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b-value of plain concrete beams based on AE Quanta

S. Muralidhara
Faculty, Department of Civil Engineering. BMS College of Engineering, Bangalore, Presently research scholar, Department of Civil Engineering, Indian Institute of Science, Bangalore, India.

Hamid Eskandari
Assistant Professor, Department of Civil Engineering. Sabzevar Tarbiat Moallem University, Iran,Formerly, Research scholar, Department of Civil Engineering, Indian Institute of Science, Bangalore, India.

B.K. Raghu Prasad
Professor, Department of Civil Engineering, Indian Institute of Science, Bangalore, India.

R.K. Singh
Outstanding Scientist, Reactor Safety Division, BARC, Mumbai, India.

ABSTRACT: In seismology, Gutenberg-Richter relationship $\log_{10} N = a - bM$ is an empirical relationship between the magnitude of earthquake and its recurrence frequency. The constant '*b*', a damage parameter, in the expression is called the b-value and is the log linear slope of frequency-magnitude distribution. An analogy is drawn between fault rupture and failure process in concrete. Acoustic emission (AE) energy is released, in the form of waves having certain peak amplitudes, during the failure process of concrete. Peak amplitudes of the AE signals are being used while estimating the *b*-value during fracture. Right from the onset of cracks till failure, the AE events are recorded with their peak amplitudes and corresponding absolute energies. Interestingly, the AE energy release has been observed to be in clusters. These clusters have been called by the authors as AE quanta. They are utilized as groups instead of using magnitudes of arbitrary group of events for obtaining the *b*-value. Unlike in seismology, wherein the *b*-value could be nearly unity, it is found more interestingly that the b-value from quanta is much less than that obtained from the amplitudes.

1 INTRODUCTION

1.1 *Guttenberg and Richter empirical relationship*

In seismology, seismic activity is designated by magnitude and is correlated to the energy released during the event. The relationship between seismic energy, *E* released during an earthquake and the magnitude *M* is given by the expression

$$LogE \approx d \cdot M \quad (1)$$

The value of *d* is 1 and 1.5 for small and large earthquakes respectively (Ekstrom et al.1988). Hence, there is a power-law function between *N* and *E* in the form: $N \approx E^{-b}$, where *N* is the incremental frequency and b is the *b*-value based on energy.

The frequency of occurrence of earthquakes with larger magnitudes is less when compared with those with smaller magnitudes. Based on the frequency of occurrence, Gutenberg and Richter proposed an empirical formula which relates magnitude and frequency.

$$\log_{10} N = a - bM \quad (2)$$

N = number of earthquakes with magnitude greater than *M*, *a* = seismic activity and the constant '*b*, a damage parameter, is the log linear slope of frequency-magnitude distribution (Gutenberg et al.1944).

1.2 *Acoustic emission (AE)*

In concrete, the fracture process zone ahead of a crack tip is the consequence of the formation of micro-cracks, a few of which coalesce to form a macro-crack. An analogy is drawn between earthquake and fault rupture in concrete. Although the scales of damage in concrete and earthquake are different, there is a similarity in the damage process wherein elastic energy is released in the form of waves from sources located inside the medium (Carpinteri. 2006). These waves are the acoustic emission (AE) waves, which are captured by piezo-electric sensors. The captured AE data is a source of information about the damage process in concrete. The technique has been utilized to assess the damage in important concrete structures like bridges (Ohtsu et al. 2002, Shigeishi et al. 2001, Colombo et. al. 2005). During the failure process of concrete, stress energy is released in the form of energy waves having certain peak amplitudes. The peak amplitudes A_{dB} (analogous to the magnitude of earthquake in seismology) are used in place of magnitudes of earthquakes in Equation 1 while estimating the *b*-value of concrete failure. However the peak amplitude is to be divided by a factor of 20, because of the fact that the AE peak amplitude is measured in dB, whereas the Richter magnitude of earthquake is defined in terms of the logarithm of maximum amplitude (Cox et al. 1993, Hatton et al. 1993, MVMS Rao et al. 2005). The modified expression is given in Equation 3.

