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Acoustic emission monitoring of flexural failure in asbestos cement composites

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SYNOPSIS

The necessity for an effective non-destructive testing assessment of the integrity of cement-based fibre composite structures is now recognized. There is also the requirement for a monitoring technique which can provide quantitative mechanistic characterisation of such composites. In this paper a comparative study has been carried out on the acoustic emission behaviour of asbestos cement composites loaded in flexure. It has been confirmed that sub-critical cracking can be detected in this material at relatively low loads; however, no useful correlation could be found between various acoustic emission parameters and effective fracture energy. Further, tests designed to modify the relative proportions of the different failure modes possible in this material, through changes in specimen geometry and fibre processing treatment, indicate no possibility for differentiation between alternative mechanisms by acoustic energy amplitude discrimination techniques.

KEYWORDS

Composite materials, asbestos cement products, nondestructive testing, acoustic measurement, crack inspection, materials testing, notch strength, flexural strength, fracture energy, strength of materials, failure, mechanical properties, testing equipment.

Introduction When a material under load begins to fail by cracking, the associated relaxation or redistribution of stresses gives rise to stress waves which propagate within the material. When these stress waves reach the surface they can be monitored by utilising a piezo-electric crystal transducer which converts the energy received from the stress wave into an electrical impulse. This procedure is known as acoustic emission monitoring, and within the last decade a growing interest has developed in this technique as a tool for the non-destructive testing of structural materials. For example, acoustic emission has been used for continuous monitoring of reactor pressure vessels [1], for machinery surveillance [2] and for the detection of post weld cracking [3].

Acoustic emission monitoring has also been used quite extensively in the investigation of deformation and failure of composite materials (4–10) and, as an 'early warning' indicator, there is evidence to suggest that acoustic emission can be detected in composites down to as low as 50% of the failure load [11]. Much of this current literature has recently been reviewed in depth by Williams and Lee [9], and it would appear that acoustic emission has been used with success in composite materials on a qualitative basis for both flaw detection and the evaluation of failure modes.

In general, for fibre composites, failure mechanisms include fibre breakage, fibre-matrix debonding, fibre pull-out and matrix cracking. Each of these mechanisms should contribute to the total acoustic emission, and it has been suggested [4,10] that these various forms of matrix-fibre interaction have their own characteristic

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amplitude and/or frequency band of the acoustic emission signal. It is then possible that these mechanisms — and their respective dominance or otherwise — can be distinguished using amplitude or frequency distribution analysis.

Asbestos cement composites are probably the most important cement-based fibre composites currently in industrial use, and they are widely employed in construction engineering. Certainly there are some critical applications, for example in buried pipelines, where a reliable and (relatively) inexpensive non-destructive tool could be of enormous benefit for the detection, and subsequent location, of defective areas. In addition, the reported health risks associated with the use of asbestos fibres have contributed to significant efforts aimed at finding suitable alternative fibres for use in a cement matrix. The failure process in asbestos cement composites is complex, however, and effective replacement programmes can only be founded on an inherent mechanistic understanding of the behaviour of the material under load. Any technique which could provide some critical evaluation of the inter-relation between the various failure mechanisms in these materials would therefore be most useful.

The potential for the use of acoustic emission more generally for studies of cement matrices containing asbestos fibres, and their replacement, therefore looks promising. However, Williams and Lee [9] have emphasized the need for greater care in both acoustic emission monitoring research and reporting if it is really to be used in a reliable, quantitative manner, and particularly to facilitate a more meaningful comparison of data obtained from different sources. Indeed, it is probably fair to say that in more recent years the technique of acoustic emission has fallen somewhat out of favour in certain quarters, primarily because of some unjustifiable and exaggerated claims made on its behalf.

The object of this paper, therefore is to describe a study of the use of acoustic emission monitoring in predicting failure in asbestos cement, and its potential for providing discrimination between the various fracture mechanisms which can occur in this composite.

Experimental work Asbestos cement samples were manufactured with a chrysotile fibre content of 10% and rapid hardening portland cement, cut to the specimen size 24 hours after manufacture and cured under water for 7 days. Specimens of dimensions 200 × 75 × 6 mm were tested in four-point loading with a transducer placed on the specimen surface to monitor acoustic emission as a function of applied load. In order to ensure good contact with no energy losses, a recommended high viscosity grease was used between the surfaces in contact. Small sheets of filter paper were placed under each loading pin in order to minimise noise originating with the servo-hydraulic testing machine used.

