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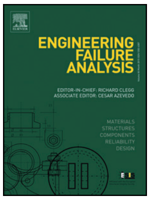

Damage process in heterogeneous materials analyzed by a lattice model simulation

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ABSTRACT

Several materials of technological interest could be considered as heterogeneous and their random nature can be accounted to be the cause of the nonlinear behavior. The quantitative evaluation of damage in materials subjected to stress or strain states has great importance due to the critical character of these phenomena, which, at a certain point, may suddenly give rise to catastrophic failure. In previous studies, Carpinteri and his coworkers have presented different aspects of the damage process characterization in heterogeneous materials. Three of these aspects demand our attention: (i) the brittleness number to measure the brittleness level of the structure under investigation; (ii) the fractal dimension in which the damage process develops; and (iii) the global indexes obtained for the Acoustic Emission (AE) analysis. In the present work, a version of the discrete element method formed by bars is used to explore these concepts. A set of quasi-brittle material specimens is simulated and, when it is possible, the numerical results are compared with experimental data. Moreover, a discussion of the obtained results aids to better understand the behavior of this kind of materials, describing the numerical method as a viable tool to extract information from experimental tests on the damage process.

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1. Introduction

The process of damage in structures is a main topic in the solid mechanic area. Originally it was analyzed by Kachanov [1] and then by Lemaitre [2], they are considered among the most important researchers that proposed models of damage suitable to be applied with success, mainly in ductile material. This approach was used not only in metals but also in other kind of materials characterized by non-linear damage such as rubbers and others plastic with hyperelastic behavior [3–5].

Heterogeneous materials constitute a very large part of our natural environment as well as a substantial fraction of man-made objects: glasses, polymers and amorphous materials are among the vast array of examples [6]. On a larger scale, porous media, composites and suspensions can be also mentioned. The characterization of damage in this kind of materials is often governed by more than a single crack. The studies of a set of small fractures interacting at different scale levels have great importance to understand and simulate the behavior of these materials. Accounting each individual crack in the heterogeneous materials, assessing its influence on the structural response and ultimately on the structural failure, is not a task that can be approached using conventional methods of analysis in solid mechanics [7]. In this kind of materials, in which scale effects, anisotropic damage, and associative behavior among defects are likely to occur, the methods where the possibility to naturally represent the discontinuity could be an alternative. Among these methods, it is possible to include a version of the lattice method used in the present work. In several works developed by Carpinteri, concepts and models to analyze this kind of materials have been developed, some of them are discussed below.

1.1. The concept of brittleness number

It is known that the structural brittleness is related to the susceptibility of fractures to propagate in unstable condition. The structural brittleness can be measured by the material toughness and its interaction with the plastic collapse mechanisms. Another aspect that plays a very important role is the characteristic dimension of the structure. Carpinteri [8] proposed a dimensionless parameter, the brittleness number s, that allows to measure the structural fragility,

$$s = \frac{K_c}{\sigma_p R^{1/2}}, \tag{1}$$

where K_c represents the material toughness in terms of the critical stress-intensity factor, σ_p represents the yield stress, and R is a characteristic dimension of the structure. This number was used in several publications in the last three decades. Among others, it could mention its applications in the biomechanical field [9].

1.2. Acoustic Emission techniques: relation between the b-value and the damage process evolution in heterogeneous materials

A promising method for a non-destructive quantitative evaluation of damage is the Acoustic Emission (AE) technique [10]. Physically, AE is a phenomenon caused by a structural alteration in a solid material, in which transient elastic-waves due to a rapid release of strain energy are generated. AE's are also known as stress-wave emissions.

AE waves, whose frequencies typically range from kHz to MHz, propagate through the material towards the surface of the structural element, where they can be detected by sensors which turn the released strain energy packages into electrical signals [10–18]. Traditionally in AE testing, a number of parameters are recorded from the signals, such as arrival time, velocity, amplitude, duration, and frequency. From these parameters, damage conditions and localization of AE sources in the specimens could be determined [19].

Using the AE technique, an effective damage assessment criterion is provided by the statistical analysis of the amplitude distribution of the AE signals generated by growing microcracks. The amplitudes of such signals are distributed according to the Gutenberg-Richter (GR) law [11,20] $N(\geq A) \propto A^{-b}$, where N is the number of AE signals with amplitude $\geq A$. The exponent b of the GR law, the so-called b-value, changes with the different stages of damage growth. While the initially dominant microcracking generates a large number of low-amplitude AE signals, the subsequent macrocracking generates more signals of higher amplitude. As a result, the b-value progressively decreases when the damage in the specimen advances: this is the core of the so-called "b-value analysis" used for damage assessment.

On the other hand, the damage process is also characterized by a progressive localization identified through the fractal dimension D of the damaged domain. It may be proved that $2b = D$ [21–23]. Therefore, by determining the b-value, it becomes possible to identify the energy release modalities in a structural element during the AE monitoring. In the theoretical extreme case $D = 3.0$, which corresponds to $b = 1.5$, a critical condition in which the energy release takes place through small defects distributed throughout the volume. For $D = 2.0$, which corresponds to $b = 1.0$, the energy release takes place on a fracture surface. In the former case, diffused damage is observed, whereas in the latter case two-dimensional macrocracks are formed leading to the