$$\log N = a - b(A_{dB}/20) \quad (3)$$

The *b*-value analysis of acoustic emissions is in general obtained by grouping the events based on either time or number to groups of events, each containing about 50 events. Researchers have (Shiotani et al 2001 & Colombo et al.2003) showed that the number of events in each group can influence the b-value. Although studies to determine b-value of concrete fracture using maximum amplitudes of AE waveforms are reported, very few are reported with AE absolute energy. In fact a preliminary study has been made on beams cast with self consolidating concrete and loaded under three point bend condition, to determine b-value using AE absolute energy instead of the usual peak amplitude (Hamid 2008). The energies and the magnitudes of earthquakes are related by the expression $LogE \approx d \cdot M$. Incorporating the above into Equation 2, the relationship between frequencies of recurrence and energy the following expression is obtained.

$$\log_{10} N = a - \left(\frac{b}{d}\right)\log_{10} E \quad (4)$$

in which the value of *d* is 1 for small earthquakes and 1.5 for large earthquakes. Equation 3 is made suitable in AE technique by assuming *d* equal to 1, since the extent of energy release in concrete fracture is very small when compared with that in earthquakes. The modified expression is

$$\log_{10} N = a - b\log_{10} E \quad (5)$$

in which b = *b*-value based on AE energy and E = AE energy.

1.3 *Absolute AE energy*

Generally, micro-cracks emit waves with smaller amplitudes and waves from macro-cracks have larger amplitudes (Landis 1999). However, total counts and period of the wave along with amplitudes give a clear description of AE energy. A plot of amplitude versus absolute AE energy from the AE data of a beam is shown in Figure 1. It is seen that at lower energies and higher amplitudes, the latter may not be directly proportional to the energies. It clarifies the fact that the same absolute AE energy level may show different amplitudes and vice versa. Hence using AE energy instead of amplitude improves the accuracy of results from the analysis. Hence the maximum amplitude of the wave signal recorded by the sensor, which is generally used in the AE analysis, cannot be considered to characterize fully the fracture in concrete. Instead, the absolute AE energy seems to be an appropriate replacement to represent an event.

1.4 *Peak absolute energy*

An event in AE studies corresponds to an internal activity due to deformations and dislocations. The location of the event is computed by AE software (AE Win SAMOS) [p]. The sensors are located at different points on the surface of the structure. The energy recorded by each sensor varies since it depends on the distance of the sensor from the event location; closer the sensor to the event, higher the energy recorded. It is evident that, only one energy level is associated with an event, although different sensors will record different energy levels depending on their proximity to the event. Making use of this event energy for analysis, it is possible to get a more authentic scenario of the activities inside the body of the structure. There is no direct way to measure this single event energy. However an indirect way of measuring this energy is by choosing the maximum of the energies recorded by the sensors (peak energy) corresponding to that event, since that sensor is closest to the event location. This could also be explained by the wave attenuation as observed by Berthelot et.al [11]. A more accurate result could be obtained if the attenuation of the energy is also considered in the analysis.

It is evident from the AE event shown in Figure 1 that sensor-1 would register the maximum energy, since it is closest to the event. The relationship between the single event energy, the energy captured by the sensor and the distance of sensor from the event is given in the following equation

$$E_i \propto \frac{E}{r_i^2} \quad (6)$$

where i =1, 2, 3 and r_i the distance between the i^{th}

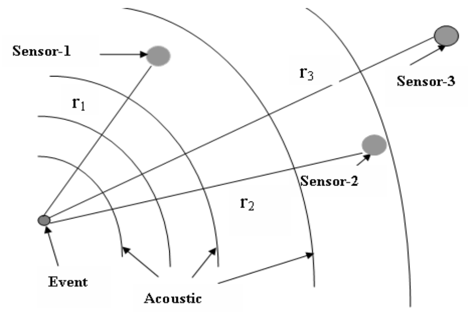

Figure 1. Location of event from sensors.

sensor and the event. E = energy released during that event while the E_i = energy recorded (captured) in the i^{th} sensor.

