ratios, of $\lambda = h/d = 0.5$, 1 and 2, with *d* taken to be 27.7, 59 and 94 mm, respectively. For each

			Pier P_1		Pier P_2	
Specimen type	**Diameter *d* [mm]**	**Slenderness $\lambda = h/d$**	**Peak stress σ_u [Mpa]**	**N_{max} at σ_u**	**Peak stress σ_u [Mpa]**	**N_{max} at σ_u**
C 11	27.7	0.5	91.9	1186	84.7	1180
C 12	27.7	1	62.8	1191	46.7	1181
C 13	27.7	2	48.1	1188	45.8	1186
C 21	59	0.5	68.1	8936	57.5	8924
C 22	59	1	53.1	8934	41.7	8930
C 23	59	2	47.8	8903	38.2	8889
C 31	94	0.5	61.3	28502	45.2	28484
C 32	94	1	47.8	28721	38.2	28715
C 33	94	2	44.1	28965	38.1	28956

Table 1: Average values for the specimens obtained from piers P_1 and P_2.



(a)   (b)

Fig. 5: Geometries of the tested specimens (a). Stress and cumulated event number versus time (b).

of these nine geometries, three specimens were tested, to a total of 54 cases (two piers). The geometries of the specimens tested are illustrated in Figure 5. The average values obtained from the experimental data are given in Table 1.

The tests were performed under displacement control by means of an MTS machine, with rigid steel platens, using the AE data acquisition system described above. During the tests we adopted a displacement rate of 10^{-4} mm/sec for all specimens, in order to obtain a very slow-crack growth and to detect all possible AE signals. In this way, we were able to capture the softening branch of the stress-strain diagrams [8]. The testing campaign demonstrated that the amount of energy dissipated during a compressive test is strictly correlated to the amount of energy detected by the AE transducers. The stress and cumulated event number versus time for a specimen of intermediate size is represented in Figure 5.

In the figure the critical number of AE cumulative events N_{max} is represented in correspondence of the peack stress σ_u. Similar results can be observed in the other cases.

A fractal criterion for AE monitoring

A statistical and fractal analysis of laboratory test data was performed, considering the multiscale aspect of cracking phenomena. The fractal criterion takes into account the multiscale character of energy dissipation and its strong size effects. This makes it possible to introduce a useful energetic damage parameter for structural assessment based on a correlation between AE activity in a structure and the corresponding activity recorded on a small specimen drilled out from the structure and tested to failure [8]. Fragmentation theories have shown that the energy dissipation, E, taking place during microcrack propagation, occurs in a fractal domain comprised between a surface and the specimen volume V [5-7].

This means that fractal energy density, having anomalous physical dimensions :

$$\Gamma = \frac{E_{max}}{V^{D/3}} \qquad (1)$$

(in lieu of energy density) can be considered as a size-independent parameter. In the fractal criterion (1) E_{max} stands for total dissipated energy under the whole stress-strain curve, Γ is fractal energy density and D is the so-called fractal exponent, of between 2 and 3. Limiting our attention on the hardening branch of the stress-strain curve, during microcrack propagation, acoustic emission can be clearly detected (Fig. 5). Since dissipated energy *E* is proportional to the number of AE events, N, according to eq. (1), the critical number of AE events, N_{max}, evaluated at peak-stress σ_u, can be considered as a size-independent parameter:

$$\Gamma_{AE} = \frac{N_{max}}{V^{D/3}} \qquad (2)$$

where Γ_{AE} stands for fractal acoustic emission density. Eq. (2) predicts a volume-effect on the maximum number of AE events for a specimen tested up to failure (dead load control).

The damage level of a structure can be worked out from the AE data obtained on a reference specimen (subscript r) taken from the structure and tested until the achievement of peak stress σ_u. From eq. (2) we have:

$$N_{max} = N_{maxr}\left(\frac{V}{V_r}\right)^{D/3}, \qquad (3)$$

from which we can work out the total number of acoustic emission events N_{max} that a structure may withstand before reaching collapse. An energy parameter describing the damage level of the structure can be defined as the following ratio:

$$\eta = \frac{E}{E_{max}} = \frac{N}{N_{max}} \qquad (4)$$

N being the number of acoustic emissions recorded.

