Analysis of *b*- and *ib*-Value for Damage Evaluation in Reinforced Concrete Structures Subjected to Dynamic Loads Using the Acoustic Emission Method

Francisco A. SAGASTA*, Tomás FERNÁNDEZ*, Elisabet SUÁREZ*, Antolino GALLEGO*, Amadeo BENAVENT-CLIMENT**
* University of Granada. School of Engineering Building, Granada, Spain
** Polytechnic University of Madrid, Madrid, Spain

Abstract. This paper presents analysis and discussion of the *b*- and *ib*- values calculated from the Acoustic Emission (AE) signals recorded during dynamic shake-table tests conducted on a reinforced concrete (RC) frame subjected to several uniaxial seismic simulations of increasing intensity until collapse. The intensity of shaking was controlled by the peak acceleration applied to the shake-table in each seismic simulation, and it ranged from 0.08 to 0.47 times the acceleration of gravity. The numerous spurious signals not related to concrete damage that inevitably contaminate AE measurements obtained from complex dynamic shake-table tests were properly filtered with an RMS filter and the use of guard sensors. Comparing the *b*- and *ib*-values calculated through the tests with the actual level of macro-cracking and damage observed during the tests, it was concluded that the limit value of 0.05 proposed in previous research to determine the onset of macro-cracks is not appropriate in the case of earthquake-type dynamic loading. An alternative value of 0.04 is proposed instead. Finally, the *b*- and *ib*- values were compared with the damage endured by the RC frame evaluated both visually and quantitatively in terms of the Inter-story Drift Index.

Introduction

Reinforced concrete (RC) structures located in earthquake-prone areas are susceptible to suffering damage caused by the cyclic loading induced by ground acceleration during seismic events. It is well known that even moderate tremors, which may occur several times during the lifetime of a structure, produce cumulative damage to concrete. For this reason, it is strongly desirable to establish non-destructive inspection methods to evaluate the deterioration of concrete structures quantitatively in early stages. The Acoustic Emission (AE) technique has been proven as a reliable method to monitor the formation and growth of cracks in concrete at the material and structural level [1-4].

In analyzing AE data acquired during tests, parameter analysis is widely employed. One example is the AE peak amplitude, a parameter closely related to the magnitude of fracture. Of particular significance is the *b*-value, obtained from the amplitude distribution of AE data. This parameter is computed on the basis of the power-low relation between the amplitude of AE events and their frequency, applying the Gutenberg-Richter relationship [5], modified for the AE technique in terms of the peak amplitude in AE decibels. This index was applied in the past for assessing the damage of reinforced concrete beams subjected to (static) cyclic loading [4]. Other applications include the health monitoring of retrofitted RC structures [7] and the evolution of cracks in concrete and cement mortar [8]; these studies suggest a limit *b*-value that determines the transition from micro-crack growth to macro-crack formation in concrete. Accordingly, macro-cracks start to develop when the *b*-value is less than 0.05. Later, the technique for calculating the *b*-value was modified by Shiotani and collaborators, who incorporated statistical values of amplitude distribution analysis and defined the so-called improved *b*-value, or *ib*-value. This index has been evaluated from the AE recorded in uniaxial (static) compression tests on granite, rock, and concrete [9-10]. Both the *b*-value and the *ib*-value were properly compared during rock fracture by Rao and collaborators [10].

The interpretation of the *b*-value and the *ib*-value in relation with the development of macro-cracks in concrete has only been based on static and quasi-static (cyclic) tests, however. The validity of this limit in the case of dynamic earthquake-type loading has not yet been addressed, and it stands as the main purpose of this paper. More specifically, the *b*-value and *ib*-value were calculated here using the AE signals measured during several dynamic tests carried out on an RC frame structure with the shake-table of the Laboratory of Dynamics of Structures of the University of Granada. After filtering spurious signals, by comparing the *b*- and *ib*-values with the actual damage observed in the RC frame, it was found that the 0.05 limit of the *b*-value that previous research associates with the onset of severe damage (i.e. development and growth of macro-cracks in concrete) is not appropriate for dynamic earthquake-type loadings. An alternative and lower value of 0.04 is proposed in this research. The validity of the new 0.04 value is supported by the actual (qualitative) damage observed by the naked eye during the tests, and by the (quantitative) damage measured with the well-known Inter-story Drift Index (IDI) [11].