Notched specimens (Figure 1) were also tested in order to evaluate the sensitivity of the acoustic emission equipment to different fracture modes, particularly in regard to discriminatory procedures. Thus, in the notched specimens used, the total energy stored in the material becomes small in comparison with the energy required to cause fracture such that crack growth in these nominally 'brittle' materials can occur at very small loads and can propagate in a controlled, or stable manner. When loaded in flexure, asbestos cement normally fails catastrophically or semi-catastrophically, with load/deflection curves as shown schematically in Figure 2(a), which should be contrasted with the typical

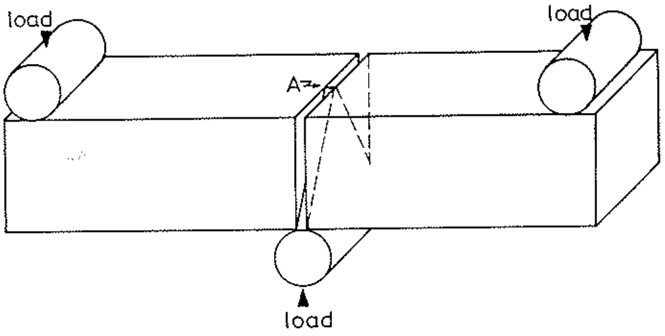


Figure 1 Notched specimen geometry for work of fracture measurements and acoustic emission studies. Cracking initiates at A, at the apex of the triangle

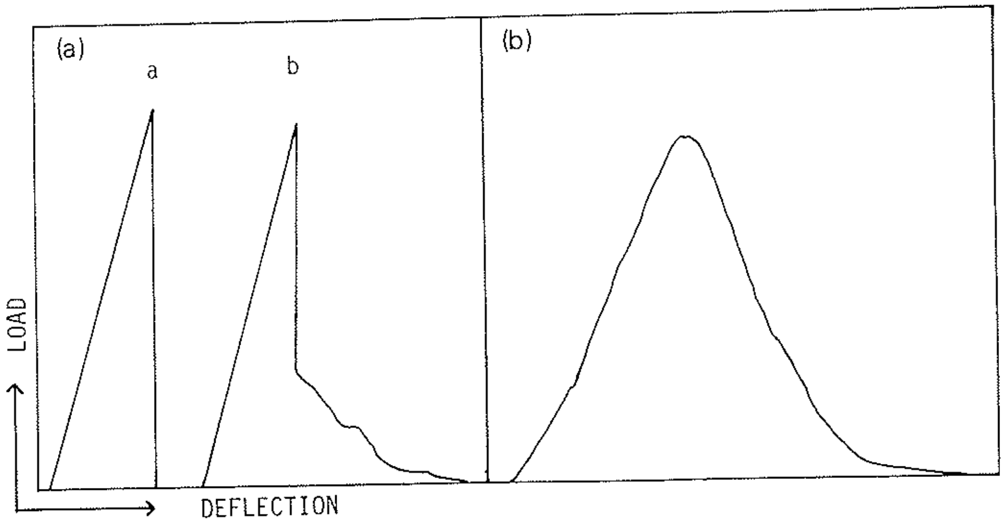


Figure 2
(a) Schematic load/deflection curves for a: catastrophic failure and b: semi-catastrophic failure
(b) Typical load/curve for non-catastrophic failure, e.g. asbestos cement specimen notched as per Figure 1

load/deflection curves obtained for non-catastrophic failure, Figure 2(b). In this latter case, in pre-notched samples, cracking which occurs after the maximum load will be dominated by fibre pull-out and, to a lesser extent, by fibre breakage. Extensive matrix micro-cracking which occurs up to the maximum load can therefore be separated out for purposes of the acoustic emission monitoring study.

