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Damage Mechanisms Interpreted by Acoustic Emission Signal Analysis

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Abstract. Acoustic emissions (AE) are ultrasonic waves generated by the rapid release of energy from discontinuities or cracks spreading in materials subject to a stress and strain field. By identifying the complete shape of the signals and taking into account a larger quantity of data, it becomes possible to ascertain the three-dimensional location of damage sources from AE sensor records. In this connection, the authors have fine-tuned an original procedure that uses seismic analysis techniques, such as the moment-tensor solution. The experimental program consisted of tests conducted in situ on masonry walls of historical buildings.

Introduction

Present-day non-destructive and instrumental investigation methods are widely used to measure and check the evolution of negative structural phenomena, such as damage and cracking, and to predict their subsequent developments. Among these methods, the non-destructive methodology based on Acoustic Emission (AE) proves to be very effective [1,2]. It 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.

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. The signal is therefore analysed by a measuring system counting the emissions that exceed a certain voltage threshold measured in volts (V). The leading-edge equipment adopted by the authors consists of six units USAM®, that can be synchronized for multi-channel data processing. The most relevant parameters acquired from the signals (frequencies in a range between 50 and 800 kHz, arrival time, amplitude, duration, number of events and oscillations) are stored in the USAM memory and then downloaded to a PC for a multi-channel data processing (Fig. 1). Microcracks localisation is performed from this elaboration and the condition of the monitored specimen can be determined [3,4].

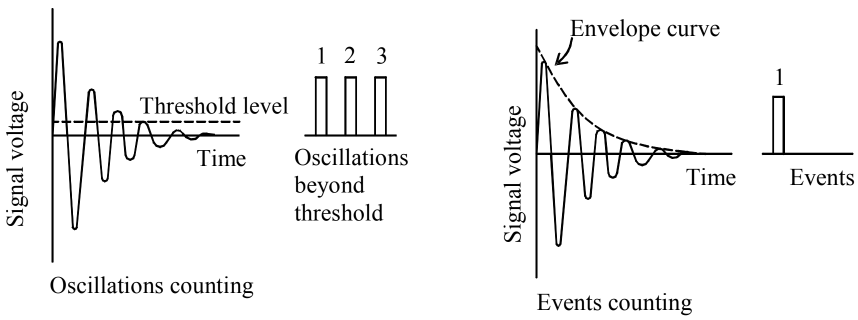


Fig. 1. Detected signals by AE technique.

Acoustic emission size and time scaling

Recently, AE data have been interpreted by the authors on the basis of the statistical and fractal theories of fragmentation [1,5]. The following *size-scaling* law is assumed during the damage process:

$$W \propto N \propto V^{D/3}. \tag{1}$$

In Eq.(1), W is the dissipated energy, V the structural element volume, D the so-called fractal exponent comprised between 2 and 3, and N the cumulative number of AE events that the structure provides during the damage monitoring. The damage level of a structure can be obtained from AE data of a reference specimen (subscript r) extracted from the structure and tested up to failure. From Eq. (1) we have:

$$N_{\max} = N_{\max r}\left(V / V_r\right)^{D/3}. \tag{2}$$

from which we can obtain the critical number of acoustic emission events $N_{\max}$ that the structure may provide before achieving the collapse. The details of the method are given in references [1,5]. As we shall see later on, this theory – developed initially for monitoring concrete structures – can also be profitably applied to the analysis of damage in masonry structures. In the latter case, compressive tests were performed on site, with the aid of flat jacks, on masonry test pieces of different sizes [6].

The authors have also shown that energy dissipation, as measured with the AE technique during the damaging process, follows the *time-scaling* law [5]:

$$W \propto N \propto t^{\beta_t}, \text{with } 0 \le \beta_t \le 3. \tag{3}$$

where t is the monitoring time and β_t stands for the time-scaling exponent of the released energy. The experimental validation of Eq. (3) was carried out through laboratory compressive tests conducted on concrete cylinders of different diameters and slenderness ratios. All compressive tests were performed under displacement control, by imposing a constant rate to the upper loading platen. The trend observed was that of an increase in β_t with increasing specimen diameter [5]. By means of Eq. (3) the extent of structural damage, observed also in situ during each monitoring period, can be correlated to the rate of propagation of the microcracks and we can make a prediction as to the structure's stability conditions [1,6].

