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# Experimental analysis and truss-like discrete element model simulation of concrete specimens under uniaxial compression

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ABSTRACT

In this work, the Acoustic Emission signals were captured by sensors applied to the external surfaces of a prismatic concrete specimen subjected to compression loads. In this context, the experimental results are presented in terms of stress–time diagram and also, the variation in the Gutenberg–Richter law, that is, the relation proposed between the Acoustic Emission cumulative counts and its magnitude. This law is obtained during each phase of the test and in the final stage.

A three-dimensional lattice model, known as truss-like Discrete Element Method, also modeled the same specimen. The numerical results present a good correlation with those obtained from the experimental test also in terms of typical Acoustic Emission parameters, such as count rate, cumulative counts, and the variation in the Gutenberg–Richter law.

Using the truss-like discrete element model, the relationship between the Acoustic Emission signal magnitude and the energy released from each localized rupture has also been analyzed. The obtained results are compatible with the Gutenberg–Richter energy–magnitude relation. Finally, the numerical results have been analyzed in terms of Acoustic Emission signal frequency. The simulation presents the same pattern with the experimental results: a shift towards lower Acoustic Emission signal frequencies during the evolution of the damage process.



## 1. Introduction

From a physical point of view, the phenomenon of damage can be seen as surface discontinuities in the form of cracks, or volume discontinuities in the form of cavities [1,2]. Since the size of cracks or interior defects cannot be identified, it is very difficult to macroscopically distinguish a highly damaged element from an undamaged one. Therefore, it becomes necessary to define internal variables, which are directly accessible to measurement, in order to represent the deteriorated state of the material [1–3].

An advanced method for the quantitative non-destructive evaluation of damage progression is the Acoustic Emission (AE) technique. Physically, AE is a phenomenon caused by the structural alteration of a solid material, in which transient elastic-waves are generated due to a rapid release of strain energy. AEs are also known as stress-wave emissions. AE waves, whose frequencies usually range from kHz to MHz, propagate through the material towards the surface of the structural element, then, sensors, which turn the released strain energy packages into electrical signals [4–13], can detect them. In the present study, USAM resonant sensors (accepting signals from 50 to 800 kHz frequency range) have been used, since concrete strongly attenuates emissions and high sensitivity is required [9,10,13]. Traditionally, in AE testing, a number of parameters,

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**Nomenclature**

| | |
|---|---|
| $A$ | Acoustic Emission (AE) amplitude |
| $N(\geqslant A)$ | number of Acoustic Emission (AE) signals with amplitude $\geqslant A$ |
| $D$ | fractal dimension |
| $E_r$ | energy released during an earthquake or Acoustic Emission event |
| $m$ | Acoustic Emission amplitude $A$ in logarithm scale ($m = \text{Log}_{10}A$) |
| $b$ | called "$b$-value", is the negative slope of the Log$N(\geqslant A)$ vs. $m$ relation |
| $g$ | coordinate in the origin in the Log$N$ vs. $m$ diagram |
| $N(\geqslant E_r)$ | number of events with value $\geqslant \text{Log}E_r$ |
| $\alpha$ | adjustment coefficients in the Log$N(\geqslant \text{Log}E_r)$ vs. Log$E_r$ relation |
| $\omega$ | adjustment coefficients in the Log$E_r$ vs. Log$A$ relation |
| $\Delta$ | increment |
| $E_e$ | elastic energy stored in the body during the fracture process |
| $E_d$ | energy dissipated in the fracture process |
| $E_k$ | kinetic energy evaluated during the fracture process |
| $L$ | length of the side of the cubic module in the lattice model used |
| $A_l$ and $A_d$ | cross-sectional areas of the longitudinal and diagonal elements respectively in the lattice model used |
| $\phi$, $\eta$ | coefficients that let to compute the transversal area of the elements and the length $L$ |
| $\nu$ | the Poisson's ratio |
| $\mathbf{x}$, $\dot{\mathbf{x}}$ and $\ddot{\mathbf{x}}$ | vectors that contain the nodal displacements, velocities and accelerations, respectively |
| **M** and **C** | mass and damping matrices |
| $F_r(t)$ and $\mathbf{P}(t)$ | the internal and external nodal load vectors |
| $t$ | time |
| $C_p$ | propagation velocity of longitudinal waves |
| $E$ | the longitudinal elastic module |
| S | fracture area of a solid cube of side $L$ |
| $F$ | elemental axial force in truss-like discrete element model |
| $\varepsilon$ | strain |
| $\vartheta$ | energy dissipated by the fracturing process of a solid cube, due to a crack parallel to one of its faces |
| $G_f$ | specific fracture energy |
| $A_i^*$ | equivalent fracture area of each element is defined in order to satisfy the condition that the energies dissipated by fracture of the continuum and by its discrete representation are equivalent. ($i = l$ indicates a longitudinal bars, $i$:$d$ indicates diagonal bars) |
| $\varepsilon_p$ | critical failure strain defined as the largest strain attained by the element before the initiation of damage |
| $\varepsilon_r$ | limit strain, where the element loses its load carrying capacity |
| $R_f$ | failure factor, which may account for the presence of an intrinsic defect of size $a$ |
| $a$ | the intrinsic defect of size into the element in the lattice model |
| $Y$ | dimensionless parameter that depends on both the specimen and crack geometry |
| $K_r$ | failure coefficient that relates the critical strain $\varepsilon_p$ with the limit strain $\varepsilon_r$ ($\varepsilon_r = K_r\varepsilon_p$) |
| $L_{cr}$ | value of the elemental length $L$ when $K_r = 1$ |
| $\beta$ and $\gamma$ | scale and shape parameters in the Weibull distribution function |
| $\Omega$ | Weibull type probability distribution function |
| $\Gamma(x)$ | Gamma function |
| $\mu$ | mean value |
| $s$ | standard deviation |
| $u$ | random number with a uniform probability distribution in the [0,1] interval |
| $CV$ | coefficient of variation |
| $P_{max}$ | maximum value reached by the load |
| $\delta_r$ | displacement when the rupture takes place |
| $h$ | value of acceleration computed in the numerical simulation |
| $h_o$ | reference value of acceleration computed in the numerical simulation that let to normalize the magnitude of the AE events obtained numerically |
| $A_{thres}$ | relative AE magnitude threshold considered in the compute of the $b$-values using the results obtained in the simulation |
| $N_{\text{inst}}$ | rate of the AE events |
| $t_f$ | time when the collapse takes place |
| $E_k(t_i)$, $E_d(t_i)$ | kinetic and damaged energy during the simulation measured in specific time $t_i$ |
| $t_F$ | instant at which the typical drop in the potential energy occurs during the simulation process |
| $t_{Fa}$ and $t_{Fb}$ | times in which the potential energy drops during the simulation |
| $\chi$, $\lambda$, $\theta$, $\tau$ | adjusting coefficients |