Elastic Emission or Very Low Frequency Acoustic Emission in Solids Under Compression

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Abstract. In this paper are summarized the recent findings on detection of acoustic emissions at very low frequencies (i.e. from few Hertz to 10 kHz) in solid materials, such as rock and concrete, under compression until fracture in laboratory tests. These emissions, defined Elastic Emissions (or ELE), are characterized by wavelength greater than the maximum specimen size and by a very important amount of released energy.

The ELEs are the effect of the propagating micro-shock waves due to the macro-cracks forming in the bulk of the materials detected at the specimen surface.

A spectral analysis of the ELEs, realized with metrological reliability, provides quantitative informations about the macro-crack effects in terms of released energy, measuring the local acceleration in the accelerometer point of application.

Introduction

The fracture of materials is a complex phenomenon which occurs according to two broadly defined scenarios. In the first one, a homogeneous solid subjected to loading will fail in a perfectly brittle manner (without any warnings announcing the incipient failure) with sudden propagation of a single fracture [1]. This “one-crack” mechanism is perfectly realised in the presence of a perfect crystalline lattice with a pre-existing crack or notch to concentrate the applied stress.

In the second scenario that applies to heterogeneous materials such as fiber composites, rocks and concrete under loading, the structure progressively deteriorates, first in an uncorrelated way reflecting the intrinsic heterogeneities (dislocations, flaws, etc.), or disorder. As the density of microcracks increases with the increasing loads, the stress fields of the microcracks interact and the microcracks become correlated. In these systems, the microcracks may coalesce to form a through-going fracture as the culmination of a progressive damage. This second kind of behaviour, called quasi-brittle, is characterized by well-defined precursors including progressive decay of the Young’s modulus, changes in transport, electric properties, etc. announcing an imminent failure [2-4].

In particular, acoustic emission (AE) due to microcrack growth precedes the macroscopic failure of rock and concrete samples under constant stress or constant strain rate loading [5].

Numerous investigations established that AE phenomenon varies while materials experience evolving damage [6-8]. Examples include two major damage mechanisms in composite materials —matricial cracks and decohesion between fiber and matrix— characterized by different AE amplitude distributions and rates [9]. Furthermore, AE energy released in different stages of damage process is concentrated in different sections of the frequency range.

Recently, a distinction between high-frequency and low-frequency AE, the latter called elastic emission (ELE), has been proposed, which is able to discriminate the different stages of damage process – nucleation and growth of microcracks with AE at the beginning, formation of macrocracks with ELE during late stages [10].

This differentiate analysis of acoustic emissions will allow setting of two warning levels in structural monitoring: the first level, given by the presence of AE associated with micro-damage, suggests repairing and strengthening interventions or, anyway, monitoring damage evolution; the second level, higher, given by the ELE phenomenon and associated with macro-damage, indicates the need of prompt intervention due to macrocracks leading to the structural collapse.

ELE monitoring will be performed using calibrated piezoelectric accelerometers with a flat frequency response in the range of 1–10 kHz. Using accelerometers with calibrated sensitivity (the ratio of the electrical output to the acceleration input) allows description of ELEs in terms of mechanical quantities (acceleration, velocity and displacement) and estimation of their energy content.

In stressed solid materials, such as concrete and rock specimens (characterized by elastic wave velocities from 2000 up to 5000 m/s) under compression, low-frequency ELEs (1-10 kHz), with high amplitude and wavelengths (0.3-5 m) greater than the maximum specimen size (~ 0.1 m) can be detected during the late stages of damage process. Remarkably, the ELE phenomenon can be observed also in perfectly brittle materials (in the sense of Hook’s law), proving to be a valuable fracture precursor.

Definition of Elastic Emission

ELE are defined as acoustic emissions with half-wavelength λ_{ELE} greater than the maximum size d_{MAX} of the tested specimen, i.e. the half-wavelength of the elastic waves is greater than the medium of propagation [8,10].