Damage level in the piers monitored

Through a statistical analysis of average test values (Tab. 1), we can quantify parameters D and Γ_{AE} in eq. (2). Parameter D stands for the slope, in a bilogarithmic diagram, of the curve correlating N_{max} to specimen volume. Through best-fitting, we obtain $D/3 \cong 0.766$, so that the fractal exponent, as predicted by fragmentation theories, turns out to be comprised between 2 and 3 ($D \cong 2.3$). Moreover, fractal acoustic emission density is found to be: $\Gamma_{AE} \cong 170\,\mathrm{cm}^{-2.3}$ [8].

During the observation period (172 days), we obtained a number of events $N \cong 2\mathrm{x}10^5$ for the more damaged pier, P_1, and $N \cong 8\mathrm{x}10^4$ for the less damaged pier, P_2. Since the volume of each pier is about $2\mathrm{x}10^6$ cm^3, from eq. (2), using the fractal exponent $D \cong 2.3$ and the critical value of fractal acoustic emission density $\Gamma_{AE} \cong 170\,\mathrm{cm}^{-2.3}$, we obtain a critical AE number of $N_{max} \cong 11.51\mathrm{x}10^6$. Introducing the values of N and N_{max} into eq. (4), we get $\eta \cong 1.7\%$ for P_1, and $\eta \cong 0.7\%$ for P_2. These values represent, in percentage terms, the amount of energy released in proportion to the amount corresponding to the achievement of the ultimate stress in the structural members.

Damage detection on a masonry tower

The 13th century masonry building called "Torre Sineo" is the tallest and mightiest medieval tower still rising in the town of Alba (Fig. 6). The structure has a square plan, measuring 5.9 x 5.9 m, it is ca 39 meter high, and leans towards the north side. Wall thickness ranges from 2.0 to 0.8 m. The construction of the bearing walls is *a sacco* with the outer layers of bricks joined with 1 cm thick mortar. The filling material is a mixture of chips and bricks bound by a lean mortar. A 15 m portion of the tower is incorporated in an earlier building; the storeys in this lower portion of the tower are topped by masonry vaults, while the upper part of the tower has wooden roofs.

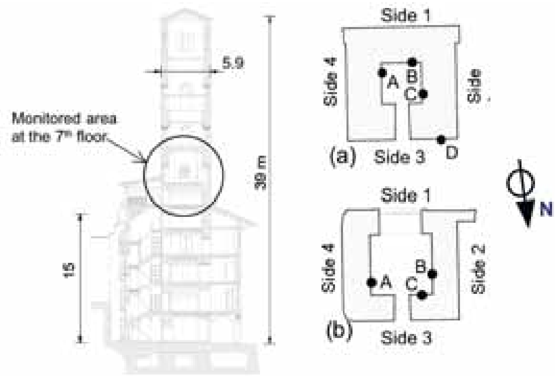


Fig. 6: Cross-sectional view of the Sineo Tower and plan views of the levels tested by means of single and double flat-jacks, foundation level (a), ground floor (b).

The cracking pattern can be observed from both the internal and the exterior views. The most significant cracks are inside the tower, mainly located between the 6th and the 8th storey. On the external side we can observe minor cracks, mostly near the windows, more specifically between the 6th and the 7th storey.

Through AE monitoring two cracks were detected in the inner masonry layer at the 7th storey level (Fig. 6): one next to a window, and another nearby. The monitoring revealed an on-going damaging process, characterized by slow crack propagation inside the brick walls. In the most damaged zone, crack spreading had come to a halt, the cracks having achieved a new condition of stability, leading towards compressed zones of the masonry.

