Fracture Mechanics of Concrete Structures, de Borst et al (eds) © 2001 Swets & Zeitlinger, Lisse, ISBN 90 2651 825 0

Acoustic emission measurements of fracture energy

E.N.Landis
University of Maine, Orono, Maine, USA

L.Baillon
École Polytechnique Fédéral de Lausanne, Switzerland

ABSTRACT: Acoustic emission was used to measure energy associated with fracture of standard test specimens. The goal of the work was to identify ways in which acoustic emission could be used to quantify damage in laboratory specimens for the purpose of tuning damage models. A series of mortar and concrete specimens of different compositions were tested for fracture energy, G_f while simultaneously being monitored for acoustic emission energy release. Reasonable proportionality between the two quantities was observed, however additional work is required for generality.

1. INTRODUCTION

1.1 Background

Because of its importance as a construction material, fracture and failure of concrete has been the subject of extensive research, the results of which have resulted in a number of comprehensive texts (Bazant and Planas, 1998; Karihaloo, 1995; Shah et al, 1995; van Mier, 1997). The result of this extensive work is an understanding of concrete as a quasibrittle material. One in which the energy required to propagate cracks is higher (although size-dependent) than would be predicted by linear elastic fracture mechanics. Many of the mechanisms that are responsible for the quasibrittle behavior have been identified and include crack bridging, friction, and microcracking. Numerous experimental techniques have been applied further our understanding of the fracture processes, and a number of modeling approaches have been developed to predict fracture behavior.

Despite the extensive work, and the numerous successes at modeling fracture behavior, our understanding of the physical processes that ultimately control fracture behavior is weak. Although to some extent we are able to predict failure loads and damage patterns, we still do not have a good understanding of the relationships between microstructural phenomena and the corresponding effects on macroscopic behavior. It logically follows that if we have a better understanding of the relationships between microstructural events and macroscopic behavior, we will be in a better position to formulate predictive models for large-scale structural performance and reliability. Microstructure-performance relationships are the key to true understanding of a material.

Towards this end we conducted experiments to relate the energy released at a micro-scale to the bulk fracture energy as measured on a global scale. We used acoustic emission techniques to monitor energy released at a microscopic scale, and we correlated these measurements with the results of standard fracture energy tests. The experimental variable considered in these experiments was the specimen composition. Specifically, we varied the maximum aggregate size. While specimen geometry is certainly an issue, we restricted ourselves to a single specimen size in order that the acoustic emission measurements may be consistent.

The hypothesis to be tested is as follows. A certain fraction of the energy dissipated by fracture should be detected by an acoustic emission monitoring system. Assuming we can remove effects of material attenuation that alter the acoustic signals as they travel from source to receiver, then the distribution of energy received by the acoustic emission transducers should be a function of the distribution of the fracture energy released during crack propagation. Our goal then is to measure the distribution of acoustic energy released during a standard fracture test, and to use that information to make inferences on the different fracture mechanisms at work in the different materials.

The work described in this paper is a preliminary step in relating acoustic emission energy to damage mechanisms.

2. ACOUSTIC EMISSION TESTING

Acoustic emission (AE) is an experimental tool well suited for monitoring fracture processes. It is a passive ultrasonic technique where the elastic waves generated from cracking events can be measured and processed using seismic analysis techniques. Fracture processes in concrete have been monitored over the last 20 years using a variety of different AE techniques with varying degrees of sophistication (Ohtsu, 1996). Recent work has focused on relating acoustic emission characteristics to properties of the fracture process zone (Maji and Shah, 1988; Nomura et al, 1991), and using AE source location analysis to evaluate damage localization (Berthaud et al, 1991; Li and Shah, 1994). More advanced moment tensor analysis (Ohtsu, 1987) has been used to examine mixed mode fracture (Suaris and van Mier, 1995), microfracture mode – fracture toughness relationships (Landis and Shah, 1995), and fracture properties of reinforced concrete structures (Ohtsu et al, 1998). Clearly, the strength of AE measurement techniques is the ability to monitor microscopic damage occurring *inside* the material.

In the work described here we used the energy of the AE signal as a way to look at micro-macrofracture relationships. Because acoustic emissions result from the conversion of strain energy to kinetic energy through the formation of cracks, it is reasonable that studies of AE energy should reveal information about fracture processes. Relating AE energy to fracture and failure has been done for rock among other materials (Lockner et al, 1991).