1. Test Model, Experimental Set-up and Instrumentation

An RC frame sub-structure consisting of four columns and two beams connected by rigid joints was designed and built at the Laboratory of Dynamics of Structures of the University of Granada. Figure 1-Left shows the names assigned to the columns: C1-C4. The connection of each column with the beam will be referred to hereafter as the beam-column connection P1-P4, respectively. The connections that have beams only at one side (right side) of the column (i.e. P1 and P3) will be called “exterior connections”, and those with beams at both sides (i.e. P2 and P4) will be referred to as “interior connections”. The concrete compressive strength assumed in calculations was 25MPa, and the yield strength of the reinforcing steel was 500MPa. The test model was designed following modern codes to develop “a strong column-weak beam” mechanism under lateral loading [11].

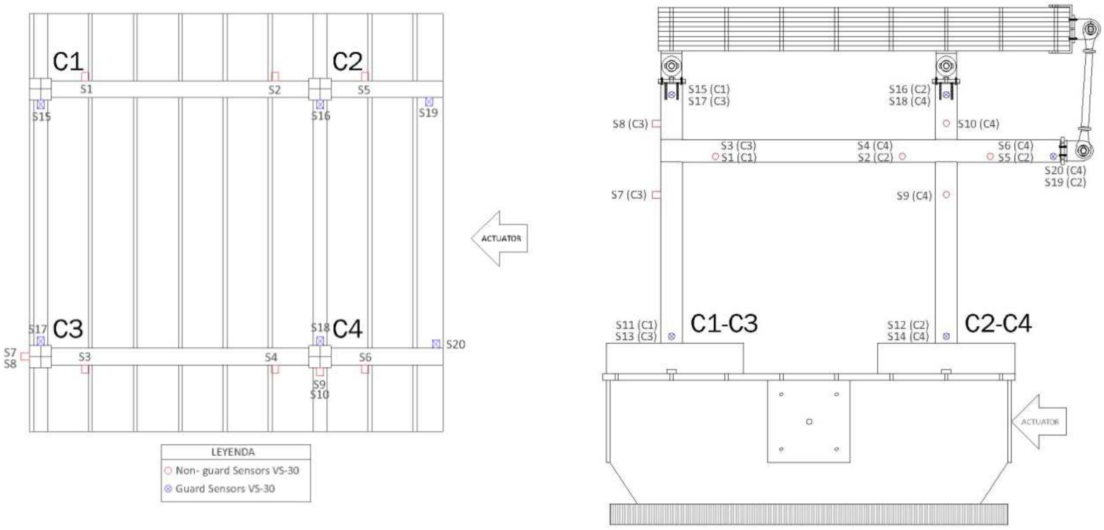

Fig.1. Test model with AE sensor positions. Left: Plan (bottom view); right: Elevation

The test specimen was subjected to five seismic simulations, referred to as C50, C50B, C100, C200 and C300 hereafter, with the uniaxial MTS 3x3m^2 shake table of the University of Granada. In each seismic simulation, the shake-table was set to reproduce the ground motion recorded at Calitri station (Italy) during the Campano Lucano (1980) earthquake, respectively scaled in acceleration amplitude to 50%, 50%, 100%, 200%, and 300%.The corresponding peak ground accelerations, PGAs, were 0.08, 0.08, 0.16, 0.31 and 0.47g. Each PGA represents a different seismic hazard level (SHL) SHL-1 and SHL-1B represent a “very frequent” earthquake, SHL-2 a “frequent” earthquake, SHL-3 a “rare” earthquake, and SHL-4 a “very rare” earthquake or the “maximum considered”.

An AMSY-5 Vallen System was used to capture the AE signals during testing. Only beam-column connections P3 and P4 were instrumented with AE sensors. Twenty VS30 AE flat low-frequency sensors were placed on the P3 and P4 beam-column connections, at the twenty positions indicated in Fig. 1. These sensors were set in the range 20-80kHz, using the 25-180kHz frequency band during signal acquisition with a sample period of 0.4μs and 2048 data for recording waveforms. Thus, the entire duration of the record window was t_{max}=819.2μs. During acquisition, 34dB gain preamplifiers and a 50dB detection threshold were used.

