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Determination of size-independent specific fracture energy and acoustic emission energy of concrete

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ABSTRACT: Much has been said in literature about the fracture energy of concrete and its importance. Many important structures like nuclear containment vessels contain very thick concrete components of the order of a metre in size. Certainly size effect should be present in such structures. Fracture energy needs to be determined in order to assess the brittleness of such structures. It is also observed that AE energy could be related to fracture energy. Having said that, it is needed to understand the behavior of AE energy with several parameters of concrete like its strength and size. In the present work the results of such a study are presented. As fracture energy is size dependent, it may not be very useful unless its size dependency is eliminated. In the present study, experiments were conducted to use Acoustic emission (AE) energy as a quantitative measure of size-independent specific fracture energy of concrete beams and the concepts of boundary effect and local fracture energy are used.

1 INTRODUCTION

Because cement concrete is an important material, fracture and failure of concrete has been the subject of widespread research. Much has been said in literature about the fracture energy of concrete and its importance. Many important structures like nuclear containment vessels contain very thick concrete components of the order of a metre in size. Certainly size effect should be present in such structures. It is known that size effect lowers the tensile strength and the material tends to be brittle. Therefore fracture energy needs to be determined in order to assess the brittleness of such structures. The fracture energy of concrete is a basic material property needed to understand fracture initiation and propagation in concrete. Whether fracture energy is size dependent or not is being discussed earlier by researchers. Strictly the fracture energy if taken as a material property should be constant, and should be independent of the method of measurement, test methods, specimen shapes and sizes. The fracture behavior of quasi-brittle materials has drawn the attention of many researchers and significant research has undergone in the last decades and there is consensus among the research community to introduce fracture mechanics theory into design methodology (Karihaloo 1995). Earlier researchers concluded that fracture energy vary with the size and shape of the test specimen. Researchers studied the size effect on the fracture energy, size effect on concrete strength broadly and also a number of size effect models have been proposed by earlier researchers. Among these are Bazant's size effect model, Karihaloo et al , Carpinteri et al are a few models dealt about the concept of size effect(Bazant 1998, Karihaloo 1995). To a great extent these research works are aimed at the explanation why the fracture parameters such as fracture energy, CMOD vary with the specimen size (Mindess 1984). In a few models, for example "local fracture energy model" proposed by previous researchers dealt with the possibility of constant fracture energy of concrete(Duan et al 2001, Abdalla and Kariahloo 2003). One important point related to fracture process in concrete is it is necessary to understand the relationships between micro structural phenomena and corresponding effects on macroscopic behaviour. And also microstructral performance relationships are the important aspects to understand the material behaviour clearly (Landis and Baillon 2002).

2 SCOPE AND OBJECTIVES OF THE PRESENT STUDY

Following Duan *et al.,* and Abdalla and Karihaloo, in this present experimental study, the concept of 'boundary effect' and 'local fracture energy distribution', are used to study the size independent fracture energy of concrete and the same concept is used to study the acoustic emission energy as a quantitative measure of size-independent specific fracture energy of concrete (Abdalla and Karihaloo 2003), Duan et al(2001)).

3 EXPERIMETNAL DATA ANALYSIS

The experimental data analysis consisted of calculating fracture energy for each specimen using the RILEM method of Hillerborg model and analyzing size independent AE energy for each specimen.

Acoustic emission activity is attributed to the rapid release of energy in a material, the energy content of the acoustic emission signal can be related to this energy release(Ohtsu 1996). The true energy is directly proportional to the area under the acoustic emission waveform. In the present experimental study it was considered that the energy of an electrical signal is proportional to the square of the voltage, so in a simplified analysis it is necessary to square and integrate the recorded voltage transients for each channel.

$$E_i = \int_{t_0}^{t_1} V_i(t)^2\,dt \tag{1}$$

i = the recorded voltage transient $V(t)$ of a channel

t_0 = the starting time of the voltage transient record

t_1 = the ending time of the voltage transient record

An ideal representation of a AE wave is shown in Figure 1 (Miller et al 1987). In the experimental study the authors obtained AE energy by summing up of all the AE energy release values of 8 channels to get the cumulative AE energy release. It is obvious that the crack propagation starts from the predefined notch tip. The AE transducers are placed near to the notch.