It is evident that the energies E_1, E_2, and E_3 captured by sensors 1, 2 and 3 would be such that $E_1 > E_2 > E_3$. It is obvious that E_1 is the peak value of energy among the energies recorded by the sensors because it is the closest to the event and is assumed to be equivalent to the actual event energy. Hence it is sensible to make use of this peak recorded energy amongst the sensors, in the analysis. Further justification can be made by observing the plot (Fig. 2) showing absolute energy of individual channel corresponding to each event, superposed with peak absolute energy. Matching to each event, only one of the channels shows maximum AE energy which is the peak energy. It is also observed that the sensor, recording the maximum energy, is not the same for all events. In literature, channel wise results are often discussed and plots from the data recorded by each channel are considered in the analysis. However it is more appropriate to discuss the AE analysis from event point of view rather than channel wise. This is the contribution from the study on AE applications to concrete fracture.

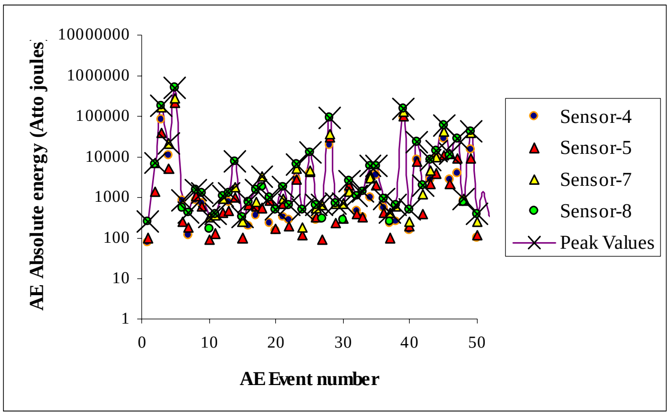

Figure 2. A partial plot showing absolute energy of individual channel corresponding to each event, superposed with peak energy from AE data of D2T20UB02 beam of event from sensors.

1.5 *AE Quanta*

Right from the onset of micro-cracks till failure, the AE events are recorded with their peak amplitudes and corresponding absolute energies. Interestingly, the peak absolute AE energy recorded has been observed to be in clusters. These clusters have been named as AE quanta. It is observed that the quantum of AE energies occurs in a definite pattern and appear to be periodic. The energies start with a low value and rise to a peak in a typical quantum and that pattern repeats. One can interpret the physics of the pattern saying that the low energies are due to the formation of micro-cracks at the interface (could be even at nano level) while the high energy could be associated with complete de-bonding. In Figure 3, a plot of AE energy-time over a small time interval is shown. It could be observed that the value of the absolute AE energy rises over a time interval. Micro-crack formation records less AE energy than macro-crack formation. In other words a waveform with less energy is captured. A macro-crack is formed after coalescence of several micro-cracks. The same is seen as a record of large AE energy value after several smaller values in AE data. The smaller values are due to disturbances at micro level, while the larger values are due to larger cracks. A cumulative value of these energies is seen as quanta. Each quantum of energy represents a stage in the damage process. Instead of using arbitrary group of fixed number of events with their amplitudes, AE quanta are used to determine b-value. The number of events in each quantum is a capricious.