The notched specimen geometry shown in Figure 1 has in fact been developed (12–14) to provide a quantitative assessment of effective fracture energy in nominally brittle materials. In the present study variations in the asbestos fibre processing treatment were made in order to evaluate any correlation between measured acoustic emission monitoring parameters and the materials fracture resistance, as measured by the effective fracture energy (which was determined from the area under the load/deflection curve for stable fracture and the fractured cross-sectional area.)

Two commercial acoustic emission systems (designed for amplitude discrimination) from different manufacturers were used and compared. These were

1. Dunegan/Endevco amplitude detector model 921, distribution analyser model 920, preamplifier model 801 P, transducer model 9201 and an X-Y recorder model 115.
2. Brüel and Kjaer pulse analyser type 4429, wideband conditioning amplifier type 2638, preamplifier type 2637 and transducer type 8313.

Table 1 lists the optimum operating conditions used for the tests described in this paper. (Various system parameters were tried until optimum conditions were achieved.) In order to pre-empt any subsequent criticism made on the basis of operator inexperience, tests were carried out in conjunction with the relevant technical sales personnel of the organisations concerned. Indeed this was essential since the study was in part made as a feasibility evaluation for the possible equipment purchase.

Table 1 Operating specifications for acoustic emission monitoring equipment

Instrumentation	Dunegan/Endevco	Brüel and Kjaer
Transducer resonance frequency	140 KHz	200 KHz
System gain	40 dB	50 dB
Signal filtering	2 KHz – 2 MHz	100 KHz – 2 MHz

Results and discussion Figure 3 shows typical load/time curves for the plain flexural specimens superimposed over acoustic emission/time read outs for both interval counting, Figure 3(a) (where peaks represent the number of emissions above a pre-set threshold counted within a specific time interval) and cumulative counting, Figure 3(b) (total number of emissions counted from the start of the test). Corresponding results for the notched specimens are shown in Figure 4.