The specimen was instrumented with 192 strain gages, 10 uniaxial accelerometers and 9 displacement transducers (linear variable differential transformers, LVDTs). Strain gages were attached to the surface of longitudinal reinforcement when construction was in progress; they were located at column and beam ends. The displacement transducers measured the in-plane translations and the inter-story drifts in the direction of the seismic loading. These data were acquired continuously with a scan frequency of 200Hz.

2. *b* and *ib*-Value Calculation

Prior to calculating the *b*-value and *ib*-value, some procedures were applied to separate as much as possible the AE signals coming from concrete cracking (primary sources) and the spurious AE signals (secondary sources) coming from other mechanisms —e.g. the movement of the shake table, the friction between the test specimen and the shake table, or friction between the test specimen and different parts of the experimental set-up. The presence of a large amount of such spurious AE signals is actually the main difference between the AE measurements obtained from dynamic and from static or quasi statics tests. These spurious signals can make data analysis with the AE technique very challenging. In this study a filtering procedure is used for pre-processing the AE signals, for a suitable separation between pertinent and not pertinent signals. It is based on the use of the Root Mean Square (RMS) in several temporal windows as the signal feature. The secondary sources and the parameters of the RMS filter can be studied in [14].

2.1 b-Value

In seismology the well-known Gutenberg-Richter law establishes that [10]

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

where *N* is the total number of earthquakes with magnitude higher than *M* in any given region and period of time; *a* is an empirical constant; and *b* is the well-known *b*-value, defining the slope of the linear relationship given by Eqn. (1). This law has been adapted to the AE signals measured during a given period of time in a material that fractures under a given loading as [11]

$$Log\,_{10}N = a - b\left(\frac{A_{dB}}{20}\right), \tag{2}$$

where A_{dB} is the peak amplitude of the AE signals measured in decibels and *N* is the number of AE events with amplitudes higher than $A_{dB,}$ measured during the considered period of time. Taking into account that the AE peak amplitude is directly related with the magnitude of fracture, the *b*-value, defined in Eqn. (2) as the slope of the AE peak amplitude distribution, has proven to be an effective index to characterize the formation and growth of cracks during the time period considered. Indeed, this is a global parameter appropriate for characterizing signals of stochastic processes such as earthquakes or AE signals. According to previous work [8-10], the *b*-value calculated at successive time windows of the loading process changes systematically and hence can be used to study the development of the cracking process. For a given time period of observation, high *b*-values indicate the occurrence of a large number of small-amplitude AE hits, associated with micro-crack formation and slow crack growth. In contrast, low *b*-values are associated with macro-crack formation and faster growth. The latter (i.e. the fast development of macro-cracks) involves much more damage on the structural elements than the former (i.e. the slow development of micro-cracks). Past research [7-11] established *b*=0.05 as the boundary value between slow micro-crack and fast macro-crack formation. Note that the *b*-value is divided by 20 for comparison with the *ib*-value. We should underline that the limit *b*=0.05 was obtained from static and pseudo-static tests. Its validity for realistic earthquake-type dynamic loadings is examined in this paper, as explained below. It should also be stressed that the *b*-value provides a snapshot of the cracking process, that is, insight regarding the damage occurring in the time period considered, but it does not provide information on the accumulated damage of the structure.

For both beam-column connections, P3 and P4, Fig. 2 shows the *b*-value obtained at each instant *t* from the onset of the first seismic simulation C50 to the end of the last one, C300. According to Eqn. 2, the *b*-value at a particular instant *t* was calculated using the last sixty AE signals recorded before this instant *t*, i.e. using a population data of 60. It can be observed that the *b*-value oscillates, with peaks and valleys that can be associated with instants of slow micro-cracking (low damage generation) and fast macro-cracking (high damage generation), respectively. This behavior is to be expected, since the loading is cyclic and the acceleration $\ddot{u}_g$ applied to the shake-table oscillates. However, if a group of instants *t* corresponding to increasing values of $\ddot{u}_g$ are selected (indicated in Fig. 2 with circles), the trend of their *b*-values is downward.

Similarly, a quick look at these figures would suggest that the exterior beam-column connection P3 suffered more severe damage than the P4 interior connection. Also evident is that values lower than 0.05, correlated with macro-cracks in view of the criterion established in [9-10], appear from the very beginning of the test (seismic simulation C50). However, this result is not corroborated by means of other damage indexes and visual observation, suggesting the need to revise the limit 0.05 in the case of dynamic tests.