This is a remarkable issue since, in principle, this definition implies rigid body vibrations, while high-frequency AE, due to micro-crack growth, are pure vibration modes of the material “particles” around their equilibrium position (Fig.1a) in a medium macroscopically at rest. As the collapse is approached, macro-cracks open and macroscopic portions of the specimen are suddenly subjected to appreciable displacements. In practice, the released energy is able to excite both the natural vibration modes of the specimen and the so called “quasi-rigid-body vibrations” (Fig. 2b), resulting from the specimen flexibility and the imposed constraints (with the press platens).

These vibrations are detected at the specimen surface as ELEs, which, then, have to be considered as signature of irreversible damage and failure precursors.

Based on these considerations, it is therefore possible to distinguish the effects of the two different emissions, AE and ELE, and analyse them separately.

Taking into account that the Rayleigh superficial waves velocity, c_R, is about 0.92 of the S waves velocity c_S and, at least, $c_S \approx c_L/\sqrt{3}$, the propagation velocity c_R of the Rayleigh superficial waves in the tested materials has been estimated to be roughly $0.531 \cdot c_L$, from the measured c_L of the longitudinal elastic waves. As ELE wavelengths λ_{ELE} must fulfil the relationship $\lambda_{ELE} \geq 2 \cdot d_{MAX}$, the upper limit for ELE frequencies is:

$$f_{ELE} \leq \frac{c_R}{2 \cdot d_{MAX}} \approx \frac{0.92 \cdot c_L}{2 \cdot \sqrt{3} \cdot d_{MAX}} \approx 0.265 \frac{c_L}{d_{MAX}} \qquad (1)$$

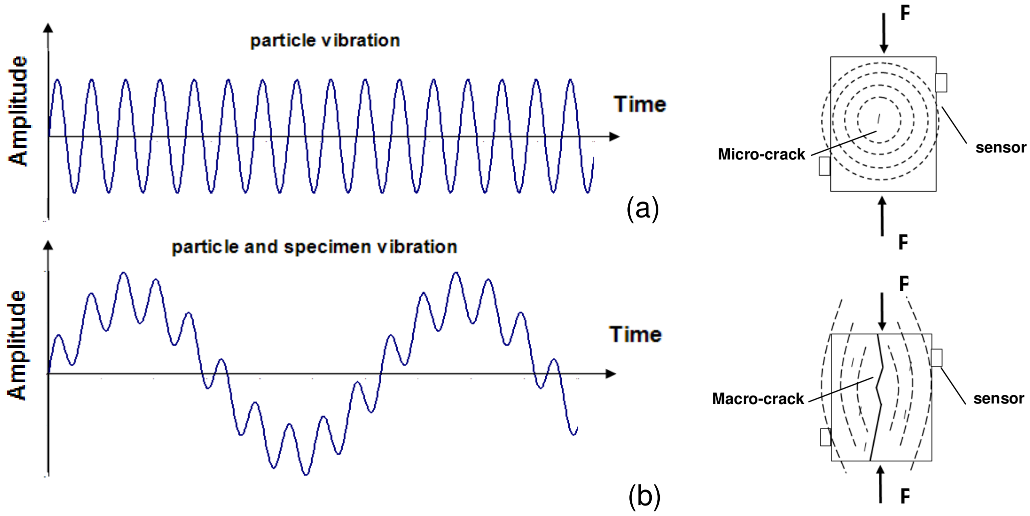

Figure 1: (a) Schematic representation of AE due to particle vibration around their equilibrium position. (b) Schematic representation of ELE due to relevant oscillations of the entire specimen.

Detection of Elastic Emission

The compressive tests are performed in displacement control at constant piston velocity of 0.5·mm/s, using a servo-hydraulic press with a maximum capacity of 500 kN, equipped with control electronics. The specimen adheres to the press platens without any coupling material (specimen-platen contact with friction). The applied force is determined by measuring the pressure in the loading cylinder by means of a transducer. The stroke of the press platen in contact with the test specimen is controlled by means of a wire type potentiometric displacement transducer. Two kind of "delta shear" accelerometers, with respectively the upper frequency limit of 10 kHz and 20 kHz, for detection of ELE events are used, depending on the typology and size of specimen tested. The events are characterized by the output response of the calibrated transducers (charge sensitivity 9.20 pC/m·s^{-2} and 0.33 pC/m·s^{-2}), expressed in mm/s^2. The accelerometer transducers are rigidly (fixed) coupled to the specimens in order to detect the surface acceleration. In order to filter out environmental background noise, we set appropriate detection thresholds for acquisition systems, i.e. 60 dB (referred to 1 mm/s^2) for ELE signals and a pass-high filter in order to filter out any residual background vibration under 1 kHz.