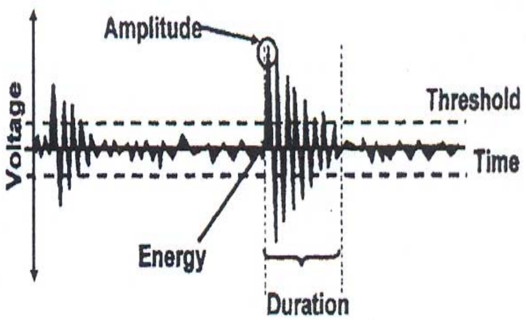

Figure 1. Ideal representation of AE wave.

4 APPLICATION OF BOUNDARY EFFECT AND LOCAL ENERGY CONCEPT ON ACOUSTIC EMISSION ENERGY

To study the applicability of boundary effect model, AE energy and AE events are studied for three specimens of different sizes. All the AE events are recorded with 8 channel AE system. The largest AE energy value is taken into account. The total AE events are divided into four classes.(Class I = 10,000 volt^2-μsec, Class-II =100,000 volt^2-μsec and Class-III=10, 00,000 volt^2-μsec). AE events and the AE energy taken place during testing of specimens with depth 320mm and also the energy level and the percentage in relation to the total AE energy released were calculated and shown in Figure 2.(Otsuka et al 2000).

It is observed that AE events for energy levels less than Class I are relatively higher. But the AE energy associated with these AE events are quite low (Fig. 2). It can be said that these AE events contribute very less to the facture process of concrete. Figure 2 show the AE events distribution for energy levels higher than Class I, Class II and Class III respectively for large size specimen. It is observed that the events concentration is higher for energy levels higher for Class I and Class II. But very less percent of the energy falls between Class I and Class II energy levels (Fig. 2). It is observed that most of the events had energy more than Class II level during the fracture. The same observation is made for the medium size specimen and smaller size specimen. The percentage of energy involved (which is greater than Class II level) is 95.17, 90.7 and 94.67 of the total energy for large, medium and small beam specimens respectively. It is observed that AE energy levels higher than Class II have a significant contribution to the fracture process zone (FPZ). As a result it can be considered the AE events above Class II level directly contribute to the fracture process zone owing to its high contribution of AE events and energy. However it is observed that the AE energy which is greater than Class III level has relatively high AE energy per unit area of FPZ although their total AE events and energy is less. This AE energy may also contribute to the fracture process of concrete. Figure 2 shows that the distribution of AE events and energy in the intervals does not vary much for the large, medium and small beam specimens showing similar modes to fracture process(Otsuka 2000).

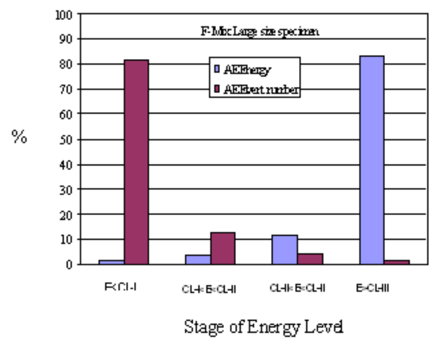

Figure 2. Distribution of AE energy in large specimen [d=320mm].

It is observed that as the depth of the specimen increases the cumulative AE energy released also increases. Figure 4 shows the typical recorded plot of cumulative AE energy and load with time. It is observed that before peak load very little AE activity has taken place. On the onset of crack formation occurring at or near the peak load, the acoustic emission release took place. Hence the initial behavior of all the specimens is similar but varies as the fracture reaches well into the post peak range. The rate of AE emissions goes on increasing till it reaches saturation. The slope of the curve for notch to depth ratio 0.5 which may be indicative of the brittle failure. Also it is observed that the AE energy release is relatively less for beam specimen of high notch to depth ratio and more for specimen with low notch to depth ratio which confirms the above mentioned fact that AE energy is also indicative of strength. From Figure 3, one can observe that variation of AE events during the loading process. Hence one can cite besides fracture energy, AE energy also vary from point to point in concrete. From these observations it can be concluded that the AE energy release vary with point to point during fracture process. The fracture process zone (FPZ) is influenced by the boundary of the specimen. Because of this, FPZ size which is measured by its length and width will be changed as the crack is reaching boundary. The change in the size of the FPZ will cause in variation in the fracture energy consumed and the corresponding released AE energy in the fracture process.

