A Novel Wavelet b-Value of Acoustic Emissions to Evaluate Local Damage in RC Frames Subjected to Earthquakes

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Abstract. The macroscopic fractures in concrete at a beam-column junction in a RC frame submitted to earthquake-type tests with the shaking table of the University of Granada (Spain) were assessed by the AE technique. The Continuous Wavelet Transform (CWT) was applied to the AE signals acquired in the junction zone, which allowed reconstructing the filtered signal corresponding to the scale-frequency band ascribed to concrete fracturing; thus the AE energy assigned to concrete damage could be evaluated. Novel *ib*- and *b*-values were defined and obtained from the CWT energy signals in the pertinent scale, which resulted as useful parameters for assessing local macroscopic concrete fracturing at the junction.

Introduction

The assessment of damage is an important issue in validating the seismic design codes for buildings searching to avoid local or global collapse under earthquakes [1]. According to Spanish code NCSE-02 [2], reinforced concrete (RC) moment resisting frames are designed with the strong column-weak beam criterion; structural damage is expected to occur basically in the plastic hinges. The AE technique has been applied to RC elements at the level of material (concrete) or individual elements (beams, columns) [3-8].

The AE signals recorded during seismic events are in general highly contaminated by noise coming from different sources: friction between different parts of the structure; hydraulic actuator; electronic noise; and even internal friction between the faces of the already existent macro- and micro-cracks. The different measures implemented to avoid such noise sources (secondary AE sources) are in general not sufficient. For this reason special signal post-processing techniques are necessary to extract pertinent information from the AE signals (primary AE sources).

In previous work [9], the frequency band (45-64 kHz) could be assigned to cracking processes in concrete, considering AE signals generated in a concrete slab subjected to simulated earthquakes. In the present work, the complex Morlet Continuous Wavelet Transform (CWT) [10] was applied to AE signals recorded during the test in search of detecting fractures of concrete at the beam-column junctions. The objective of the present study is to determine the *local* concrete fracturing level at the beam-column connections of an external pillar, specifically at the beam-column junction of column 3 (see Figure 1).

The amplitude of the AE signal is widely used for evaluating the appearance of macro cracks in brittle materials using the indices *b* and *ib* [11-13]. In the present work the AE Energy obtained through CWT allows defining new energy indices *b* and *ib* of damage dedicated to concrete macro fracturing.

1. Test Model, Seismic Simulation and Instrumentation

The tested specimen comes from a scaled prototype of a building located in the municipality of Granada and is fully described in [14] (see Figure 1). The NS component of the Campano- Lucano (Italy, 1980) event, recorded at the Calitri station was reproduced with the shaking table of the University of Granada, with a temporal scale λ= 0.41/2. Five seismic uniaxial dynamic simulation tests, named C50, C50B, C100, C200 and C300, with increasing peak acceleration were performed; the same accelerogram but with different acceleration scale factor of the Peak Acceleration (PA) was used in all tests (the factor was approximately 50%; 100%; 200% and 300% of the original; (see Table 1).