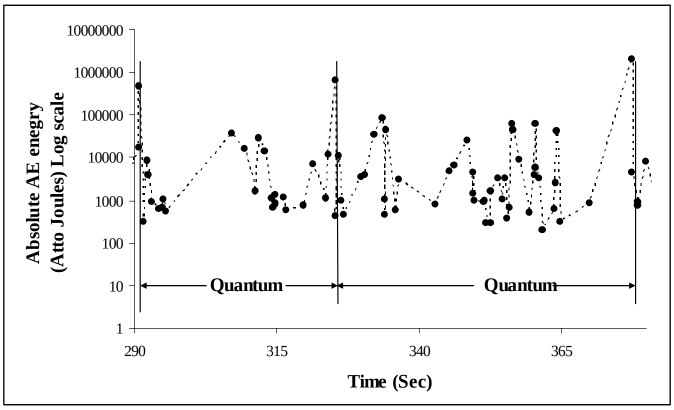

Figure 3. Plot of AE energy-time to indicate Quantum.

2 RESEARCH SIGNIFICANCE

The b-value of AE data from concrete specimens is used to describe the damage process. However it is beset with the variations due to sampling size of event group. As already been pointed out the number of events in each sampling group is likely to influence the b-value. Standardization of event group size seems a requirement to bring consistency into analytical study on b-value. In this study an attempt has been made to determine the b-value from AE energy and the event group is chosen based on clusters of energy or quanta. Quanta conform to the damage stages and justify well for their use in the determination of the b-value, apparently a damage parameter.

3 EXPERIMENTAL SETUP

Plain concrete single edged notched beam specimens of characteristic strength 45 MPa and with the geometrical proportion as given in Table.1 were tested under three point bending and monotonic loading conditions. The notch to depth ratio varied from 0.25 D to 0.33 D. A 500kN capacity servo controlled DARTEC machine under crack mouth opening displacement (CMOD) control was employed. The central deflection of the beam was recorded by a LVDT which could measure up to 0.1 micron. The clip gauge was used for the measurement of CMOD having a resolution of 0.1 micron. The test was performed keeping the CMOD rate at 0.0005 mm/sec. The acquisition of loading and displacement parameters along with the acoustic emission data were simultaneous.

Table 1. Dimensions of the beams.

Type	Length, mm	Depth, mm	Width, mm	Span, mm
D1	375	95	47.5	282
D2	750	190	95	564

The AE equipment used was from Physical Acoustic Corporation, Princeton, New Jersey, USA. The AE instrument was an 8 channel with AEwin for SAMOS (sensor based Acoustic Multi-channel Operating System) E2.0 system. The AE instrument has sensors to receive the AE signals, pre-amplifiers and data acquisition system to acquire and analyze AE data. A typical AE sensor is 19 mm in diameter and 22 mm in height with a resonant frequency of 60 kHz. The threshold value was kept at 45 dB to minimize the effect of noise. Sensors were attached to the specimen surface by using vacuum grease (High vacuum silicone grease).Before applying the vacuum grease to the specimen surface at the sensor locations, the surface was gently rubbed and cleaned using acetone solution to remove dust and to ensure better bonding between sensor and the specimen.

Four sensors used for the AE acquisition were arranged on one face of the specimen as shown in Figure 4. The locations of events have the origin of reference at the bottom left corner of the specimen. The sensors were initially tested for their sensitivity by pencil lead-breaking test. Further automatic sensor testing (AST) available in the AE software was employed to check the proper fixity of the sensors to the concrete surface.

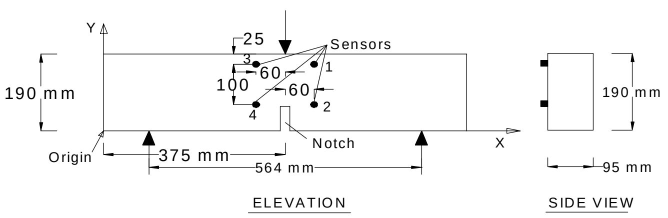

Figure 4. Profile of the D2 type beam showing the location of sensors.