Localisation of acoustic emission sources

The first stage in the localisation method consists in recognising the data needed to identify the AE sources, followed by the triangulation procedure [3,4]. During the first stage, the groups of signals, recorded by the various sensors, that fall into time intervals compatible with the formation of microcracks in the volume analysed, are identified. These time intervals, of the order of micro-seconds, are defined on the basis of the presumed speed of transmission of the waves (P) and the mutual distance of the sensors applied to the surface of the material. It is usual to assume that the amplitude threshold of 100μV of the non-amplified signal is appropriate to distinguish between P-wave and S-wave arrival times. In fact, P-waves are usually characterized by higher value signals [3]. In the second stage, when the formation of microcraks in a three-dimensional space is analysed, the triangulation technique can be applied if signals recorded by at least five sensors fall into the time intervals. Thus, with this procedure it is possible to define both the position of the microcracks in the volume and the speed of transmission of P-waves. The localisation procedure can also be performed through numerical techniques using optimisation methods such as the Least Squares Method (LSM) [4].

Moment tensor analysis

Damage can be considered from the microscopic standpoint as consisting of a succession of discrete events, localised in space and time. They develop at different times in the parts of the structure where stresses are the highest. If the AE source during the localization procedure have been identified by all the six sensors it is possible to evaluate the orientation, the direction and the modalities of the microcracks. Moment tensor analysis was developed in seismology to describe the mechanics of earthquakes [7]. The same method, transferred to the field of acoustic emissions, is able to represent a source of ultrasonic waves in terms of motion and orientation. The procedure fine tuned in this study relies from the theoretical standpoint on the procedure defined by Shigeishi and Ohtsu [8]. This procedure, called SiGMA, characterised the AE signal by taking into account only the first arrival time of P-waves.

In this procedure the moment tensor components m_{pq} are proportional to the amplitudes $A(\mathbf{x})$ of the first P-waves to reach the transducers:

$$A(\mathbf{x}) = \frac{C_s \; REF(\mathbf{t},\mathbf{r})}{R} (r_1 \; r_2 \; r_3) \begin{pmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{pmatrix} \begin{pmatrix} r_1 \\ r_2 \\ r_3 \end{pmatrix}. \tag{4}$$

C_s in Eq. (4) is a calibration coefficient of the acoustic emission sensors, R is the distance between the AE source at point $\mathbf{y}$ and the sensor located at point $\mathbf{x}$. Vector $\mathbf{r}$ represents the components of the distances, R, obtained through the localisation procedure, and $REF(\mathbf{t},\mathbf{r})$ is the reflection coefficient of the sensitivity of the sensor between vector $\mathbf{r}$ and direction $\mathbf{t}$. The moment tensor provides a general representation of the seismic source. Seismic moment tensors is a variety of stress tensor for an elastic medium, similar to stress tensor for elastomechanics. However, it differs in a couple of very important ways. Seismic moment tensor or acoustic moment tensor is created from a measured event such as an earthquake or material cracking. Sound waves are emitted at the event and can be measured. Thus, one major difference is that moment tensor represents a strictly elastodynamic source. Second, in elastomechanics, a stress tensor is related to the forces applied on the exterior surface of a volume. Moment tensor instead is related to the equivalent forces that cause displacement across an internal surface, where the internal surface represents a hidden crack.

Since the moment tensor is symmetrical, to be able to represent it, it is necessary to determine the six independent unknowns m_{pq}. To this end, in order to determine the components of the moment tensor, the amplitude of the signal $A(\mathbf{x})$ must be received from at least six AE channels. From an eigenvalue analysis of the moment tensor, it is possible to determine the type of crack localised:

$$\lambda_1/\lambda_1 = X + Y + Z\,, \quad \lambda_2/\lambda_1 = 0 - \frac{Y}{2} + Z\,, \quad \lambda_3/\lambda_1 = -X - \frac{Y}{2} + Z\,. \tag{5}$$

where, $\lambda_1, \lambda_2, \lambda_3$ are the maximum, middle and minimum eigenvalues, respectively, X is the component due to shear, Y is the deviatoric tensile component, Z is the isotropic tensile component. Ohtsu classified an AE source with $X > 60\%$ as a shear crack, one with $X < 40\%$ and $Y + Z > 60\%$ as a tensile crack, and one with $40\% < X < 60\%$ as a mixed mode crack [8]. Moreover, from an eigenvector analysis, it is possible to determine the versors, $\boldsymbol{l}$ and $\boldsymbol{n}$, which determine the direction of the displacement and the orientation of the crack surfaces [8].