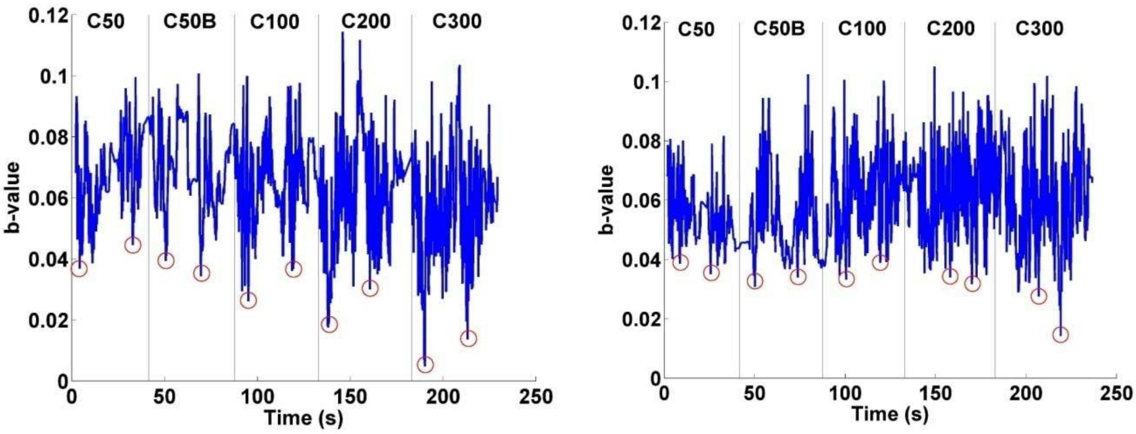

Fig. 2. *b*-value: Left: exterior beam-column connection P3. Right: interior beam-column connection P4. The *b*-value is divided by 20 for comparison with *ib*-value

2.2 ib-Value

ib-value is calculated from a constant number of data points β, the number of population data. Values of β from 50 to 100 have been previously suggested [9-10]. A value of β is considered suitable when the relationship between log *N* and AE amplitude approaches a straight line. Furthermore, the greater β is, the better the approximation to a straight line. The level of fitting to a straight line can be mathematically evaluated by using the correlation coefficient. β=60 was chosen for calculating the *ib*-value (the correlation coefficient is close to 0.95).

The cumulative frequency-amplitude distribution graph does not tend to a line in its entire domain of amplitudes. For this reason, Shiotani et al. [9] proposed calculating the slope (*ib* value) using only the data bounded by the AE amplitudes $a_1=\mu+\alpha_1\sigma$ and $a_2=\mu-\alpha_2\sigma$. Here, μ and σ are the mean and standard deviation of the AE amplitude distribution, respectively; and α_1 and α_2 are two constants established by the user in each test. Thus, the ib-value is obtained with

$$ib = \frac{\log_{10} N(a_1) - \log_{10} N(a_2)}{(\alpha_1 + \alpha_2)\sigma}. \qquad (3)$$

In this study, α_1 and α_2 were determined as follows. First, α_1 was set to 1 for both beam-column connections P3 and P4. However, determining α_2 was much more cumbersome because the range of AE amplitude corresponding to a straight line varies significantly depending on the instant t and the seismic simulation considered. To make a reasonable choice of α_2, the relationship between the correlation coefficient and α_2 for a fixed values β=60 and α_1=1 was calculated. The value α_2=1.5 was chosen, providing a correlation coefficient of about 0.95.

Finally, Fig. 3 shows the ib-value obtained for both beam-column connections, P3 and P4. It is clear that the general trend for ib-value coincides with that described in the previous subsection for the b value. This also corroborates that the level of damage imparted to the structure increased along with the increase of accelerations applied to the shake-table. Furthermore, comparison of the left and right graphs of Fig. 3 makes it evident that the exterior beam-column connection P3 suffered more damage than the interior beam-column one, P4.

