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Numerical DEM simulation of AE in plate fracture and analogy with the frequency of seismic events in SCRs

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ABSTRACT

The present paper examines, by Monte Carlo simulation employing the Discrete Element Method (DEM), the occurrence of micro-fractures and the evolution of damage, as cracks coalesce in large fractures, in a plate subjected to increasing stress. Numerical simulations results which in previous studies predicted successfully acoustic emission (AE) in laboratory samples, are compatible with the conclusions of the assessment of instrumental data in a Stable Continental Regions (SCR). The locations of AE sources, correlated with the growth of a diagonal fracture in the plate, are numerically determined. Seismic activity, on the other hand, is higher along inter-plate boundaries, decreasing in intra-plate regions (SCR) where it's prediction for engineering purposes presents great difficulties. The authors examined, in previous papers, instrumental seismic data for a 1200 km square region in the South American SCR, showing that the distribution of amplitudes *is not exponential*, as implicitly assumed in the Gutenberg-Richter law, and also that the largest events *do not occur according to the distribution of small events*. These contentions are also applicable to the numerical simulations described in the paper, illustrating similarity between the distributions of simulated AE events in the plate and seismic activity within a SCR.

1. Introduction

Seismic activity is higher along the boundaries of continental plates, decreasing towards the interior of the so-called *intra-plate* regions. In the latter, also designated *Stable Continental Regions* (SCR), the largest events rarely exceed $M_w \approx 7$. The prediction, for engineering purposes, of future seismic risk in intra-plate regions is difficult, due to the scarce instrumental evidence available. Consequently, it led to intense research on the subject, resulting, for instance, in EPRI Reports [1, 2] and to the consolidation of the notion of SCR. Also, the identification of seismic sources is necessarily affected by large uncertainties. As a consequence, the diffuse seismicity model is usually adopted. Criteria to accept or reject such assumption is examined by Riera & Iturrioz [3], following a previous contribution of Beauval et al. [4].

The diffuse seismicity model justifies the adoption of a Poisson process to describe the occurrence in time of seismic events in a SCR. Now, if in addition the probability distribution of seismic events magnitudes in the region is *an exponential distribution*, the Gutenberg-Richter (G-R) law results. In such case, the annual frequency of occurrence of seismic events in the region, with magnitudes larger than M, is a decreasing linear function of M which is usually a poor approximation to observed seismic data. In a previous paper [3], instrumental data is examined from a 1200 km sides square region within the South American SCR, showing that the distribution of observed magnitudes *is not exponential*. A Weibull (type III, minimum) function satisfactorily fits the data and,

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since the exponent is different than 1.00, it led to a relation that differs from the G-R law and does not require the introduction of an artificial cut-off magnitude or a transition curve.

On the other hand, recent developments in Solid Mechanics allowed the prediction of fracture processes in heterogeneous quasi-brittle materials subject to increasing applied load, including robust predictions of the process of *damage localization*. With such purpose, the authors applied a model consisting of nodal masses linked by non-linear axial elements in an orthotropic 3D arrangement that belongs to the group of *Discrete Element Methods* – (DEM). The approach was originally suggested by Riera [5] for the determination of fracture of concrete plates subjected to impact and later employed in various applications, as the prediction of motion in the vicinity of a fault during fracture propagation [6]. Similar 2D and 3D models were proposed by other authors [7].

Acoustic Emission (AE) techniques constitute an approach to monitor the process of damage in structural systems and have, therefore, found numerous applications in Civil, Mechanical, Aeronautical and other engineering branches. Acoustic Emission refers to the process in which micro fractures in the interior of a structural system causes elastic waves to propagate through the system and are, thus, susceptible to detection by means of sensors, usually located on free surfaces [8]. AE events typically produces waves with frequencies in a range between 1 kHz and 1 MHz and amplitudes that depend either on the amount of energy liberated and the distance from the fracture to the sensor. The distribution of the amplitudes of AE signals in simulated DEM tests are examined in this paper. Various models, such as the G-R law previously mentioned, have been used for this purpose, as discussed for instance by Colombo et al. [9], Shiotani et al. [10], Carpinteri et al. [11]. The DEM numerical AE predictions as well as available instrumental evidence of seismic data suggests that the hypothesis of a uniform distribution of AE or seismic sources that justifies the Poisson process model, is valid only at the beginning of the process and applicable until *damage localization* takes place. Afterwards, larger amplitude events along the damage localization regions tend to occur at more regular intervals, as observed by Krajcinovic et al. [7] and Riera & Iturrioz [12]. These considerations lead to the conclusion that AE or seismic events of large magnitude cannot be predicted on the basis of records of small magnitude events.