These results show that initial microcracking can be

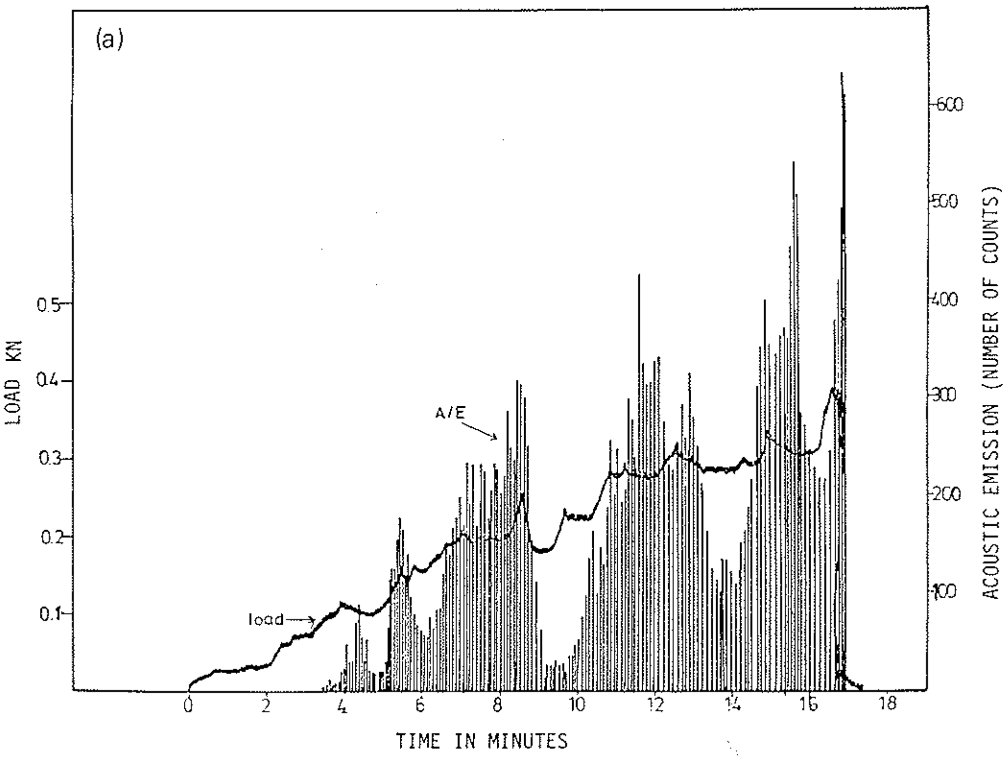
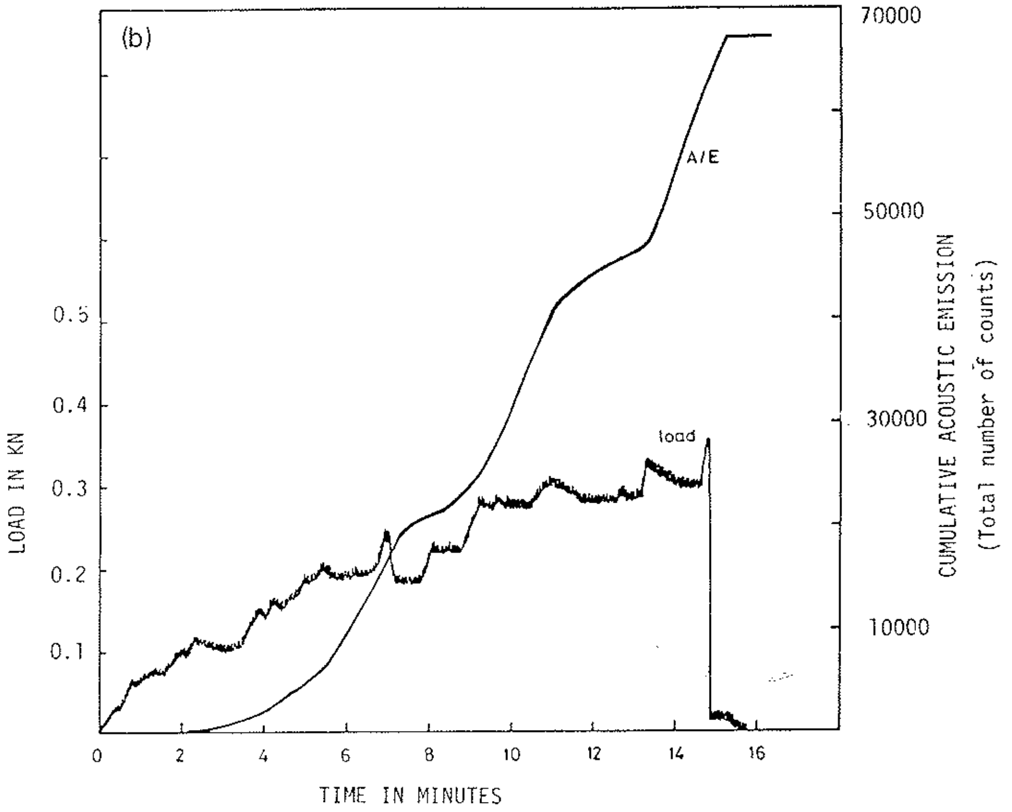


Figure 3
Typical load/time and acoustic emission/time readouts for plain specimen flexure tests:
a) interval counting.



b) cumulative counting.

detected at loads of about 30% of the maximum in modulus of rupture tests (Figure 3), and almost immediately the load is applied in notched specimens designed for work of fracture evaluation (Figure 4). This therefore confirms that acoustic emission monitoring can be a useful method for the detection of the onset and development of pre-failure cracking in asbestos cement composites.

For the notched specimens, a plot of the cumulative total number of counts divided by twice the cross-sectional area (i.e. the area of the two fractured halves) against work of fracture produced no simple relationship between the two parameters (Figure 5(a)) other than a more general trend towards more counts per unit area for higher toughness samples. This is hardly unexpected and is likely to be due to an overall increase in fibre-matrix debonding area and increased fibre pull-out in the tougher specimens. The area under the cumulative acoustic emission counts/time curve, normalised with respect to the fracture surface area, does however relate