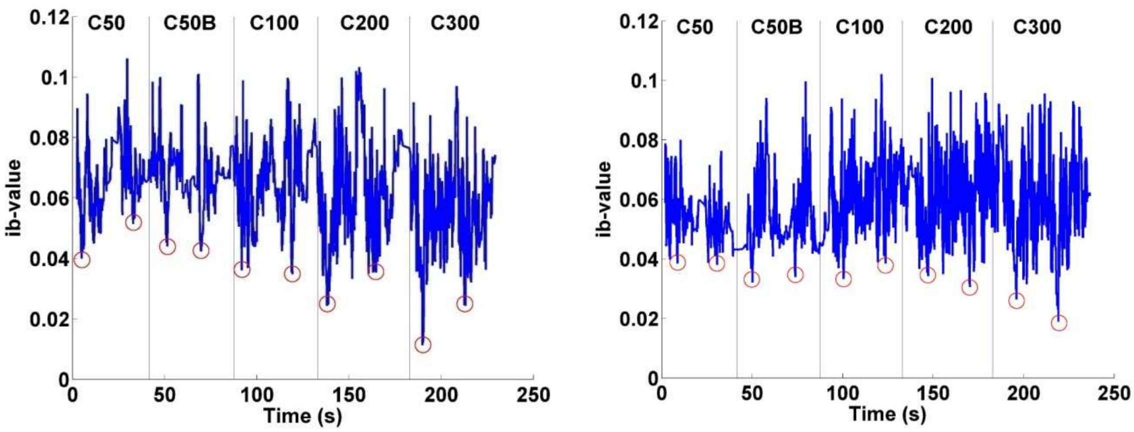

Fig. 3. *ib*-value. Left: exterior beam-column connection P3. Right: interior beam-column connection P4

3. Discussion

As can be seen in Figs. 2 and 3, both the b- and ib-value decrease as the acceleration applied to the shake-table increases. Moreover, the damage imparted to the exterior connection P3 appears greater than that imparted to the interior connection P4, since the b- and ib-value present a more intense decrease for P3 than for P4 (i.e. the lower bound of both indexes is smaller for P3 than for P4). In contrast, the number of times at which the ib-value is lower than 0.05 (the critical value associated with the onset of macro-cracks, according to previous studies based on static tests [9-10]) is larger for the interior connection P4. Accordingly, the macro-cracks in P4 should be more numerous than in the exterior connection P3. However, the opposite pattern was observed —that is, the number of macro-cracks in the exterior connection P3 was larger than in the interior connection P4. This contradictory result suggests that the boundary value of ib=0.05 associated with the onset of macro-cracks on the basis of static or quasi-static tests is not appropriate in the case of dynamic tests, meaning it should be revised for earthquake-type events. This observation is supported by the fact that, for example, ib=0.05 is reached many times during simulation SHL-1 for both connections, although no macroscopic crack was visually detected. During this seismic simulation the reinforcing steel remained elastic, according to the strain measurements provided by the gages attached to the reinforcing rebars. This fact is further corroborated by other damage indices calculated in these tests, as discussed later.

3.1 Critical Events

Figure 4 shows cumulated AE events whose *b*-value is equal or less than 0.05 These AE events are referred to as "*Critical Events*" [3]. The second, third and fourth rows of graphs show the Critical Events for several limits: 0.045, 0.04 and 0.035. The *ib*-value is represented similarly in the right side of Fig. 4. In all cases the Critical Events are seen to be mainly located near the acceleration peaks. Moreover, as the acceleration increases, the concentration of Critical Events increases.