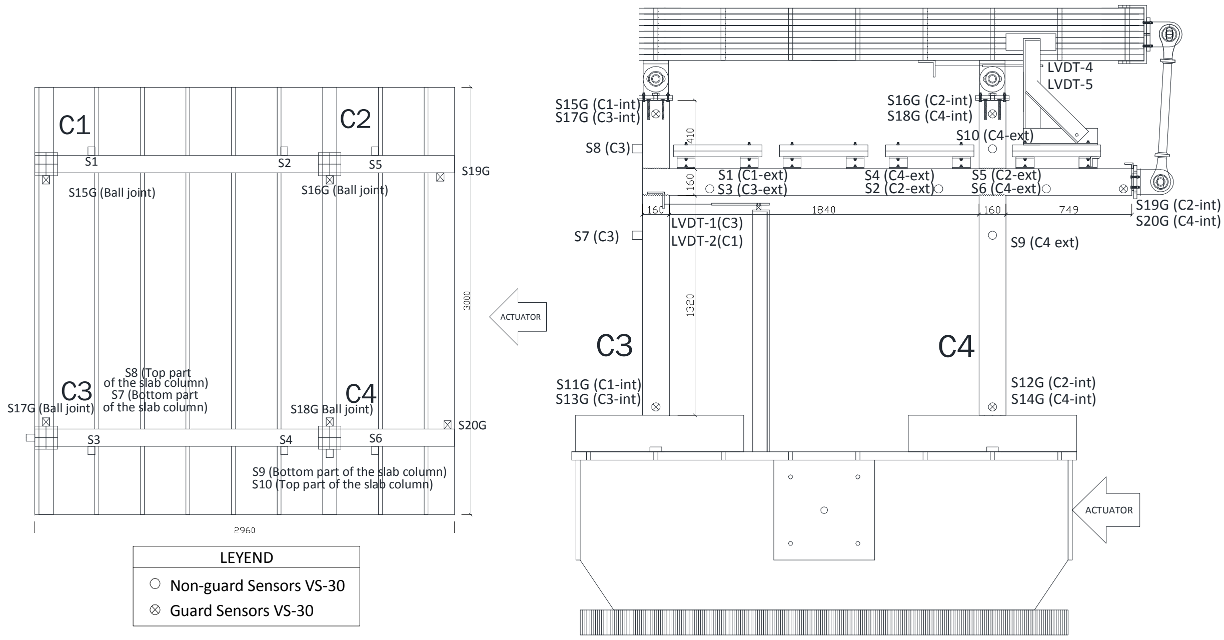


Fig. 1. Test model with AE sensor positions. Left: Plan (bottom view); right: Elevation

AE signals were acquired with a Vallen System ASMY-5. Twenty low frequency VS30 sensors (25-80 kHz) were placed on the tested model. Sampling frequency was 2.5 MHz, and the number of samples was 2048, which means one sample per 0.4 μs. The pre-trigger was of 200 samples, and the threshold was 50 dB. The electronic noise in the laboratory was measured and a calibration test for all the sensors was performed with the standard Hsu-Nielsen test following the standard EN 1330-9:2009. The filters used were in the (25-180 kHz) range. Before seismic simulations, identification and removal of undesirable mechanical noise sources as far as possible was carried out; the noise sources were prevented by means of guard sensors. During the acquisition 34 dB gain preamplifier was used in each channel.

Table 1. Loading history applied to the test model

Seismic Tests	PA (g)	Duration (s)
C50	0.110	50
C50B	0.083	50
C100	0.180	50
C200	0.345	50
C300	0.580	50

2. Procedure

2.1 Local Character of Measurements

The objective is to obtain information about local damage due to concrete fracturing in critical points of the structure through AE measurements; these are the plastic hinges located at the beam-column junctions. The software *Event Builder* of *Vallen Systeme* [15] based on the identification of the sensor firstly reached by the mechanical wave emerging from a particular event was used to ensure locality. Additional a RMS pre-filtering was added after the guard filtering in order to separate the AE continuous signals coming from the described noise sources.

2.2 The Amplitude b-Value as Indicator of Damage Intensity

The b value based on amplitude of signals was originally defined in seismology. The Gutenberg-Richter law expresses the relationship between the magnitude and the total number of earthquakes in any given region and time period of at least that magnitude. It is usually computed using the cumulative frequency-magnitude distribution data, i.e.

$$Log_{10}\, N(M) = a - bM, \tag{1}$$

where, N is the total number of earthquakes with magnitude higher than M, M being the amplitude of the earthquake in Richter scale (which is a logarithmic scale), a is an empirical constant and b is the b-value, which is around 1.

In AE, the b-value is widely used to evaluate fracture processes. The b-value changes systematically during the different stages of the failure process and hence can be used to estimate the failure development. High b-values are related to a large number of small amplitude AE hits, as those originated in micro-crack formation and slow crack growth. In contrast, low b-values indicate faster growing or unstable crack formation, and can be caused for instance by the breakage of concrete between the ribs of the reinforcing steel bars, or by a sudden increase in the width of the cracks. The usual formula in AE is given by

$$Log_{10}\, N(A_{dB}) = a - b\,\frac{A_{dB}}{20}, \tag{2}$$

2.3 AE Energy Obtained with the CWT

The wavelet transform is widely used to analyze time series that contain non-stationary power at many different scales (frequencies). The CWT of a function *f(t)* is defined as the integral transformation in Eq. (3) [10]

$$(Wf)(s,b) = \int_{-\infty}^{\infty} f(t)\,\overline{\psi_{s,b}(t)}\ dt\,, \qquad s \neq 0,\ \ with \quad \psi_{s,b}(t) = \frac{1}{\sqrt{|s|}}\psi\left(\frac{t-b}{s}\right), \tag{3}$$

where b is a time translation and s is a dilatation ($|s| > 1$), or a compression ($0 < |s| < 1$).