In this particular case it can be seen that, in the zone monitored, each appreciable crack advance is often correlated to a seismic event. In the diagram shown in Figure 7, the cumulative AE function relating to the area monitored is overlaid with the seismic events recorded in the Alba region during the same time period; the relative intensity of the events is also shown. Seismic event data were provided by the National Institute for Geophysics

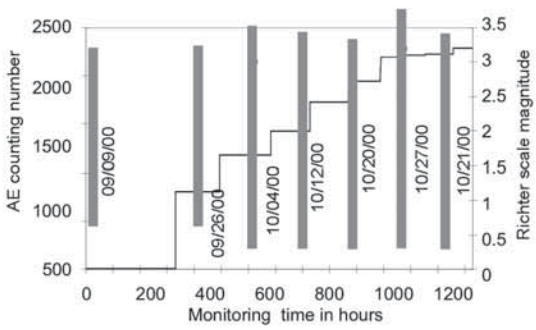


Fig. 7: AE and seismic events

and Volcanology in Rome. It can be seen that the tower behaviour is stable when the structure is subjected to vertical loads alone, whereas the structure is unable to respond elastically to shaking or horizontal actions.

Flat-jack and AE tests

Non-destructive tests were performed by means of flat jacks to determine the stress level in different masonry sections of the tower (Fig. 6). The results are reported in the Table 2. Furthermore, in order to assess the damage level in the zone monitored by means of the AE technique, a compressive test was conducted on the masonry through the combined use of double jacks and AE sensors (Fig. 8).

Fig. 8: Combined flat-jack test and AE monitoring

Points	Foundation Floor		Ground Floor	
	σ_z	E	σ_z	E
A	2.455	-	0.871	-
B	0.297	-	0.746	-
C	1.059	-	-	-
D	0.502	-	-	5000

Table 2: Results from single and double flat-jack tests. Average compressive stresses and Young's Moduli are in MPa

As is known, the double jack test is carried out by introducing the jacks into two parallel cuts made into the masonry at a distance of ca 50 cm apart [15]. By increasing the pressure applied by the jacks, the compressive stress in the masonry is gradually increased. In this manner, we may obtain stress-strain diagrams by measuring the deformations occurring in the masonry between the two cuts (Fig. 9). From this test, we can also work out the local failure stress in the masonry, by increasing the pressure applied with the jacks up to the onset of cracking. During the test, three complete loading cycles were carried out to evaluate the tangent elastic modulus of the masonry at different stress levels. From the diagram in Figure 9 we can identify the onset of cracking in the materials, corresponding to failure stress σ_u, i.e., to the point when horizontal strains begin to grow to an appreciable extent for small load variations.

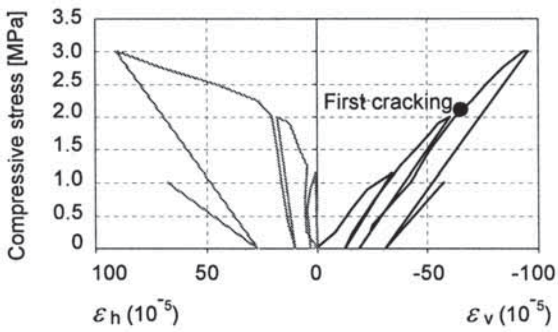


Fig. 9: Double flat-jack test. Cyclic loading are plotted versus horizontal and vertical strains.

In order to define the damage level in the area monitored, we may adopt the same fractal criterion defined in Section 3.3. In particular, for a similar structure [16], compressive tests were performed with double flat-jack tests on three different masonry sections. The prismatic masonry volumes tested in compression were delimited crosswise by vertical cuts (Fig. 10). The dimensions of the cross-section of the elements shown in Figure 10 correspond to the effective area of the masonry to which the pressure of the flat-jacks is applied. The tests are in keeping with the procedures specified in [15], other than for the vertical cuts produced in order to eliminate, in the element damaged, the influence of the adjacent masonry portions. Figure 10 shows the results obtained from these tests for the intermediate element (Vol. 2). Similar results were obtained for the other two elements. The figure illustrates the three loading cycles performed as a function of time and the diagram of the cumulative number of AE events. From the AE diagram it can be clearly seen that the material releases energy when the stress level reached previously is exceeded (*Kaiser effect* [14]). Moreover, from the diagram, we find that the cumulative number of AE events at failure stress is $N_{max} \cong 12000$. The experimental results obtained on the three masonry elements are summarised in Table 3.

Specimen	Volume [cm³]	Peak stress [Mpa]	N_{max} at σ_u
Vol. 1	8640	2.07	~ 6500
Vol. 2	16992	1.61	~ 12000
Vol. 3	33984	1.59	~ 18000

Table 3: Experimental values obtained from flat-jack tests and AE measurements.