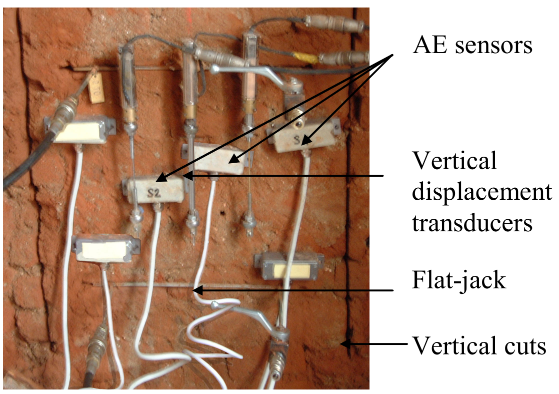
Damage analysis in masonry structures

By means of the AE technique, we have interpreted the damage mechanisms in different concrete and masonry structures. Tests were performed on site in order to assess the stability of the structures under service loads and further tests were carried out in the laboratory in order to identify the mechanical properties of the materials [1]. In this section, however, special attention is devoted to a technique fine-tuned by the authors, which consists of using flat-jacks mated to AE measurements, for the on-site characterisation of the mechanical properties in compression of the masonry of historic buildings. This technique was used to analyse the masonry structures of three medieval towers rising in Alba and the Royal Palace of Venaria Reale (Piedmont, Italy) [6]. The description of this methodology is of interest because flat-jack testing is a versatile and powerful technique that provides significant information on the mechanical properties of historical constructions. The first applications of this technique on some historical monuments [6] clearly showed its great potential. When double jacks are used, this test works according to the same principle as a standard compressive test. The difference is that it is performed in situ and the load is applied by means of two flat-jacks instead of the loading platens.

There is not much in the literature concerning masonry testing in compression, while more extensive theoretical studies exits on other brittle materials such as concrete and rocks, some of them using the acoustic emission technique. Prism size effects are one of the major aspects characterising the behaviour of masonry under compression. These effects are related to the ratio between the nominal dimensions of the specimens, *d*, and strength. One of the few studies addressing the two aspects from the numerical viewpoint is a report by Lourenço of 1997 [9]. The example given in [9] is an analysis of a masonry pier subject to a point load. The study of the structural elements is conducted beyond peak load. After peak load, a splitting crack opens in the centre of the pier and propagates in a catastrophic manner. The computed crack path is straight and vertical, indicating that the crack spreads through the pier unit from one end joint to the other. The results of the numerical analysis also show that as a function of the scale of the item analysed, i.e., using piers with increasing nominal dimensions, *d*, the evolution of the cracking configuration remains the same. We always witness the formation of a long vertical crack resulting in the separation of the two piers into two elements whose slenderness is twice that of the original. With increasing specimen scale, instead, we observe an appreciable reduction in failure stresses.

The tests performed on the load-bearing masonry of the Alba towers and the Royal Palace of Venaria used flat-jacks measuring 24×12 cm^2. The cuts made into the masonry wall to obtain a smaller-sized specimen were made into two horizontal mortar joints spaced about 30 cm apart. A typical setup of a compressive test in situ is shown in Fig. 2. The tests were performed in keeping with the procedures specified in the ASTM 1991 rules, other than for the vertical cuts produced in order to eliminate, in the cracked element, the influence of the adjacent masonry portions. During the tests, the stress-strain relationship of the masonry was determined by gradually increasing the pressure applied by the flat-jacks in the course of three loading-unloading cycles. Peak compressive strength was obtained from the load-displacement diagram, when the latter became highly nonlinear, denoting imminent failure. The three prismatic masonry volumes tested in compression were delimited crosswise by making vertical cuts to a constant depth of 12 cm (Fig. 3).