In order that $\psi(t)$ be “admissible” as a wavelet, this function must have a zero mean value and be localized both in time and frequency spaces. One example is the Morlet wavelet, consisting of a plane wave modulated by a Gaussian function, i.e. Eq. (4)

$$\psi(\eta) = \pi^{-\frac{1}{4}}\, e^{i\omega_0\eta} e^{-\eta^2/2}, \tag{4}$$

where ω_0 is a non-dimensional frequency, here taken as 6 in order to satisfy the admissibility condition.

The CWT of a discrete sequence $x(n\,\delta t)$ is defined as the convolution of $x(n\,\delta t)$ with a scaled and translated version of $\psi(t)$ given in Eq. (5)

$$(Wx)(s,n) = \sum_{m=0}^{N-1} x(m\,\delta t)\,\overline{\psi\left[\frac{(m-n)\delta t}{s}\right]}\ . \tag{5}$$

Once we calculated the CWT for each s and n we can reconstruct the original time series taking into account the non-orthogonal character of the employed basis. The reconstruction could be performed using a delta function. For a real time series Eq. (6) holds.

$$x_n = \frac{\delta j \, \delta t^{1/2}}{C_\delta \, \psi(0)} \sum_{j=0}^{J} \frac{\mathbb{R}\{(Wx)(s_j,n)\}}{{s_j}^{1/2}} \,, \quad (6)$$

where $\mathbb{R}$ is the real part, and index j corresponds to the scale $s_j = s_0 \, 2^{(j-1)\delta j}$, with $j=1,2,\ldots,J$, with $J = (\delta j)^{-1} log_2(N \, \delta t \, / \, s_0)$ and $s_0 = 2\delta t$. Factor C_δ =0.776 for the Morlet wavelet from the reconstruction of a δ function.

In a previous work, [9] the authors could identify the 45-64 kHz frequency band as the one assigned to concrete cracking. For calculating the AE Energy (AEE), the CWT of each AE signal was obtained, and by only using the coefficients corresponding to frequencies between 45 and 64 kHz, the filtered signal was reconstructed. We will see in the Results Section that the AEE of a reconstructed signal shows a bimodal distribution of peaks, with low (< 1000) and high (> 1000) AEE respectively. We can guess that the low energy group could be assigned to micro-cracking and the high energy group to macroscopic cracking. The AEE signals were then used to calculate novel wavelet energy *ib* and *b* values as will be explained in Section 3.

3. Results and discussion

3.1 Amplitude ib Values

Fig. 2 shows the amplitude *ib*-values obtained from signals that have passed the guard sensors and the RMS filter. It is possible to observe a downward trend as long as the load intensity increases in the successive tests. When the same analysis was intended for the reconstructed signals corresponding to the frequency band assigned to concrete cracking, that is to say, when the amplitude *ib* value was calculated with signals that passed the guard sensors and the wavelet filter, erratic results were obtained. A decreasing trend was expected for increasing load intensity.

The fact that the *ib*-values obtained from the amplitude of the signals reconstructed in the frequency band ascribed to fracture fail in describing the macro-cracking and micro-cracking along the tests could be due to the fact that the applied Morlet wavelet filter introduces a kind of amplitude smoothing process thus modifiyng the amplitude of intense signals. This could be due to the fact that the Morlet wavelet is non-orthogonal, thereby returning inaccurate absolute amplitudes. But as it is well known [10] the Morlet wavelet is very appropriate to extract characteristics of the signal such as the energy distribution in frequency bands. That is why correct results are obtained when dealing with energy signals (see Fig. 3).

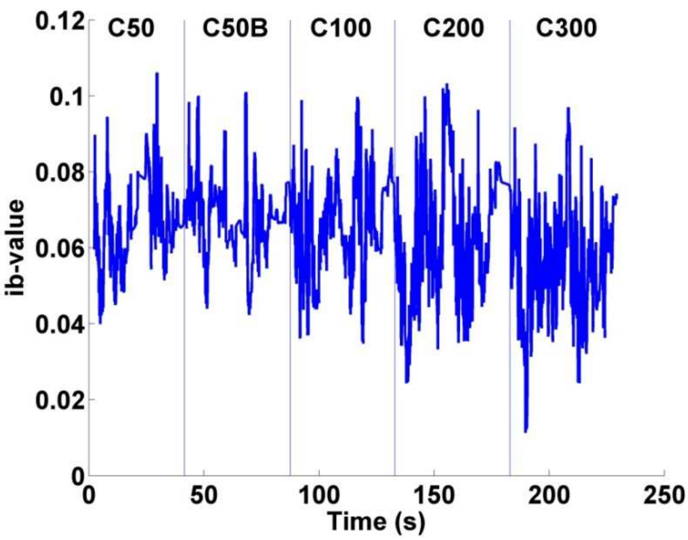


Fig. 2. *ib*_value calculated using the amplitude of signals that passed the guard and RMS filters