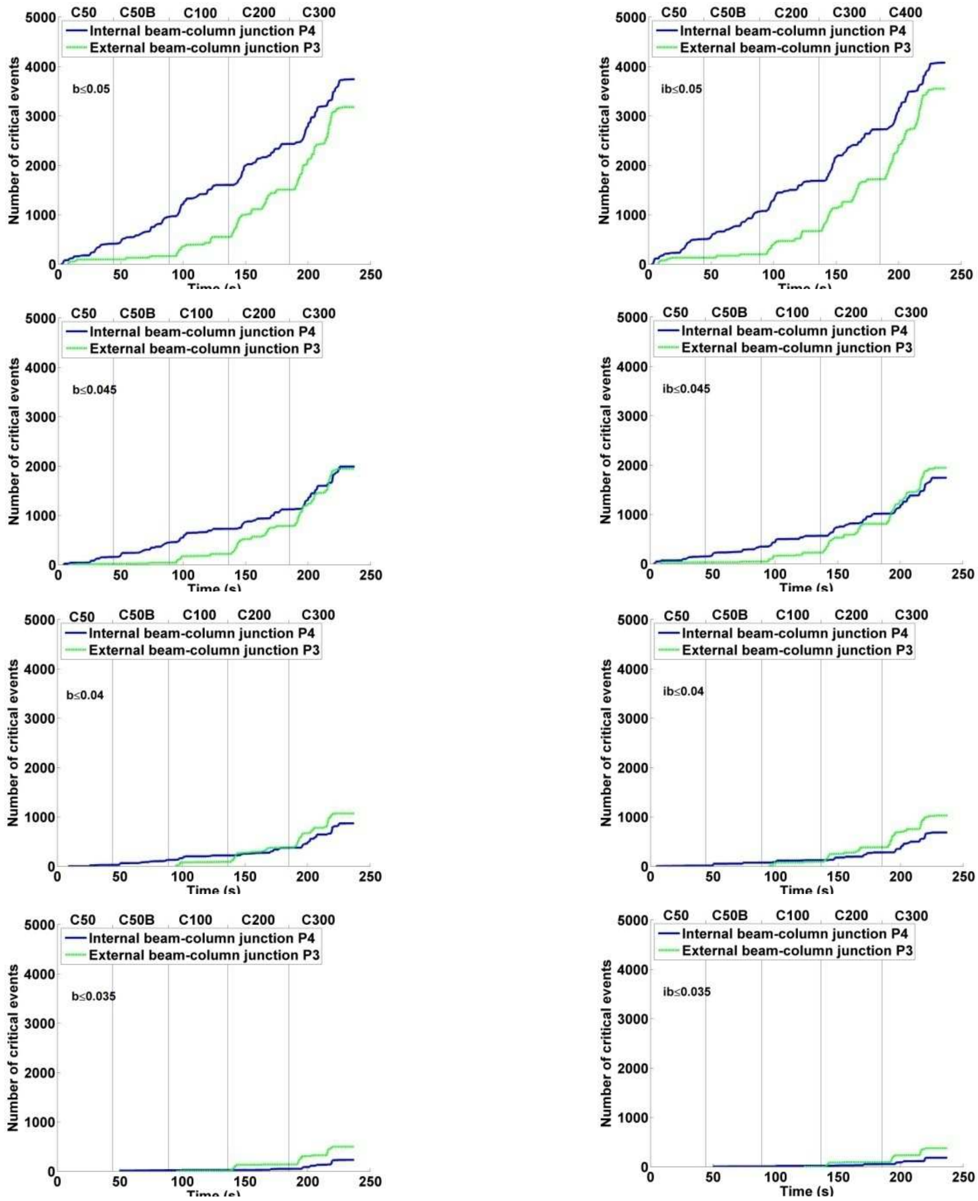

Fig. 4. History of Critical Events accumulated in both beam-column connections P3 and P4 along all seismic simulations. Left: *b*-value. Right: *ib*-value

When the limit is set at 0.05, a remarkable increase in the amount of Critical Events for the interior connection P4 is observed during the first three seismic simulations (C50, C50B, C100), suggesting the development of macro-cracks that were not observed during the tests. From then on, i.e. for seismic simulations C200 and C300, the rate of Critical Events significantly increases, suggesting an important increase of damage on the specimen. This result is especially noticeable for the exterior connection P3. When the limit is 0.045, the number of Critical Events becomes lower than for 0.05, but this number is still significant for seismic simulations C50, C50B and C100, thus contradicting the fact that no macro-cracks were observed during this seismic simulation.

However, when the limit is set at 0.04 or 0.035, two important changes can be observed: i) few Critical Events are detected during the first seismic simulations (C50, C50B and C100), which is in good agreement with the visual observation of no macro-cracks on the specimen; and ii) more Critical Events are detected for exterior connection P3 than for the interior one, P4, during seismic simulations C200 and C300. This second observation is consistent with the fact that more macro-cracks were observed by the naked eye in the exterior connection than in the interior one.

These results suggest that the limit of 0.05 proposed in past research for evaluating macroscopic cracks in static or quasi-static tests is not suitable for dynamic tests, the value of **0.04** being more appropriate. This statement is supported below by comparing the *b* and *ib* values with: (i) another damage index, the Inter-story Drift Index (IDI), commonly accepted as a good indicator of the level of damage endured by a reinforced concrete frame structure subjected to seismic actions; and (ii) with visual observation of the cracks.