(a)



(b)

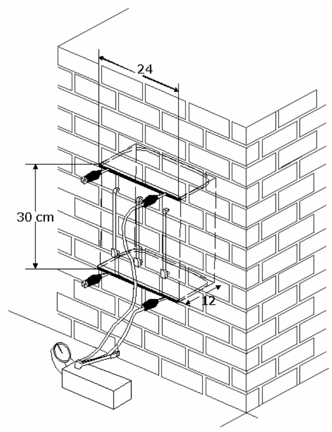


Fig. 2. (a) Combined flat-jack test and AE monitoring. (b) Typical set up for the in situ flat-jack test. The dimensions given are those of the specimen referred to as Vol. 1.

Figure 3 shows the results obtained from these tests for one of the intermediate element (Vol. 2). Similar results were obtained for the other elements. The figure also shows the three loading cycles performed as a function of time and the diagram of the cumulative number of AE counts. From the AE diagram it can be clearly seen that the material releases energy when the stress level reached previously is exceeded (Kaiser effect). Moreover, from the diagram, we find that the cumulative number of AE counts at failure stress (i.e. before the critical condition is reached) is $N_{\max} \cong 12000$. The average experimental results obtained on the basis of the three tests performed on the load-bearing masonry of the Alba towers and the three tests performed on the Royal Palace of Venaria are summarised in Table 1.

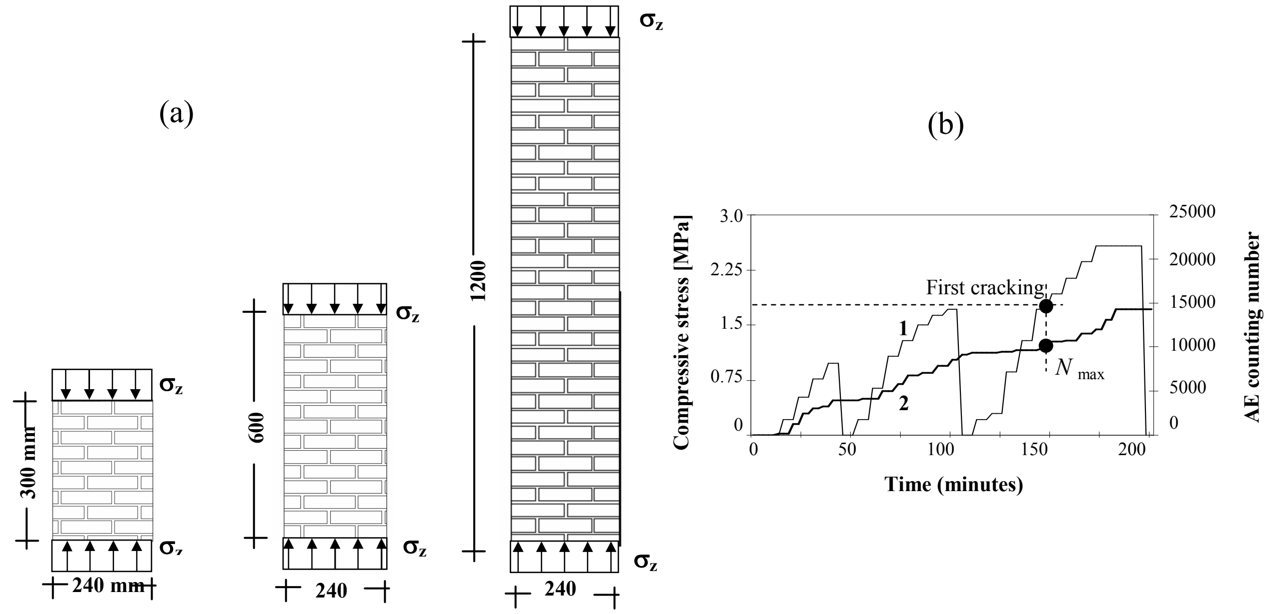


Figure 3: (a) Masonry elements tested in compression by means of double flat-jacks and AE sensors. Their depth, obtained with the vertical cuts, was 12 cm. (b) Double flat-jack test on Vol. 2. Cumulative number of AE events (2) versus cyclic loading (1).