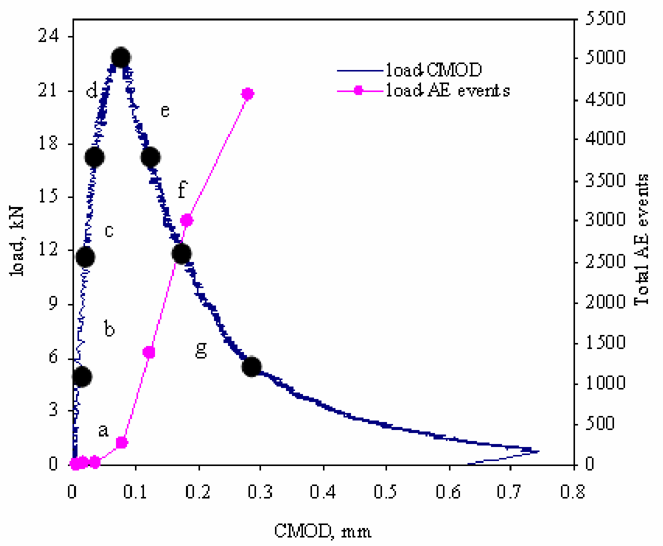

Figure 3. Load-CMOD and the total AE events[a_0/d=0.15]
(a) 0-20% of peak load
(b) 20-50% of peak load
(c) 50-75% of peak load
(d) 75% of peak load to peak load
(e) Peak load 75% of peak load
(f) 75-50% of peak load
(g) 50-20% of peak load.

The fracture energy and cumulative AE energy are decreasing with increase in notch to depth ratios for beam specimens. It is observed that as the notch to depth ratio increases the fracture energy and cumulative AE energy released decreases.

Both the parameters are seem to follow the same trend with the variation of notch to depth ratio.

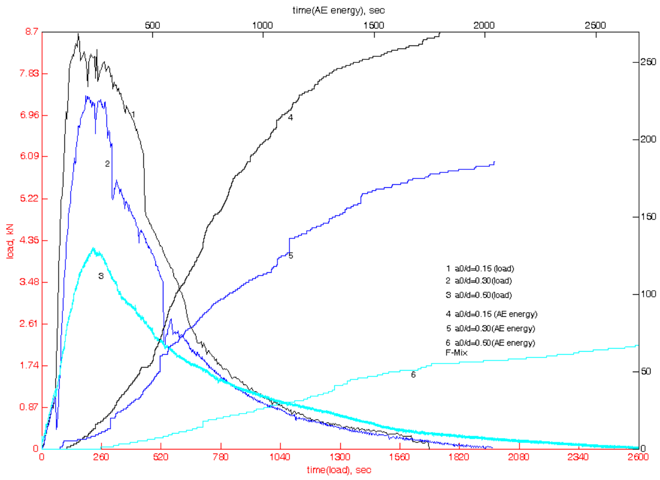

Figure 4. Variation of load and AE energy with time.

Figure 3 shows the total AE events taken place with respect to load. The load-CMOD plot was divided into seven intervals i.e., (a) - (g). It is observed that during intervals (a), (b) and (c) there is very less AE events took place. At interval (d), the AE emission begins to rise and the fracture process can be said to have initiated in this interval. During interval (e) and (f), the AE energy released is highest which confirms the propagation of the Fracture process zone. Finally towards interval (g) the AE curve bend down indicating a failure. From these observations it is concluded that AE energy release varies from point to point during fracture process in concrete.