The global level of the background-noise vibration in the frequency range of interest has been evaluated. In the range of frequencies between 1 kHz and 20 kHz, the mechanical noise has an average value of about 62±2 dB (referred to 1 mm/s^2). Nevertheless, it is possible to note that the background-noise has a negligible influence (less than1%) if compared to ELE signals. The ELE acceleration spectral levels are between 80 dB and 120 dB.

Spectral analysis and released energy of Elastic Emission

We analyzed the energy (in terms of global level amplitude) and frequency spectra of ELE during compression tests on several natural and artificial materials, such as granite, marble and concrete. In previous works such investigations were restricted to high-frequency AE. The increase of AE amplitudes as failure is approached were experimentally observed in [4]. Variation of AE frequencies during damage evolution has been studied in [10]. Here, all ELE events detected during a compression test are shown as a function of time (or load), amplitude and frequency, as shown, as an example, in Figure 2a and 2b. Figure 2a represents the initial phase of ELE activity characterized by sporadic signals with energy content concentrated in a narrow frequency interval. Similarly in Figure 2b the phase just before the specimen collapse is represented. In this case a greater number of ELE is detected with more significant energy content in a wide frequency range, probably extending beyond the observation window size. Based on these data, it is possible to describe macro-crack effects in terms of released energy, measuring the local acceleration in the accelerometer point of application.

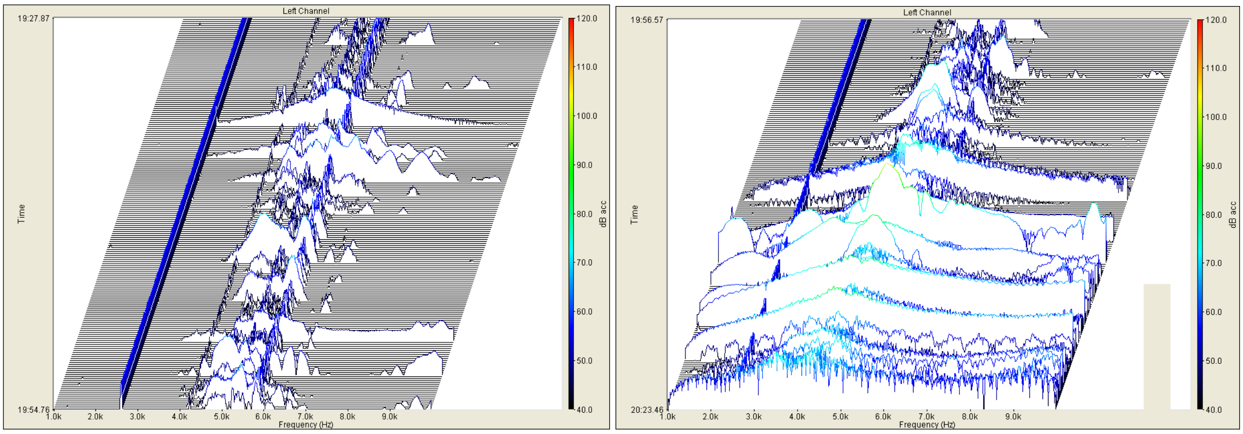

Figure 2: Spectral analysis of ELE activity during a compressive test: (a) initial phase of ELE activity and (b) ELE activity approaching the final collapse. Time window is 30 s.

From the spectral analysis the frequency peak is detected and the acceleration global level of each single event is determined. Then a 3D-graph is plotted as a function of frequency-amplitude vs. time/load.