Table 1: Average experimental values obtained from flat-jack tests and AE measurements.

Specimen	Volume (cm^3)	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

The tests confirmed the results obtained through numerical procedures in [9]. In fact, as can be seen from Table 1, the experimental peak stress in the masonry specimen is a decreasing function of the specimen volume, whereas the cumulative number of AE counts increases with increasing specimen volume with non proportional law. The pre-peak portion of the stress-strain curves shows that specimen slenderness has significant effects on peak stresses σ_u, and size effects are highly significant on the critical number of acoustic emission $N_{\max}$. Moreover, as a further confirmation of the conclusions reached in [9], during the compressive tests it was determined through the moment tensor analysis that a change in specimen shape had no appreciable effects on the configuration of damage patterns. A detailed representation of the points that originated the microcracks during one of the tests performed on Vol. 2 is shown in Fig. (4). From this figure it can be seen that all the microcracks contained in the volume, and, for the sake of convenience, projected onto the front surface of the element, concentrate around its intermediate axis. In the figure, in accordance with the moment-tensor analysis, crack type and the crack motion vector are also shown for each point localised.

In conclusion, the use of flat-jacks invariably determines the formation of a vertical crack plane, which tends to split the specimen into two separate parts. Fractured areas are more deformed, while unfractured portions recover their deformations. When critical conditions are reached, in specimens with greater slenderness the damaged volume is larger but peak stress is lower, compared to lower slenderness specimens. Peak stress, in fact, can be correlated to the quantity of defects present in the materials, whilst damaged volume is proportional to the released energy measured by the AE technique, and hence is proportional to the critical number of acoustic emission N_{max}. Furthermore, from a statistical analysis of the experimental data reported in Table 1, parameters D can be quantified (Eq. 2) [6]. 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 between 2 and 3 ($D \cong 2.23$). As pointed out in [1,6], knowing the fractal exponent, D, it is possible to make predictions on the stability of the structures monitored by determining the cumulative AE count number that corresponds to the collapse of the structural volume analysed.

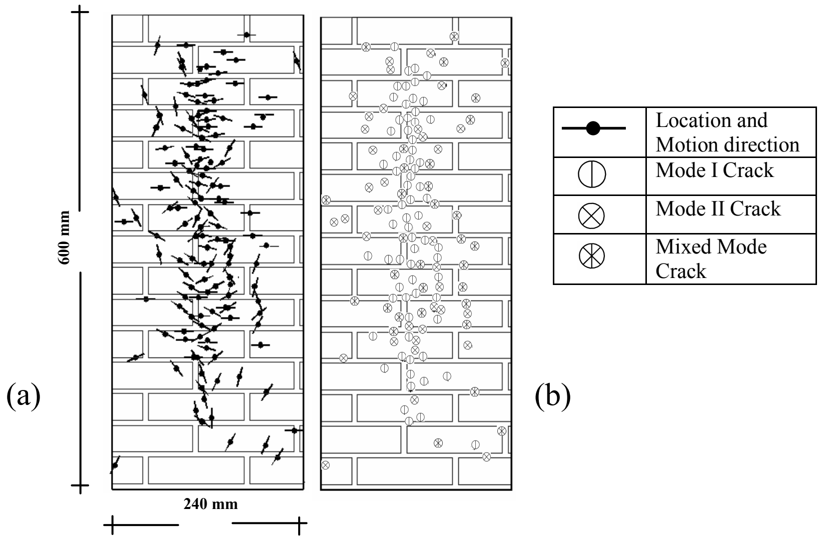


Fig. 4. AE sources on a Vol. 2 specimen. (a) Localization of microcrack sources and crack direction vectors. (b) Crack typology obtained from the moment-tensor analysis (Eq. 5).

Summary

The acoustic emission technique has the potential for performing an effective assessment of the integrity of large-sized structures, such as Civil Engineering structures, by means of a limited number of sensors. In this work, based on Fracture Mechanics concepts, a fractal or multiscale methodology is proposed to *predict* the damage evolution up to structural collapse. Through the application of AE localisation procedures and moment tensor analysis, it can be seen that this technique can also be used to *interpret* damage mechanisms during their evolution.

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