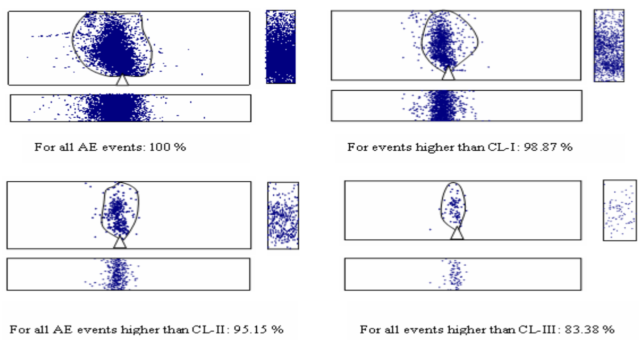

Figure 5. AE source locations represented with 4 energy stages.

Therefore, in this present experimental study the concept of “boundary effect” and “local fracture energy distribution” are used to study the acoustic emission energy as a quantitative measure of size independent specific fracture energy of concrete.

5 EXPERIMENTAL PROCEDURE

The experiments described in this paper are to investigate use of acoustic emission energy as a quantitative measure of size independent specific fracture energy of concrete beams. 27 notched TPB specimens (80mm, 160mm and 320mm) with a constant span to depth ratio of 3 are tested. Concrete mix of high strength (78 MPa) and maximum coarse aggregate size 20mm is used. The notch to depth ratios selected are 0·15, 0·30 and 0·50. Three beams are tested for each notch to depth ratio[Table 1]. The testing is carried out using a Material Testing System (MTS) machine of capacity 1200kN.

Table 1. Details of the specimens tested.

Specimen size	Notch details		Specimens tested	Specimen dimensions (mm)		
	a0 (mm)	(a0/ W)		Length (L)	Span (S)	Depth (W)
Small	12	0.15	3	290	240	80
	24	0.30	3			
	40	0.50	3			
Medium	24	0.15	3	530	480	160
	48	0.30	3			
	80	0.50	3			
Large	48	0.15	3	1010	960	320
	96	0.30	3			
	160	0.50	3			

The data acquisition records load, CMOD, midspan displacement and time. The specimens are tested under crack mouth open displacement (CMOD) control at a constant rate of 0.0004mm/sec. The mid-span downward displacement is measured using linear variable displacement transducer (LVDT) placed at center of the specimen under bottom of the beam.

The AE instrument is an 8 channel AE^{win} for SAMOS (Sensor based Acoustic Multi-channel Operating System) E2.0 system which was used in the present study. The AE acquisition system records AE event parameters. The AE transducers(R6D) have peak sensitivity at -75 dB with reference 1V/(m/s). The operating frequency of the AE sensor is 35 kHz – 100 kHz. The threshold value 40 dB was selected to ensure a high signal to noise ratio.(users manual(2005))

6 RESULTS AND DISCUSSION

During the experiments several observations have been recorded and some of them are given in Table 2. In the same table the mean value and coefficient of variation (COV) of the measured fracture energy $G_f(a_0/W)$, the mean value and coefficient of variation of measured AE energy values using TPB specimens are given. By using the same concept given in reference(Abdalla and Karihaloo 2003, Duan et al 2001) and using Equation 2 and Equation 3 which are analogous to the method adopted by (Abdalla and Karihaloo 2003, Duan et al 2001), the size independent acoustic emission energy (E_F) can be calculated by using the acoustic emission energy (E_f) released during the concrete fracture.

$$E_f\left(\frac{a_0}{W}\right) = E_F\left[1-\frac{1}{2}\frac{a_l/W}{1-(\frac{a_0}{W})}\right] \quad \text{for } 1-(a_0/W) > a_l/W \quad (2)$$

$$E_f\left(\frac{a_0}{W}\right) = E_F\cdot\left[\frac{1}{2}\frac{(1-a_0/W)}{a_l/W}\right] \quad \text{for } 1-(a_0/W) \le (a_l/W) \quad (3)$$