All the beams of type D1 and D2 were tested in servo controlled Dartec machine under three point bend condition and CMOD control. Dartec machine was set to acquire data such as time, load, CMOD and LVDT (central deflection). The actuator of servo controlled machine was made to just touch the specimen at top. The displacement rates under CMOD control for notched and un-notched beams were chosen at 0.0005mm/sec and 0.0001mm/sec respectively. After everything is set, acquisition in both Dartec and AE instrument were started simultaneously. Acquisition was stopped when the specimen fractured fully and the load value had reduced to about 0.05kN.

4 RESULTS AND DISCUSSION

At the initial and middle stages of loading history, there is continuous micro and macro-crack formations. In fact this represents the formation of fracture process zone in concrete. Correspondingly lower and higher AE energies are recorded during micro and macro-crack formations. From a thorough inspection of AE data, it is possible to identify several quanta during the entire loading history. Each quantum has smaller AE energy recordings at the initial stages and significantly large AE energies at later stages as already seen from Figure.3. The pattern could be attributed to the formation of micro-cracks and coalescence of these into a few macro-cracks of different sizes.

The *b*-values were calculated selecting amplitudes from 100 events group and using Equation 2. For *b*-values based on peak absolute AE energy, the same set of events groups was selected and Equation 4 was adopted. The *b*-value results obtained from amplitudes and energies from 100 events group and quanta are tabulated in Table 2, and plotted against time as shown in Figure 5.

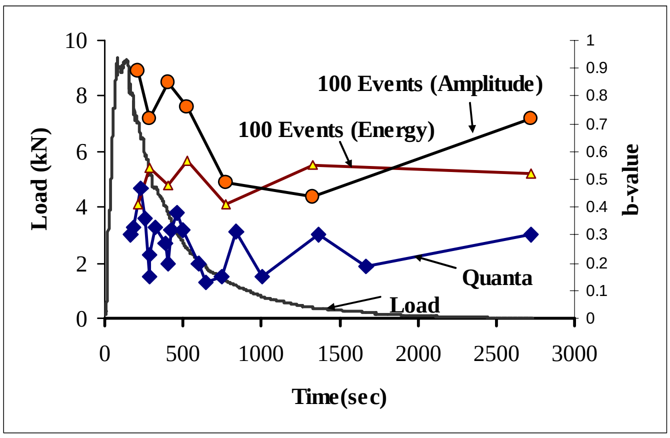

Figure 5. A combined plot of load-time- *b*-value from quanta, energy from a group of 100 events and amplitude from a group of 100 events.

5 CONCLUSIONS

The *b*-values calculated based on event energy are less than those calculated with event amplitudes. Quanta based *b*-values are found to be less than those from amplitudes and energy from an arbitrarily chosen (100events in the present study) event group. They also show more fluctuations during the initial and middle portion of loading stages. a decrease in *b*-value is seen due to material damage (micro-cracking and macro-cracking) while *b*-value show a rising trend due to toughening mechanisms like aggregate interlocking, tortuosity of crack path etc. however amplitude based *b*-values calculated using groups of 100 events show not much of activity during the same period. In other words they portray fewer activities which are not true. The least *b*-value is as low as 0.15 while the maximum is as high as 0.47. Although there is an analogy of seismic activity and concrete fracture, the range of *b*-values are different.

Table 2. Details of *b*-value based on AE amplitudes from 100 event group and AE energy from 100 event group and AE quanta.

Time (Sec)	*b*-value AE amplitudes from group of 100 events	Time (Sec)	*b*-value AE energies from group of 100 events	Time (Sec)	*b*-value Based on Quanta
209	0.89	209	0.41	167	0.3
290	0.72	290	0.54	189	0.33
407	0.85	407	0.48	229	0.47
522	0.76	522	0.57	263	0.36
779	0.49	779	0.41	282	0.15
1333	0.44	1333	0.55	290	0.23
2720	0.72	2720	0.52	325	0.33
				386	0.27
				403	0.2
				428	0.32
				461	0.38
				503	0.32
				601	0.2
				646	0.13
				745	0.15
				837	0.31
				1010	0.15
				1370	0.3
				1668	0.19
				2720	0.3

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