3. EXPERIMENTAL PROCEDURE

The experimental program was intended to relate fracture energy to AE energy by testing a series of specimens of similar geometry, but different composition. The differing compositions were intended to produce different measured fracture energies, thereby producing different AE energy measurements.

3.1 Experimental Setup

An illustration of the experimental setup is shown in Figure 1. As shown in the figure, the basic components are a load frame with data acquisition, and an acoustic emission monitoring system. The data acquisition system records load, CMOD, and midspan deflection. The AE acquisition system records AE waveforms and parameters

The AE system used was a four channel MISTRAS system manufactured by Physical Acoustics Corporation (PAC). For each AE event the system records full AE waveforms to the host PC's hard disk. The transducers used were PAC S9208 AE transducers. The S9208 model is designed to have a voltage output that is proportional to displacement. Their broadbanded frequency response makes them well-suited for AE energy measurements.

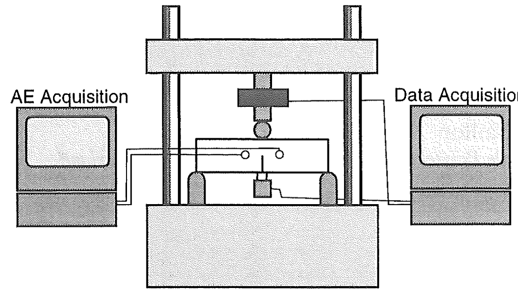


Figure 1. Illustration of experimental setup.

The load frame was an Instron electro-mechanical system that was operated under displacement control. Load, CMOD and midspan deflection were recorded using a LabVIEW-based data acquisition system. Midspan deflection was measured using a pair of LVDTs, one on each side of the specimen, attached to a yoke that connected to the specimen at the supports.

3.2 Specimens

For this work three different specimen types were cast in order to produce three different ranges of fracture energy. All specimens were prisms of 10 by 10 by 40 cm as shown in Figure 2. The specimens were subjected to three-point bending. A 6 cm center notch was saw cut prior to testing to ensure a center crack. The four AE transducers were mounted to the specimen at positions shown in Figure 2 using a specially designed mounting bracket that held the transducer tightly against the specimen. Vacuum grease was used as a coupling agent.

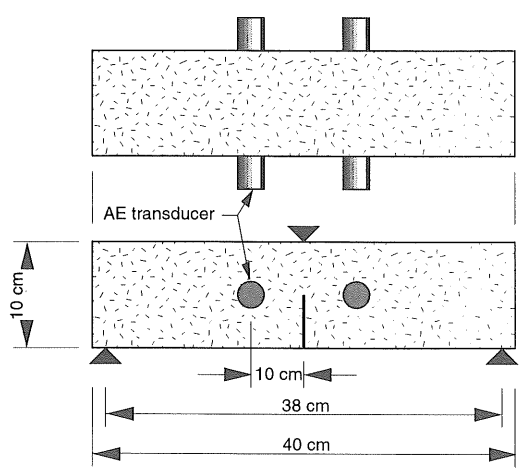
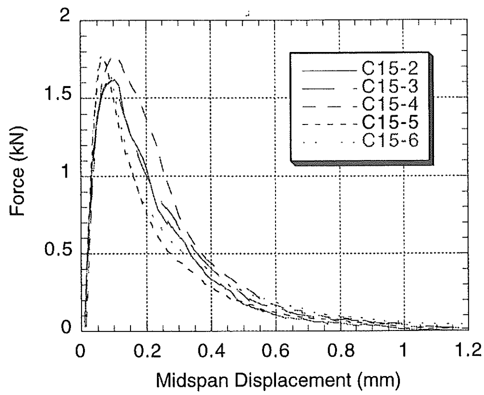
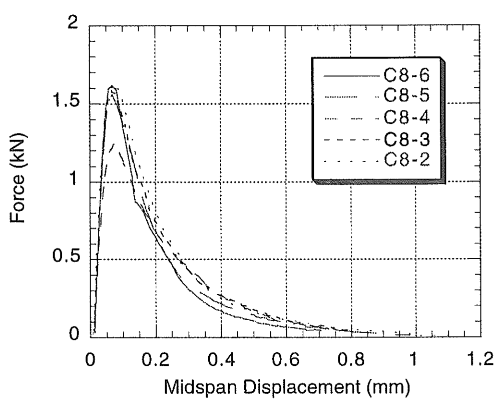