Through 3D-graphs exhaustive information on the ELE activity during the compressive test can be achieved. Each single point represents the global level of a single ELE experimentally measured, and the frequency value is related to the peak of greatest amplitude in the considered spectrum. As an example, Figure 3 shows the ELE activity in the time - amplitude - frequency diagram: the X-axis represents the time in seconds, the Y-axis is the frequency in hertz, and the Z-axis is the amplitude in dB referred to1 mm/s^2.

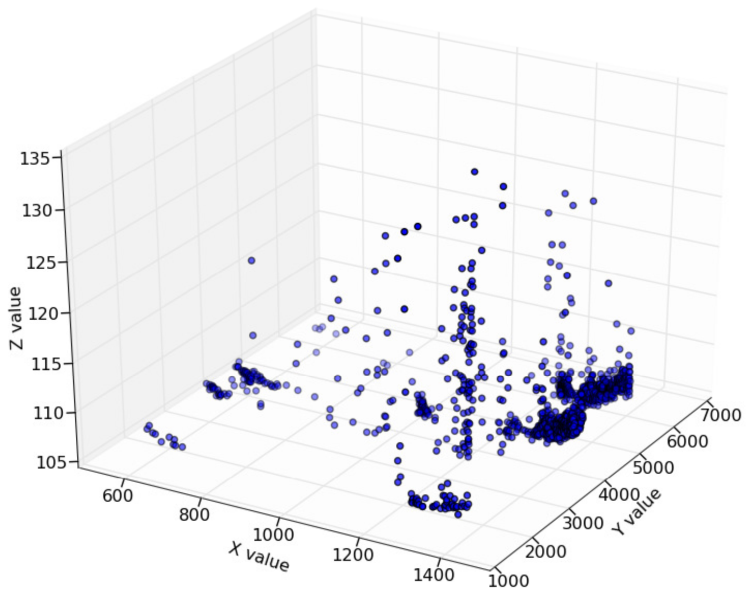

Figure 3: 3D graph of ELE event series during a compressive test. The x-, y- and z-axes represent the time (s), the frequency (Hz) and the amplitude (dB).

Besides a simple method to estimate the released energy by ELE events in terms of kinetic energy has been also proposed [9].

We assume that the fracture mode is crack opening, such an explosive source. It causes radially expanding dilatational pulses with wavelengths even longer than the specimen size, as we actually measured [11].

As observed in laboratory fracture experiments, a meso or a macrocrack causes a micro-shock type elastic wave at least very close to the tip of the crack, which would imply both natural vibrations and displacements of the entire body. As a matter of fact, the constraint induced by the friction between the end surfaces of the specimen and the loading platens restricts the specimen motion to an impulsive wrapping dilatation, which adds up to the transversal dilatation accompanying the longitudinal specimen compression. Here, as an example, we calculate the kinetic energy associated with this impulsive dilatation, modeling the velocity field at a cylindrical specimen surface under very simple assumptions. Since the wavelength associated with the motion is assumed to be greater than the height h of the specimen, we can choose a parabolic-like profile for the velocity field.

We think of the specimen as the superimposition of layers with thickness dz and mass d$m = M \cdot$dz/h, being M the specimen mass. Therefore, the contribution of each layer to the kinetic energy is ½ $v^2 \cdot$dm, where dm is subjected to a radial displacement with velocity v due to the enlargement of a newly formed crack. Thus, the average kinetic energy associated with the i^{th} ELE event is the sum of all such contributions:

$$E_{kin,i} = \int_M \frac{1}{2} v_i^2(z)\,dm = \frac{M}{2h}\int_0^h v_i^2(z)\,dz = \frac{4}{15} M v_{0i}^2 \qquad (2)$$

where a parabolic-like profile, $v_i(z) = az^2+bz+c$, is assumed for the local surface velocity, with boundary conditions $v(h/2) = v_0$ and $v(0) = v(h) = 0$.
The energy content of each ELE pulse is estimated by means of the spectral analysis of the local vibration velocity level, measured by the calibrated accelerometer attached at the specimen surface. We have found that in general the energy of ELE pulses ranges between ~10^{-13} J (~10^{-3} GeV) and ~10^{-7} J (~10^{3} GeV) depending on the tested material [.