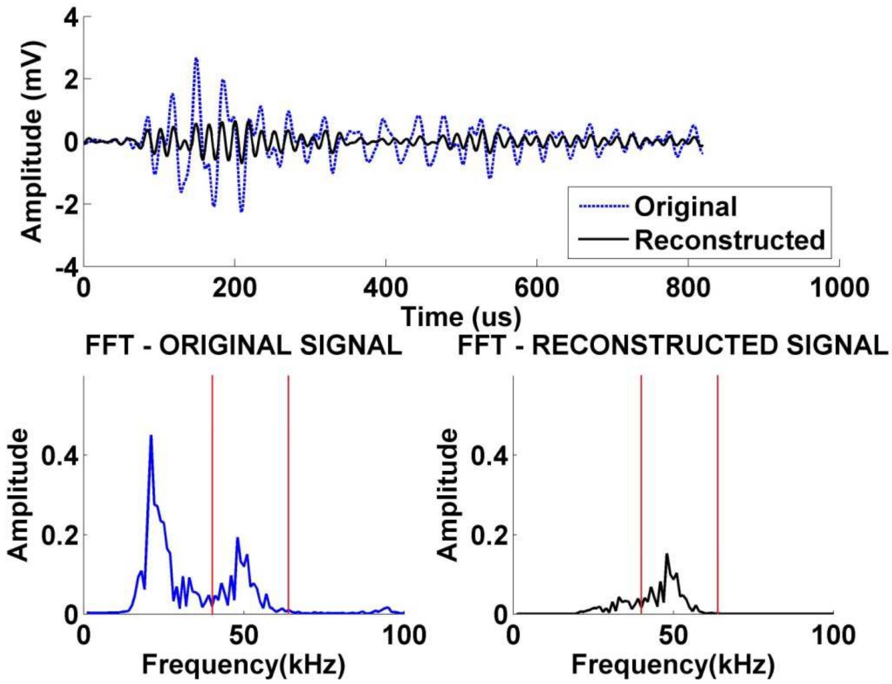
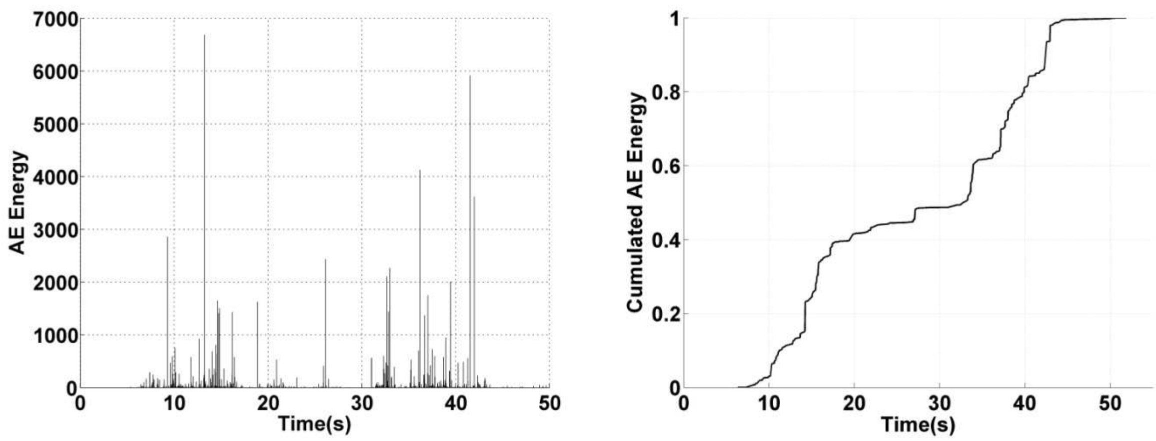


Fig. 3. Original signal and reconstructed signal in the 45-64 kHz band. Test C50B; exterior junction C3.