Table 3 shows that in compressive tests the cumulative number of AE events increased with increasing specimen volume. From a statistical analysis of the experimental data, parameters D and Γ_{AE} (eq. (2)) can be quantified. Parameter D represents the slope, in the bilogarithmic diagram, of the curve correlating N_{max} to specimen volume. By best-fitting, we obtain $D/3 \cong 0.743$, so that the fractal exponent, as predicted by fragmentation theories, turns out to be of between 2 and 3 ($D \cong 2.23$). Moreover, the critical value of fractal AE density turns out to be: $\Gamma_{AE} \cong 8.00$ cm$^{-2.23}$ [16].

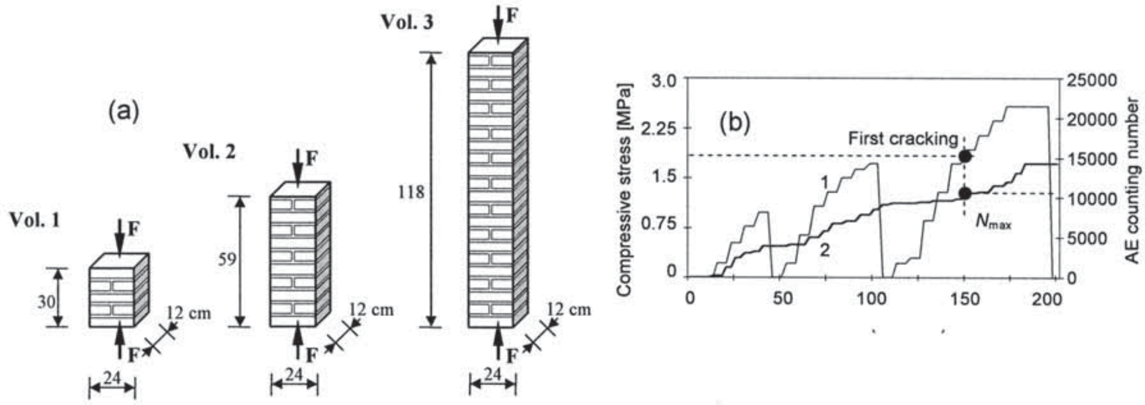


Fig. 10: Masonry elements tested in compression by means of double flat-jacks (a). Double flat-jack test on Vol. 2. Cumulative number of AE events versus cyclic loading (b).

Damage level of the area monitored

During the observation period, which lasted 60 days the number of AE events recorded was $N \cong 2250$ (Fig. 7). Through earlier tests performed on rubble filled masonry, 80 cm thick, and hence characterised by appreciable discontinuities, it was ascertained that the transducers were able to pick up the AE signals from a distance of up to 10 m from their points of application [4] and to a depth of 12 cm, i.e., over a length corresponding to the thickness of the outer layer of bricks.

Since the average width of the sides of the tower is ca 500 cm, the total volume monitored by the transducers will be: $V \cong 500\text{x}2000\text{x}12 = 1.2\text{x}10^7$ cm^3. From eq. (2), using fractal exponent $D \cong 2.23$ and the critical value of fractal acoustic emission density, $\Gamma_{AE} \cong 8.00$ cm$^{-2.23}$, we obtain a critical AE number of $N_{max} \cong 1.46\text{x}10^6$. Introducing the values of N and N_{max} into eq.(8), we get $\eta \cong 0.154\%$. This value represents, in percentage terms, the amount of energy released as a proportion of the energy that would cause the ultimate damage of the area monitored.

Conclusions

In this work a monitoring method based on AE technique is applied to detect the damage in concrete and masonry structures. This technique, based on fractal concepts, makes it possible to introduce a useful energetic damage parameter for structural assessment of concrete elements. It is based on a correlation between AE activity in a structure and the corresponding activity recorded on a small specimen drilled out from the structure and tested to failure. Moreover, by applying compressive tests through the combined use of double flat jacks and AE sensors, the safety of masonry structures undergoing damage and degradation process can be efficiently evaluated under service conditions.

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