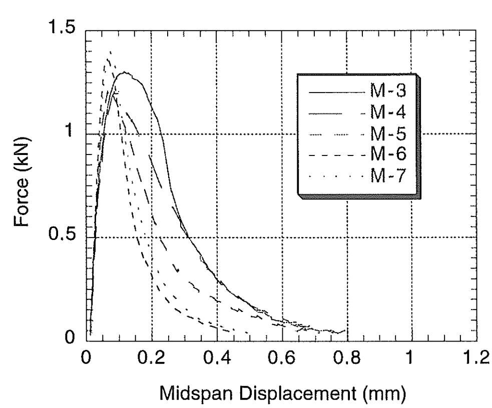
Figure 2. Specimen geometry.



(a) concrete-15 specimens



(b) concrete-8 specimens



(c) mortar specimens

Figure 3. Load vs. midspan deflection.

The three different specimen compositions varied according to maximum aggregate size. The specimens had the following designations: mortar, concrete-8, and concrete-15. The mortar had a maximum aggregate size of 3 mm, concrete-8 had a maximum aggregate size of 8 mm, and concrete-15 had a maximum aggregate size of 15 mm. The aggregate size distribution of the specimens was similar other than the maximum size. The water-cement ratio was similar for all specimens (0.60, 0.59, and 0.56 for mortar, concrete-8, and concrete-15, respectively).

Five specimens of each type (15 total) were tested according to the RILEM draft recommendation for measuring fracture energy, G_f (RILEM, 1985) The specimens were loaded at a rate such that peak load was reached in about 45 seconds. Load vs. midspan deflection is shown for all specimens in Figure 3. The figures show the specimens to be relatively consistent, with the exception of the mortar which had considerable variation.

4. DATA ANALYSIS

Data analysis consisted of calculating fracture energy, G_f for each specimen, and analyzing AE energy release for each specimen.

4.1 Fracture energy

Fracture energy was calculated according to the RILEM draft recommendation, the results of which are shown in Table 1. As was noted regarding the shape of the load-deflection curves of Figure 3, the results are reasonably consistent with the exception of the mortar specimens which have a fairly large spread.

Table 1: Measured fracture energy and AE energy

Series	Specimen	Fracture Energy, G_f (N/m)	Cumulative AE Energy (relative units)
Concrete-15	2	134	0.0380
	3	133	0.0253
	4	162	0.0270
	5	120	0.0052
	6	126	0.0139
Concrete-8	2	119	0.0099
	3	102	0.0124
	4	93	0.0106
	5	96	0.0054
	6	89	0.0114
Mortar	3	113	0.0108
	4	101	0.0098
	5	80	0.0102
	6	54	0.0040
	7	60	0.0049

4.2 Acoustic emission energy

The energy of an electrical signal is a proportional to the square of the voltage, so in our simplified analysis we square and integrate the recorded voltage transients for each channel (Harris and Bell, 1977):

$$E_i = \int V_i(t)^2 dt \tag{1}$$

where the i subscript denotes the channel of the recorded voltage transient. This value is summed over all four channels to get the total energy released for each event. The total of energy released for all events is presented in Table 1.

A problem with this energy measurement is that the measurement is not necessarily a function of the AE source alone, but also a function of the structure and measurement system. The signal attenuates as it progresses from the AE source to the transducer, and the signal can be corrupted by resonances in the measuring transducers. We tried to minimize these effects by using a geometrically consistent experimental setup, both in specimen geometry and AE transducer layout, and by using broad-banded transducers. An ideal energy calculation would reflect the true measure of the energy being transmitted by the elastic waves, and would be in the same units as fracture energy

5. RESULTS AND DISCUSSION

An example of the results from a single test are shown in Figure 4. The figure shows both load and cumulative AE energy release against a common time axis. The figure illustrates several typical phenomenon. First, as is generally observed, little acoustic emission activity occurs before peak load. In this example the jump in AE activity occurs simultaneously with crack extension and onset of strain softening. Secondly, it can be observed that in this case the AE energy release rate (slope of the plot in Figure 4) is greatest at the peak, perhaps indicating that the fracture energy released is maximum at this point. The rate of AE energy release starts to decrease when the load drops to about 40% of peak.