The test results for $E_f(a_0/W)$ from the TPB tests were substituted into Equation 2 and Equation 3 in order to determine the size-independent acoustic emission energy A_F and transition ligament length $(a_l)_{AE}$. As the number of results of $E_f(a_0/W)$ for each depth W and notch to depth ratio are 3, but the number of unknowns are E_F and $(a_l)_{AE}$, the system of three equations are solved by least squares method to get the best estimate of E_F and a_l. These are listed in Table 3. Figure 7 shows a plot $E_f(a_0/W)$ versus notch to depth ratio. There are three values $E_f(a_0/W)$ for different sizes at each notch/depth ratio. By knowing $E_f(a_0/W)$, the size independent fracture energy E_F is obtained for different sizes of TPB specimens. E_F is plotted with respect to depth as shown in Figure 6. The trend line drawn horizontal is parallel to the depth axis. The two variables $(a_l)_{AE}$ and E_F are obtained from the three equations by the least squares method, Because the equations set of are over determined. However, in-spite of all that the size independent acoustic energy E_F is not absolutely constant with depth. The mean line drawn horizontally, viz., parallel to the depth axis did not pass through all the points. There are deviations however small. Further the authors have observed that the a_l thus obtained did not match with the experimentally obtained value. The value of a_l will be substituted in Equation 2 & Equation 3 correcting E_F and $(a_l)_{AE}$. To clarify the influence of specimen size on the fracture mechanics parameters in Equation 2 & Equation 3 the predicted values of size independent fracture energy G_F and a_l are plotted against beams depth and shown in Figure 7. It can be clearly seen that specific fracture energy G_F calculated using RILEM 50-FMC method remains constant or size independent. But the transition ligament length (a_l) varies a lot for the tested TPB specimens.

Table 2. Measured fracture energy $G_f(a_0/W)$ and $E_f(a_0/w)$.

a_0/W	W	Fracture Energy (N/m)		AE energy (relative units)	
		mean	COV(%)	Mean	COV(%)
0.15	80	112.5	22	219.5	35.0
0.30	80	123.1	16.5	102.5	31.5
0.50	80	90.5	10.2	42.6	63.8
0.15	160	128.9	2.9	201.5	24.7
0.30	160	108.6	14.6	117.4	42.1
0.50	160	100.7	3.8	79.5	15.1
0.15	320	133.4	12.1	327.1	34.4
0.30	320	122.3	5.6	209.5	33.6
0.50	320	117.1	16.2	225.5	11.3

Therefore, the size independent fracture energy of the concrete is around 155 N/m. These values are obtained by averaging the three values which were given in Table 4.

The acoustic emission energy values recorded from the TPB tests are substituted into Equation 2 and Equation 3 in order to determine the size-independent acoustic emission energy E_F and transition ligament length a_l. As the number of results of $G_f(a_0/W)$ for each depth W and notch to depth ratio are 3, but the number of unknowns are G_F and a_l, the system of three equations are solved by least squares method to get the best estimate of G_F and a_l. These are listed in Table 3. The predictions based on the parameters in Table 3 are plotted in Figure 6.

It is observed in the experimental study that the nominal strength of the beams decreases with increasing beam size. The results in Table 2 show that the measured fracture energy G_f (a_0/w) of concrete TPB specimens studied here are dependent on both notch/beam depth ratio and the specimen size. However, when the model based on the local fracture energy to the fracture process zone width is applied to $G_f(a_0/w)$ a specific fracture energy G_F is obtained which is independent of specimen size. The transition ligament length a_l introduced by this model plays an important role in this evaluation. For the TPB test reported the results of the size-independent fracture energy G_F size independent acoustic emission energy are obtained using three notch to depth ratios of 0.15, 0.30, 0.5.

It is observed that for a specimen with high ultimate load, the AE energy released is also high, like fracture energy. During the travel of AE waves from the source to surface will be subjected to the attenuation. The energy loss experienced by these stress waves per unit distance travel will be related to the damping capacity (internal friction) of the material. This also causes the reduction of the total elastic wave energy that reaches the sensor. The signal attenuates as it progresses. It was well cited in the literature that material attenuation causes an exponential decrease in amplitude, A.

$$A = e^{-\alpha d}$$

where d is the propagation distance and α is the material attenuation coefficient.

