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Acoustic emission energy *b*-value for local damage evaluation in reinforced concrete structures subjected to seismic loadings

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ABSTRACT

A modification of the original *b*-value (Gutenberg-Richter parameter) is proposed to evaluate local damage of reinforced concrete structures subjected to dynamical loads via the acoustic emission (AE) method. The modification, shortly called energy *b*-value, is based on the use of the true energy of the AE signals instead of its peak amplitude, traditionally used for the calculation of *b*-value. The proposal is physically supported by the strong correlation between the plastic strain energy dissipated by the specimen and the true energy of the AE signals released during its deformation and cracking process, previously demonstrated by the authors in several publications. AE data analysis consisted in the use of guard sensors and the Continuous Wavelet Transform in order to separate primary and secondary emissions as much as possible according to particular frequency bands. The approach has been experimentally applied to the AE signals coming from a scaled reinforced concrete frame structure, which was subjected to sequential seismic loads of incremental acceleration peak by means of a 3×3 m^2 shaking table. For this specimen two beam-column connections—one exterior and one interior—were instrumented with wide band low frequency sensors properly attached on the structure. Evolution of the energy *b*-value along the loading process accompanies the evolution of the severe damage at the critical regions of the structure (beam-column connections), thus making promising its use for structural health monitoring purposes.

1. Introduction

Reinforced Concrete (RC) structures located in earthquake-prone areas are susceptible to damage caused by the dynamical loading induced by ground shaking during seismic events. Moderate tremors, which could occur several times during the lifetime of a structure, may produce damage of the concrete in the form of cracking. The assessment of damage is a prerequisite in deciding intervention to a given structure after a seismic event.

According to most current seismic codes [1,2], ordinary RC frame structures are designed to withstand severe damage (but without collapse) the so called “seismic design” associated with a mean return period of about 475 years. So, the

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code-compliant structure is furthermore expected to withstand, with minor or light damage, moderate ground motions that could occur several times during its life time. Minor or light damage in RC structures means concrete cracking; severe damage is accompanied by plastic deformations in the steel reinforcing bars. In any case, seismic codes assume that moderate or severe ground motions will inevitably produce some damage in conventional RC frame structures.

To enhance the overall energy dissipation capacity of the RC frame and to prevent structure collapse, current codes also prescribe that damage (i.e. concrete cracking and plastic strain in reinforcing steel) must be concentrated at the ends of beams and the bases of columns of the first story. The damage of beams and columns is predominantly concentrated around the so-called plastic hinges. Plastic hinges are the zones of the RC members where plastic deformations localize, usually close to the regions of maximum bending moment. The formation and development of a plastic hinge involves concrete cracking and plastic deformations of concrete and steel reinforcement. Micro-cracking in concrete initiates in the highly stressed regions when the tensile stress exceeds the tensile strength of the material, and it results in a stress transfer from concrete to steel and the activation of the later. As the external load increases, cracks propagate and grow forming macro-cracks, involving complex mechanisms that include internal friction between the surface of the steel and the surrounding concrete [3] and the yielding of the former. The emerging elastic waves and the corresponding AE waveforms provide then information about these processes. The above mentioned behavior of code-compliant RC frame structures was recently assessed experimentally through shaking table tests by some of the authors [4,5]. Determining quantitatively, through nondestructive techniques, the level of damage in a structure after a moderate or severe earthquake is of foremost importance when assessing whether the activity of a building must be interrupted, and to determine the level of seismic retrofitting required.

The importance of condition monitoring of concrete structures has been widely stated. One of the most relevant technologies used for real time diagnosis of structures, in nondestructive conditions, is the acoustic emission method (AE) [6–8]. AE technology is similar to seismology except AE is in the scale of engineered structures and in a different frequency range. Seismic phenomena occur on low frequencies (0–40 Hz) while AE operates on high frequencies (commonly from 20 kHz to 1 MHz). This governs the applicability of sensors involved. AE is constituted by elastic waves generated by the sudden internal stress–strain field redistribution in materials or structures when external load is applied. This occurs in crack initiation and growth, crack opening and closure, deformation, dislocation movement, void formation, interfacial failure, corrosion, fibre–matrix debonding in composites, etc. These waves propagate through the material and eventually reach the surface, producing small temporary surface displacements. The elastic waves are of low amplitude and of high frequency, normally ultrasonic. Sources of AE are commonly related with damage. Thus, its detection and analysis can be used to evaluate the behavior of the material under load conditions and so, to predict its failure. AE signals are bursts with a high frequency range, non-stationary and with very low amplitude. Traditional AE methods performed a parameter-based analysis (amplitude, duration, rise-time, RMS-root mean squared). Contrarily, actual quantitative AE methods deal with the waveform and the wave propagation inside the material and/or the signal processing of the recorded data by means of advanced techniques such as the Wavelet Transform (WT) which is used in the present paper [9–11].

The success of the application of the method of AE lies basically in making a correct implementation of two important aspects during data analysis (AE signals): (1) correctly extract the data providing useful information, i.e. separate the genuine AE produced by concrete cracking (primary sources) and that produced by other secondary sources; (2) define and verify reliable criteria and indexes (damage indexes) to make a correct evaluation of the accumulated damage in the structure. Many AE signal features and criteria have been proposed to address both challenges. Signal amplitude, duration, rise-time, number of counts, number of AE signals, and others are the classical AE features extensively studied and applied for these purposes. Other combinations, like angle ratio (RA) and the average frequency (AF) have been widely used for classification of cracking modes in concrete, reporting a successful separation between tensile and shear cracks [12–16].

Several evaluation criteria have been based on the Kaiser effect, i.e. the absence of detectable AE until previously applied load stress levels are exceeded. The lack of this physical phenomenon has been considered as a damage indicator [8,17]. Other evaluation criteria are based on the use of the relaxation ratio analysis of the AE signals, the calm and load ratios and the severity and historic indices [18–21].

One of the most used features is the signal AE peak amplitude, typically quantified in AE decibels. The traditional *b*-value, calculated from amplitude distribution AE data, has been proved as a good indicator of the level of damage of RC structures. This is computed on the basis of the power-law relation between the number of events surpassing a given amplitude, and the amplitude of these events. This relationship is commonly known as Gutenberg-Richter [22]. It has been successfully applied for assessing the damage of reinforced concrete beams subjected to cyclic loading [23,24], health monitoring of retrofitted RC structures [25] and to evaluate cracks in concrete and cement mortar [26]; these studies suggest a limit *b*-value that determines the transition from micro-crack growth to macro-crack formation in concrete. Shiotani and collaborators incorporated statistical values of amplitude distribution analysis and defined the so-called improved *b*-value (*ib*-value) [19,27–31]. Most of the papers have applied this index to specimens subjected to static and quasi-static (cyclic) tests. However, few works have been reported about its application to dynamic earthquake-type loading [31].

Nevertheless, although peak amplitude is closely related to the magnitude of fracture, not many studies have investigated the implementation of AE energy to develop damage qualification procedures. It is reasonable to suggest that energy content in the AE signal is correlated with the plastic strain energy of the associated deformation [32]. Energy physically expresses severity (intensity) of an AE event, so it is expected that large crack growth will emit AE signals with high energy and micro-cracks growth will emit AE signals with low energy. It should be also noticed that the type of crack (tensile cracks, shear