Similar observations can be made of the concrete specimens as shown in Figure 5. Again, the AE energy release rate takes off at the point of maximum

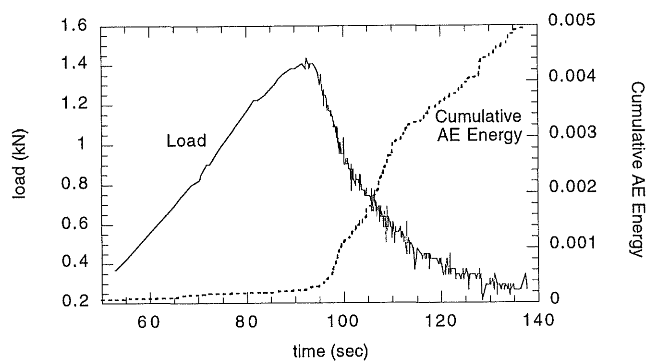


Figure 4. Plot of load and AE energy versus time for mortar specimen 7

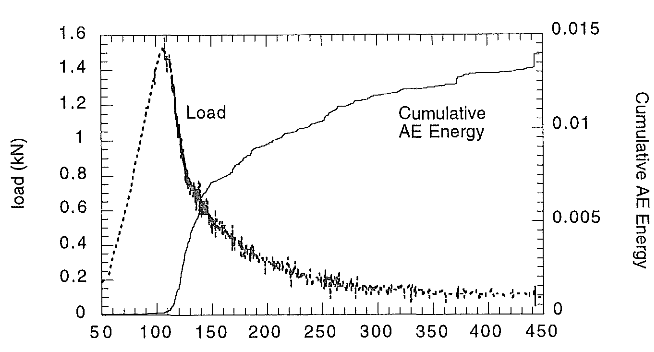


Figure 5. Plot of load and AE energy versus time for concrete15 specimen 6

load and tapers off at about 50% past peak load.

The relationship that interests us most is that between the measured fracture energy and the cumulative AE energy for all specimens tested. The data for this relationship is presented in Table 1, and is plotted in Figure 6.

The figure shows that there is clearly a relationship between fracture energy, G_f, and acoustic emission energy, however there is sufficient scatter to hide any potential functional relationship.

It is interesting to note that the mortar specimens which showed the greatest scatter in fracture energy, show the least amount of scatter in the plot. In fact the relationship seems quite linear. Alternatively, the concrete-15 specimens, which showed the least amount of scatter in fracture energy, show the greatest scatter in this plot.

The reasons for this discrepancy could be many. First of all, from an ultrasonic wave propagation standpoint, the size of the largest aggregates approach that of the shortest wavelength. For a typical ultrasonic pulse velocity in concrete of 4000 m/s, a wavelength of 15 mm would correspond to a frequency of 267 kHz, which is well within the typical frequency ranges of ultrasonic signals in concrete. Indeed, for a typical frequency range of 100-500 kHz, the corresponding wavelengths are 40 mm to 8 mm, respectively. Thus both concrete-8 and concrete-15 have aggregates in this regime of ultrasonic scattering. Ultrasonic scattering will cause additional signal attenuation and therefore reduce the total elastic wave energy that reaches the transducers.

6. CONCLUSIONS

A first attempt was made at relating acoustic emission energy to fracture energy for the purpose of developing a laboratory tool that could be used to quantify damage in concrete structures. Such a quantitative damage measurement could be used to tune and verify computational damage models for a wide range of specimen geometries and loading states.

As we expected, we found reasonable proportionality between AE energy and fracture energy, however the technique has not been sufficiently refined for general application to a wide variety of structural testing applications. Some suggestions for future work are as follows:

- Develop signal processing techniques where AE voltage transients are used to produce AE energy measurements in Joules or other force-length units.
- Develop a test protocol that can handle a wide range of specimen geometries such that effects of transducer positions are minimized.
- Incorporate ultrasonic material properties into the analysis techniques so that effects of waveform attenuation and dispersion can be taken into account.

With these additions, the technique could be an extremely powerfull tool for experimental validation of damage models.