Fig. 3 shows the amplitude of the original signal and the reconstructed signal in the pertinent frequency band, corresponding to test C50B. The smoothing effect of the wavelet filter on amplitudes can be observed. Contrarily, the FFT of both signals in the pertinent frequency band are remarkably similar. This is a clue why correct results are obtained when we deal with wavelet energies instead of amplitudes of the reconstructed signals as is shown in Section 3.2.

3.2 Definition and Obtaining of Wavelet Energy ib and b-Values

Fig. 4 shows as an example the distribution of AEE for the test C50B. The cumulative AEE is shown for emphasizing clarity and the corresponding accelerogram is included for comparison. It can be observed that the AEE peaks are not uniformly distributed, but there are relatively many low amplitude peaks and relatively less high amplitude peaks. It is later shown in this section that these features become more evident as the damage level increases.



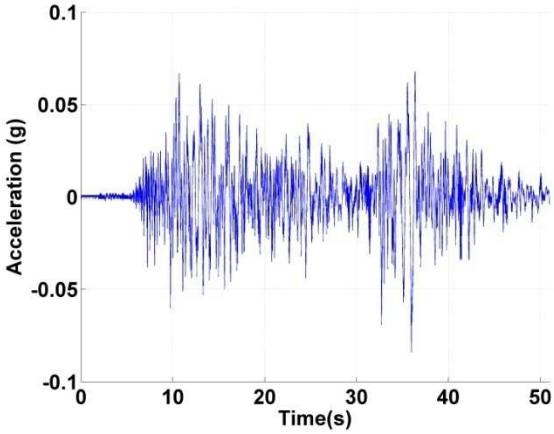
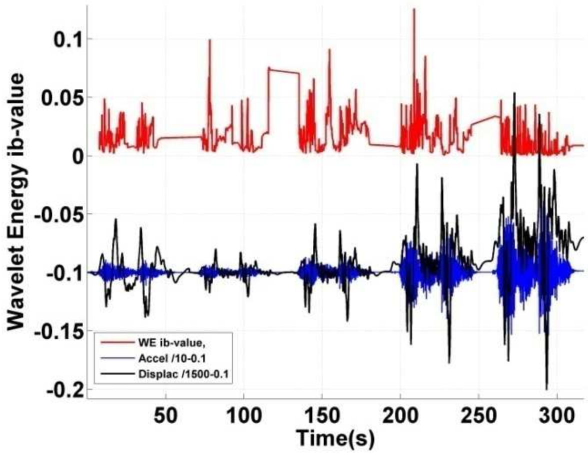


Fig. 4. Left: AE energy, in arbitrary units; Right: Cumulated AE Energy, normalized, for simulation C50B in an exterior junction C3 of the reconstructed signal; Bottom: Accelerogram of the shaking table.

The procedure of obtaining the *ib*-value was then applied to the energy signals, AEE, in order to circumvent the difficulties related with amplitude modification and searching for an *ib*-parameter obtained with the reconstructed signals not based on amplitudes. Results for the tests set are in Fig. 5.



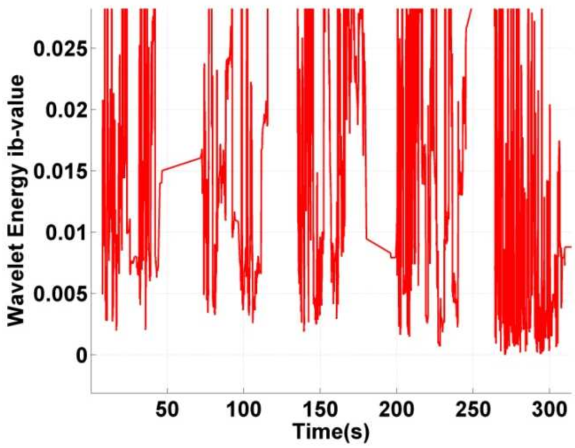


Fig. 5. *ib*_value calculated with the energy of the AE signals reconstructed with wavelet filter in the 45-64 kHz range. Acceleration and displacement of the shaking table are plotted below the wavelet energy *ib*-value. Right: Zoom of figure on the left.

