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Cracking and crackling in concrete-like materials: A dynamic energy balance

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An analysis of the Acoustic Emission (AE) activity and of the energy fields is carried out with reference to three-point bending (TPB) tests on concrete beams with different sizes. First, a cracking mode classification is performed on the basis of AE parameters like the average frequency and the rise angle of the waveforms. A compression test is also performed to verify if the identification of the fracture mode by means of the AE parameters is appropriate. Then, regarding the TPB tests, the fracture energy (dissipated) and the energy detected by the AE sensors (emitted) per unit of fracture surface are compared. The former energy increases with the specimen size whereas the latter one decreases. Therefore, a direct relation cannot be established between the two forms of energy, although an indirect relationship is given by the fact that their sum corresponds to the total energy released during the test.

1. Introduction

The Acoustic Emission (AE) technique is currently used during experimental tests to investigate on the damage evolution in ductile or brittle materials before the final failure [1,2]. The spatio-temporal evolution of ultrasonic AE signals, also known as "*crackling noise*" when they occur in the audible field, is a direct result of cracking bonds during the fracture of materials. The AE time-series are characterized by silent intervals separated by events of varying length and amplitude, that involve the emission of different energy levels. For these reasons, this non-destructive monitoring method is useful for studying the critical phenomena and to predict the durability and remaining life-time in full-scale structures [3,4].

According to this technique, it is possible to detect the transient elastic waves related to each stress-induced crack propagation event inside a material. These waves can be captured and recorded by transducers applied on the surface of specimens or structural elements. The transducers are piezoelectric sensors that transform the energy of the elastic waves into electric signals. A suitable analysis of the AE waveform parameters (peak amplitude, duration time and frequency) permits to obtain a detailed information about the damage evolution, such as the cracking pattern, the released energy, the prevalent fracture mode, and the achievement of the critical conditions that anticipate the collapse. The last analysis can be performed by calculating the *b*-value from the Gutenberg-Richter (GR) law. Even though two different dimensional scales are involved, the GR law can be applied in the same way for earthquake distributions in seismic areas as well as for the structural monitoring by the AE technique [5–7].

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The connection between fracture mode and recorded waves depends on different factors like geometric conditions, relative orientations, and propagation distances [8]. The identification of the cracking mode may be done with the AE wave's rise time (which is the time interval between the wave onset and its maximum amplitude), the value of the peak amplitude, and the Average Frequency (AF). The ratio between the rise time (expressed in ms) and the peak amplitude (expressed in V) defines the Rise Angle (RA), as shown in Fig. 1 [9–11]. The peak amplitude can be also expressed in dB by the equation:

$$A\,[\mathrm{dB}] = 20 \cdot \mathrm{Log}_{10}\left(\frac{V}{V_0}\right), \tag{1}$$

where V is the amplitude of the signal in volt, and V_0 is the maximum amplitude of the background noise.

The AF, measured in kHz, is obtained from the AE ring-down count divided by the duration time of the signal. The AE ring-down count corresponds to the number of threshold crossings within the signal duration time [9–11].

The fracture mode is then characterized by the shape of the AE waveforms: low RAs and high AFs are typical for tensile crack propagations which consist in opposite movements of the crack surfaces (Mode I), whereas shear events (Mode II) usually generate longer waveforms, with higher RAs and lower AFs, as shown in Fig. 1 [12–15]. Variations in the RA and AF values during the loading process identify a change in the prevalent failure mode of the specimen.

In general, a decrease in frequency might be also caused by the formation of large cracks during both tensile and shearing processes. In fact, it is reasonable to assume that high frequency waves are generate from small discontinuities, that characterize the beginning of the damage process, whereas low frequency ones can be produced only from large cracks, that usually develop during the final collapse [16].

Another interesting feature of the AE signals is that they can give insights on the process of energy dissipation and emission during the loading process. In this context, experimental analyses have evidenced that the scaling of the cumulative number of AE events by varying the specimen dimension can be profitably used to determine the physical dimension of the damage domain in disordered materials. The total number of AE events at the end of the test in fact varies with the specimen size according to a power-law having a noninteger exponent that is directly related to the fractal character of the damage domain [3,17]. Alternatively, the characterization of the damage domain can be also obtained by means of a statistical analysis of the distribution of AE events in a single test [17]. From the viewpoint of energy dissipation and emission, the cumulative number of AE events and the energy content of the AE events are usually correlated to the mechanical energy dissipated during the complete failure process, namely fracture energy in tension and crushing energy in compression [18,19]. However, recent studies carried out by Carpinteri and co-workers focusing on the catastrophic failure of rock specimens in compression have suggested that such a correlation is not always correct [20]. In particular, it was evidenced that a large amount of AE activity takes place during the post-peak snap-back instability. The typical shape of the load vs. displacement curve, when the global unstable behavior is fully captured, e.g. by controlling the compression test by means of the circumferential expansion instead of the longitudinal deformation, is that shown in Fig. 2a. However, this very brittle mechanical response can be observed also under tension and bending loading conditions, when brittle materials are tested in large and/or slender specimens. The behavior shown in Fig. 2a is consequent to the fact that the energy dissipated through material damage is less than all the elastic energy stored in the body. In this case, the portion of energy that is not dissipated by material damage (area E in Fig. 2a) is abruptly emitted leading to dynamic vibrations, with propagation of elastic waves. Of course, this portion of energy will be also dissipated, although through material viscosity, impacts of fragments, and heat. From the diagram in Fig. 2a, therefore, three different energy components can be distinguished: the energy dissipated by material damage (gray area), the surplus of elastic energy with respect to the dissipated one (red[1] dashed area), and the total released energy, which is the sum of the two previous areas. When a catastrophic failure occurs, the AE energy seems to be correlated to the surplus of elastic energy [20]. Accordingly, such an energy component can be referred to as emitted energy.

Certainly, global snap-back instabilities take place only under specific conditions (large sizes and slendernesses, and/or brittle materials), whereas in most of the cases a more stable response, represented by a softening behavior, is obtained. However, even in such cases, local discontinuities, which are an indication of snap-back or snap-through instabilities, are usually noticed in heterogeneous materials such as aggregative and fiber-reinforced materials. Such local phenomena, that are evident at a microscale level, are due to the fact that cracks grow in a discontinuous manner, with sudden propagations and arrests due to the bridging action of the secondary phases as well as by the rise and coalescence of microcracks in the process zone [21,22]. A load–displacement curve representative of a global softening behavior perturbed by multiple local instabilities is shown in Fig. 2b. Each drop in the load carrying capacity occurring in the post-peak phase is related to a sudden crack propagation due, for instance, to the rupture of a reinforcing fiber. Then, the load carrying capacity is partially recovered following a path with a reduced stiffness. From the energetic point of view, each local instability is due to the emission of a surplus of elastic energy, which is not dissipated by the material damage (dashed areas in Fig. 2b). This emitted energy can be detected by the AE sensors.

In the present paper, the AE parameters acquired during three-point bending tests on notched concrete beams and a compression test on a cylindrical specimen are analyzed. These analyses are performed in order to identify the dominant fracture mode and to investigate on the evolution of the released, dissipated and emitted energies during the test and on their mutual correlations. The released energy is the total elastic energy stored in the body during loading and discharged by the cracking

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[1] For interpretation of color in Figs. 2 and 18, the reader is referred to the web version of this article.