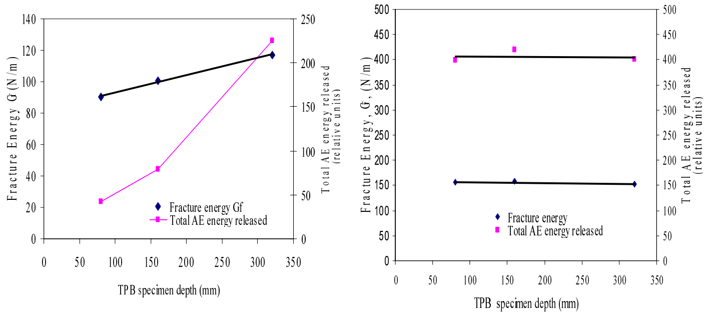

Figure 6. Variation of fracture and AE energy with size.

It is interesting to see that these plots confirm the earlier results. In the present study, a test was performed with the sensor positions vary along the span of the TPB specimen with respect to a fixed source of sound wave pulses at the left end of the beam. The amplitude variation when the sensor position changed is plotted. The amplitude reduction at the sensor position in the experiments can be obtained. Thus, if the sensor is at distance d from the AE source, the reduction on account of attenuation can be obtained. The amplitude distance relation for mix-F is Amplitude, $A = 59461e^{-0.0038d}$ where d is the distance (mm) from source and amplitude in micro-volts.

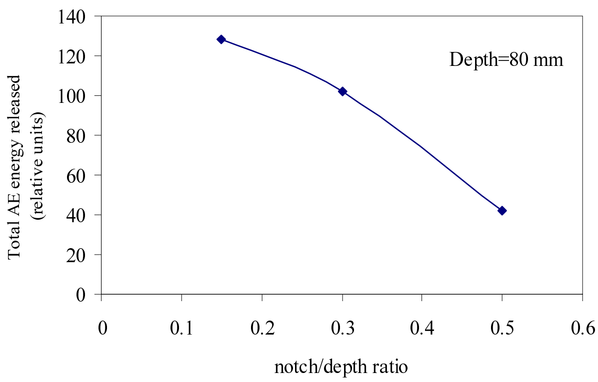

Figure 7. Variation of Total AE energy with notch/depth ratio.

But in the present study the attenuation is not taken into account.

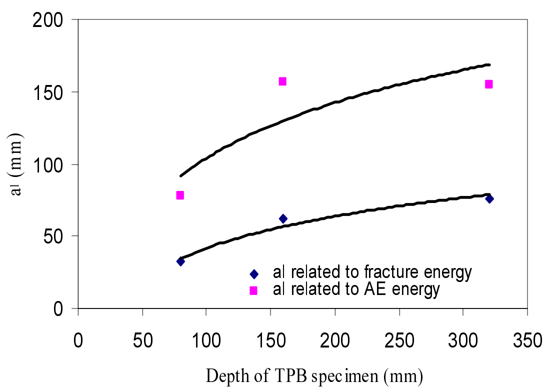

Figure 8. The transition ligament length as a function of depth W.

Table 3. Projected specific fracture energy G_F and E_F.

Beam depth (mm)	G_F (N/m)	a_l (mm)	AE_F	$(a_l)_{AE}$ (mm)
80	156.64	32.1	398	78.1
160	158.94	61.6	420	156.9
320	152.01	76.2	403	155.1

7 CONCLUSIONS

Based on the above results the following major conclusions can be drawn.

1. It is observed that AE events containing higher energy located around the notch tip.
2. The present experimental study may be useful to quantitative measure of size independent specific fracture energy of concrete.
3. It may be useful to relate acoustic emission energy to fracture energy of concrete. This relationship may be useful to develop a laboratory tool. This laboratory tool could be useful to study the damage in concrete structures. The author's opinion is that this laboratory tool can be used in a laboratory under controlled conditions, as opposed to a field technique. Regarding damage models, there is a large class of concrete performance models based on principles of continuum damage mechanics. These models often use parameters such as crack density to predict changes in stiffness due to damage. Up to now crack density is a difficult thing to measure, but AE has the potential to provide information on crack density that could then be used to tune the continuum damage models related to concrete.
4. It may be possible to cite besides fracture energy, AE energy may also be used to measure the fracture parameter of concrete.

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