It can be observed in Fig. 5 that the wavelet energy *ib*-values decrease as the load intensity increases. For these reasons, and following the definition of the *b*-value given in Eqs 1 and 2, we defined a new damage index obtained with the reconstructed AE signals after the application of the CWT filter. The new parameter was named as Wavelet Energy *b*-value (b_{WE}) and is given in Eq. 7.

$$Log_{10}\, N(AEE) = a - b_{WE}\, Log_{10}\,(AEE). \quad (7)$$

The AEE limits were between 3 and 4 for the seismic simulations C50B, C100, C200 and T300. These limits are determined taking the last linear branch that corresponds to the higher energies, as shown with the black crosses in Fig. 6, which are related to macroscopic cracks. The *b* value results obtained in this paper via AE and CWT are very significant. If we compare with the results of the usual *b*-value obtained via amplitudes of signals, both indices show very similar trends and value. *Wavelet energy b*-values lower than 1 (from simulation C100) indicated the inception of macro-cracks in the concrete.

The Fig. 7 shows the b_{WE} value versus the peak acceleration (PA) for all simulations. The b_{WE}-values decrease with the acceleration, more abruptly at the beginning. This abrupt decrease announces the occurrence of severe damage. The limit b_{WE} value is around the 0.8 value obtained by the authors in [14], indicating that the critical value for the onset of macro-cracks in the case of earthquake type dynamic loading is lower than the reported 1 value in other type of tests.

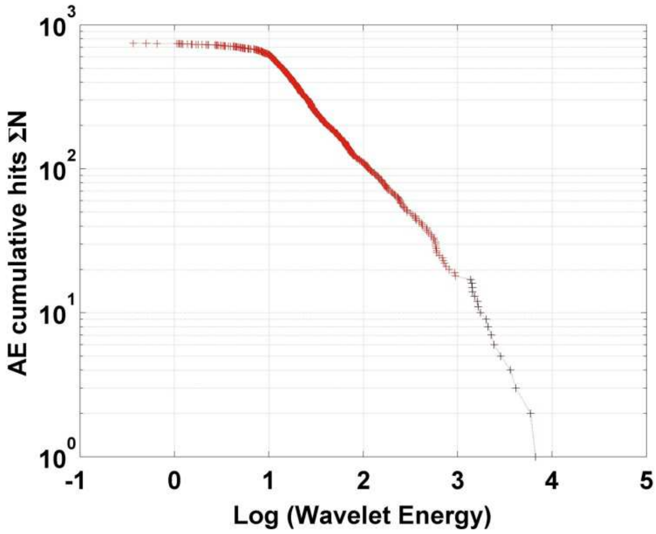


Fig. 6. AE cumulative wavelet energy distribution for the seismic simulation C50B at beam-column junction C3. Signals corresponding to black crosses are assigned to macroscopic cracking.

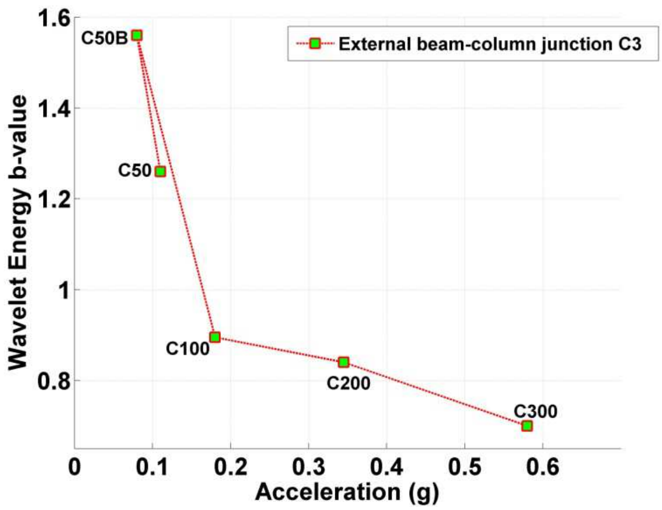


Fig. 7. Wavelet energy *b*-value vs. peak acceleration for all simulations.

3. Conclusions

Local concrete fracturing was assessed in a beam-column connection of a Reinforced Concrete Frame submitted to earthquake-type tests with the shaking table of the University of Granada (Spain). A new damage index was defined, called Wavelet Energy b-value (b_{WE}). through a formula similar to the one corresponding to usual *b*-value in terms of AE amplitudes, but considering the Acoustic Emission Energy in the frequency band corresponding to cracking of concrete. b_{WE} around 0.8 corresponded to the initiation of severe concrete macro-cracks in the zone surrounding the junctions; the lower the index, the higher the damage level. The limit value for the onset of macro-cracks in the case of earthquake type dynamic loading is consistent with previous results of the authors and is lower than the value 1 established by other authors in static tests.

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