2. The DEM in fracture analysis of quasi-brittle materials

The DEM version employed herein was proposed by Riera [5]. In this formulation, the solid under consideration is substituted by discrete nodal masses, linked by uniaxial elements (bars) with arbitrary constitutive relations, disposed in a three dimensional array. The cubic basic cell, formed by 20 elements and 9 nodes, shown in Fig. 1(a) and (b), is selected in order to determine the initial elastic stiffness of the longitudinal and diagonal elements to satisfy the properties of an orthotropic elastic material. Each nodal point has three degrees of freedom, in correspondence to the displacements in a global coordinate system.

The equations that relate the initial stiffness of the DEM elements with the elastic constants of a linear elastic and isotropic solid are:

$$EA_n = EL^2 \frac{9 + 8\delta}{2(9 + 12\delta)}, \qquad EA_d = \left(\frac{2\sqrt{3}}{3}\right) A_n, \qquad \delta = \frac{9\nu}{4 - 8\nu}, \tag{1}$$

where E and ν denote the local values of Young's modulus and Poisson's coefficient, respectively, while A_n and A_d denote the cross-sectional areas of longitudinal and diagonal elements and, L is the basic cubic length (Fig. 1a). Note that in the analysis of heterogeneous materials, such as concrete, material properties, as E or its specific mass, may be assumed 3D random fields without additional theoretical or numerical difficulties. The equations of motion can be written in the form:

$$\mathbf{M}\ddot{\mathbf{x}}(t) + \mathbf{C}\dot{\mathbf{x}}(t) + \mathbf{F}(t) - \mathbf{P}(t) = \mathbf{0}, \tag{2}$$

where the vectors $\ddot{\mathbf{x}}(t)$ and $\dot{\mathbf{x}}(t)$ represents respectively the nodal accelerations and velocities; $\mathbf{F}(t)$ the of internal forces acting on nodal masses and $\mathbf{P}(t)$ the external nodal forces vector; $\mathbf{M}$ and $\mathbf{C}$ are the mass and damping matrices, respectively. Since $\mathbf{M}$ and $\mathbf{C}$ are diagonal matrices, the equations are uncoupled and any explicit integration scheme may be used to. Moreover, since the global nodal coordinates are updated at every time increment, large displacements are accounted for without additional computational effort. Rocha et al. [13] employed the DEM approach to determine the response of quasi-brittle materials assuming the bi-linear law shown in Fig. 1(c). Note that when the specific fracture energy G_f, proportional to the area of triangle OAP, is exceeded, the element can no

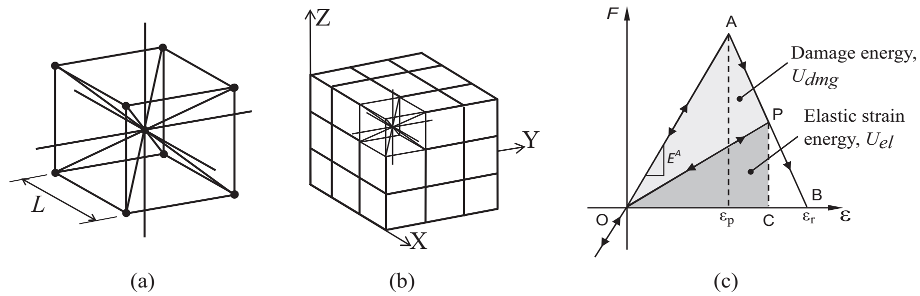

Fig. 1. Cubic array adopted in DEM formulation: (a) Basic cubic cell, (b) DEM representation of a prismatic body and (c) Load-displacement law of DEM elements.