3.2 Comparison of b and ib Values with IDI Index

In a previous work [11], the so-called maximum Inter-story Drift Index (*IDI*) was calculated for this test specimen and for the seismic simulations described above. This index has traditionally been associated with the level of damage experienced by a structure subjected to lateral displacements due to a ground motion. However, a major limitation of this index is that it does not take into account the accumulated damage in the structure. The *IDI* of the test specimen investigated here was calculated from the measurement provided by the displacement transducers (LVDTs) installed at each floor level.

The inter-story drift at a given instant *t* is defined as the ratio of the relative displacement between the upper and lower floors of a given story (δ) to the height of the story (*h*), and it is commonly expressed as a percentage. The *IDI* is the maximum absolute value of this ratio during the seismic simulation, i.e.

$$IDI = \max\left\{\frac{\delta}{h}\right\}. \tag{4}$$

The *IDI* has been associated with different levels of damage for reinforced concrete frame structures, as shown in Table 2 [11].

Table 2. *IDI* values and levels of damage

IDI(%)	LEVEL OF DAMAGE
0-0.5	No Damage
0.5-1.0	Moderate Damage
1.0-3.5	Severe Damage
> 3.5	Very Severe Damage

Table 3. *IDI* obtained for each seismic simulation

TEST	*IDI*
SHL-1	0.22
SHL-1B	0.24
SHL-2	0.5
SHL-3	1.2
SHL-4	7.9

Table 3 shows the *IDI*s obtained in each of the seismic simulations during the shake-table tests. Based on these experimental values and the corresponding levels of damage shown in Table 2, the global damage to the structure after each seismic simulation can be summarized as follows. The structure remained basically elastic during seismic simulations C50 and C50B, which is consistent with the fact that the reinforcing steel did not yield and only micro-cracks occurred in the concrete. During seismic simulation C100 the structure remained basically undamaged; this is confirmed by the fact that minor yielding of the longitudinal reinforcement occurred (strains up to about 2 times the yield strain) and the beam end sections were on the brim of yielding. The test specimen suffered severe damage during seismic simulation C200, and very severe damage (near collapse) in seismic simulation C300.

3.3 Crack Identification with the Naked Eye

A visual inspection of the test specimen at the end of each seismic simulation revealed the following pattern of macro-cracks, drawn schematically in Fig. 5:

<u>Seismic simulation C50 and C50B</u>: No visible cracks.
<u>Seismic simulation C100</u>: Some minor cracks.
<u>Seismic simulation C200</u>: Opening of new cracks and growth of previous cracks.

<u>Seismic simulation C300</u>: Large cracks were observed, coming from both the growth of previous ones and the formation of new cracks. The maximum width of these cracks was about 3mm; in some cases they were accompanied by a sudden vertical slide of approximately 10mm between the two sides of the crack.

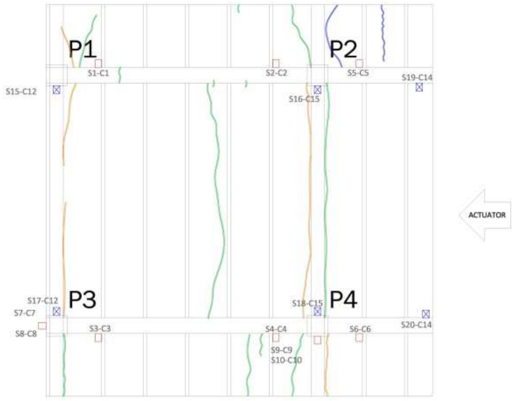

Fig. 5. Pattern of macro-cracks observed after simulations: C100 (green), C200 (orange) and C300 (blue)

4. Conclusions

The feasibility of using the *b*-value and *ib*-value calculated from AE measurements to assess the damage in RC structures subjected to earthquakes was investigated. By comparing the *b*- and *ib*-values with the actual damage observed in an RC frame tested on a shake-table, it was found that the 0.05 limit value that previous research associates with the onset of severe damage (i.e. the development and growth of macro-cracks) is not appropriate in the case of dynamic earthquake-type cyclic loadings. The global level of damage evaluated quantitatively in terms of Inter Story Drift Index, and qualitatively with the cracks identified after each seismic simulation, support adopting a limit value of 0.04, as proposed in this study for earthquake-type dynamic loadings.

Acknowledgements

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