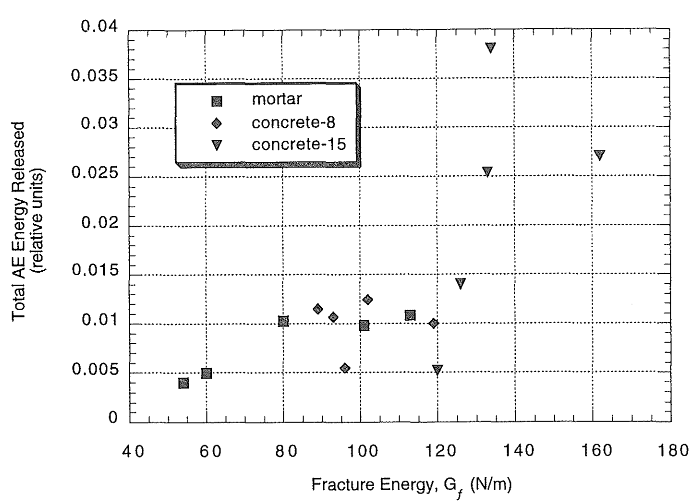


Figure 6. Plot of Cumulative AE Amplitude vs. Fracture Energy for all Specimens

7. ACKNOWLEDGEMENTS

The research described in this paper was conducted while the first author was a visitor at the Laboratory for Construction Materials (LMC) at the Swiss Federal Institute of Technology in Lausanne. The support of the LMC, and Professor Christian Huet its Director, is gratefully acknowledged. Additional support for was provided by the U.S. National Science Foundation (grant number 9733769) is also acknowledged.

8. REFERENCES

Bazant, Z. P., and Planas, J. (1998). Fracture Mechanics and Size Effect in Concrete and Other Quasibrittle Materials, CRC Press, New York.

Harris, D. O., and Bell, R. L. (1977). "The Measurement and Significance of Energy in Acoustic Emission Testing." Experimental Mechanics, 17, 347-353.

Karihaloo, B. L. (1995). Fracture Mechanics and Structural Concrete, Longman Scientific & Technical, New York.

Landis, E. N., and Shah, S. P. (1995). "The Influence of Microcracking on the Mechanical Behavior of Cement-Based Materials." Advanced Cement Based Materials, 2(3), 105-118.

Li, Z., and Shah, S. P. (1994). "Microcracking in Concrete under Uniaxial Tension." ACI Materials Journal, 91(4), 372-381.

Lockner, D. A., Byerlee, J. D., Kuksenko, V., Ponomarev, a., and Sidorin, A. (1991). "Quasi-static fault growth and shear fracture energy in granite." Nature, 350, 39-42.

Maji, A. K., and Shah, S. P. (1988). "Process Zone and Acoustic Emissions in Concrete." Experimental Mechanics, 28, 27-33.

Nomura, N., Mihashi, H., and Izumi, M. (1991). "Properties of Fracture Process Zone and Tension Softening Behaviour of Concrete." Fracture Processes In Concrete, Rock, and Ceramics, J. G. M. v. Mier, J. G. Rots, and A. Bakker, eds., Chapman & Hall, London, 51-60.

Ohtsu, M. (1987). "Mathematical Theory of Acoustic Emission and its Application." Memoirs of the Faculty of Engineering, Kumamoto University, 32, 1-28.

Ohtsu, M. (1996). "The history and development of acoustic emission in concrete engineering." Magazine of Concrete Research, 48(177), 321-330.

Ohtsu, M., Okamoto, T., and Yuyama, S. (1998). "Moment Tensor Analysis of Acoustic Emission for Cracking Mechanisms in Concrete." ACI Structural Journal, 95(2), 87-95.

RILEM Committee 50-FMC (1985). "Determination of the Fracture Energy of Mortar and Concrete by Means of Three-Point Bend Tests on Notched Beams." Materiaux et Constructions, 18(106), 285-290.

Shah, S. P., Swartz, S. E., and Ouyang, C. (1995). Fracture Mechanics of Concrete: Applications of Fracture Mechanics to concrete, Rock, and Other Quasi-Brittle Materials, John Wiley & Sons, Inc., New York.

Suaris, W., and van Mier, J. G. M. (1995). "Acoustic Emission Source Characterization in Concrete under Biaxial Loading." Materials and Structures, 28, 444-449.

van Mier, J. G. M. (1997). Fracture Processes of Concrete, CRC Press, New York.