Scaling laws and statistical distributions for ELE

Traditionally, the space-time organization of AE and earthquake source process is ruled by phenomenological power laws, among them, the Gutenberg-Richter (GR) law [11,12] and the Omori law [13]. Recently, it has been established the existence of a scaling law, valid both for seismic [14,15] and AE events [16-18], for the probability density functions of the time intervals between consecutive events (waiting times), defined by the first P-wave arrival times. It has been demonstrated that the organization of waiting times between ELE in solid materials is likewise ruled the scaling law established for high frequency AE and earthquakes.
Starting from the pioneer work of Bak *et al.* [14], Corral found that the distributions of waiting times between consecutive earthquakes follow a universal scaling law in different regions of the world and earthquake catalogs if appropriately rescaled [15], which has been extended to the AE and ELE time series in laboratory fracture [16-18]. This suggests that timing of fractures might be self-similar over a larger range of magnitude than had been suggested earlier. Here, the rescaling and collapsing procedure for waiting-time distributions in a sequence of rupture events is illustrated. We select the $N(M_{th})$ events with magnitude M above a certain threshold M_{th}. The sequence is transformed into a point process where events occur at times t_i with $1 \leq i \leq N(M_{th}) \equiv N$, and therefore, the waiting time between consecutive events can be obtained as $\tau_i \equiv t_i - t_{i-1}$. Thus, we compute the waiting-time probability density function (PDF) as $p_{Mth}(\tau) \equiv \mathrm{Prob}(\tau \leq \text{waiting time} < \tau + d\tau)/ d\tau$. Performing the transformation $\tau \rightarrow \tau / <\tau>_{Mth}$, changes also the units of the PDF, $p_{Mth}(\tau) \rightarrow <\tau>_{Mth}\, p_{Mth}(\tau)$. In the following, the rescaled waiting time will be expressed as a function of the mean event rate $R_{Mth} \equiv N(M_{th}) / T$:

$$<\tau>_{Mth} \equiv R_{Mth}^{-1} \tag{3}$$

This rescaling procedure is applied to PDFs obtained for several values of M_{th}. All the rescaled PDFs collapse onto a single curve f, proving the fulfilment of a scaling law [14-18]:

$$p_{Mth}(\tau) = R_{Mth} f(R_{Mth}\tau) \tag{4}$$

Supersonic fracture and Elastic Emission

Since ELE events are supposed to be associated with macro-crack growth in the bulk of the material we propose to link, at least some very energetic events, to micro-shock waves generated by transonic or supersonic crack motions. Recently it has been demonstrated that cracks can propagate in the material faster than the classical limit of the Rayleigh. and longitudinal speed waves [19,20].
It means that the material, in particular around the tip of the propagating crack, becomes "hyperelastic". This phenomenon suggests that around the tip of the supersonic crack a significant density discontinuity can be recognized, i.e. a classical shock wave.

ELE events, detected on the specimen surface, are then only a sort of *vestige* of the actual energy released in the proximity of the crack, in particular in each infinitesimal volume of the material around the tip of the crack. In other words, detected ELE on the specimen surface can be considered as the "sound" of a far "explosion", consequently the energy determined from the measured global level is greatly lower than the actual energy released in the proximity of the crack.
Considering the propagating crack tip as a supersonic event, the atomic bonds are necessarily broken too fast to be compensated by the specimen elasticity, and an instantaneous "hyper-compaction" of atomic planes can occur. What could happen to the material close to the tip of supersonic propagating crack? Several hypothesis can be expressed.
The pressure produced on the fracture surfaces by this "hyper-compaction" (and the relative "hyper-rarefaction") of the atomic planes, could probably generate analogous phenomena such as Prandl-Glauert singularity. Moreover, a significant increasing and sudden decreasing of local temperature gradients can occur, such as in cavitation phenomena in liquids. The atomic planes at rest around the tip are hit by "hyper-compacted" front waves, such as in a sonic boom effect, which may induce a kind of perturbation in the molecular and/or atomic vibrational modes (1 THz)

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