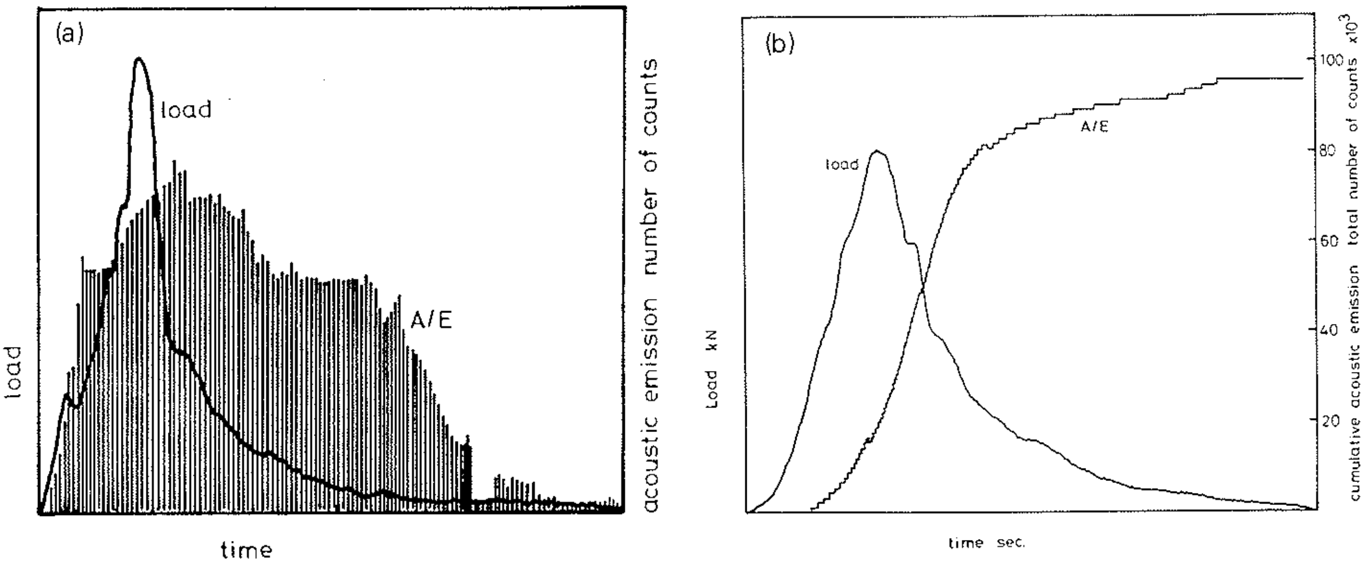
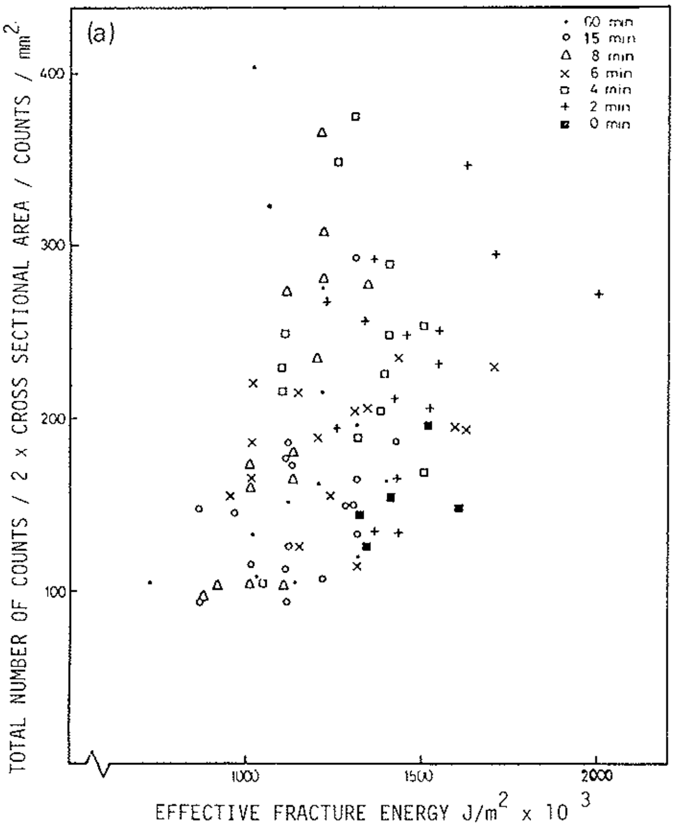


Figure 4 Typical load/time and acoustic emission/time readouts for specimens notched as per Figure 1: a) interval counting, b) cumulative counting.



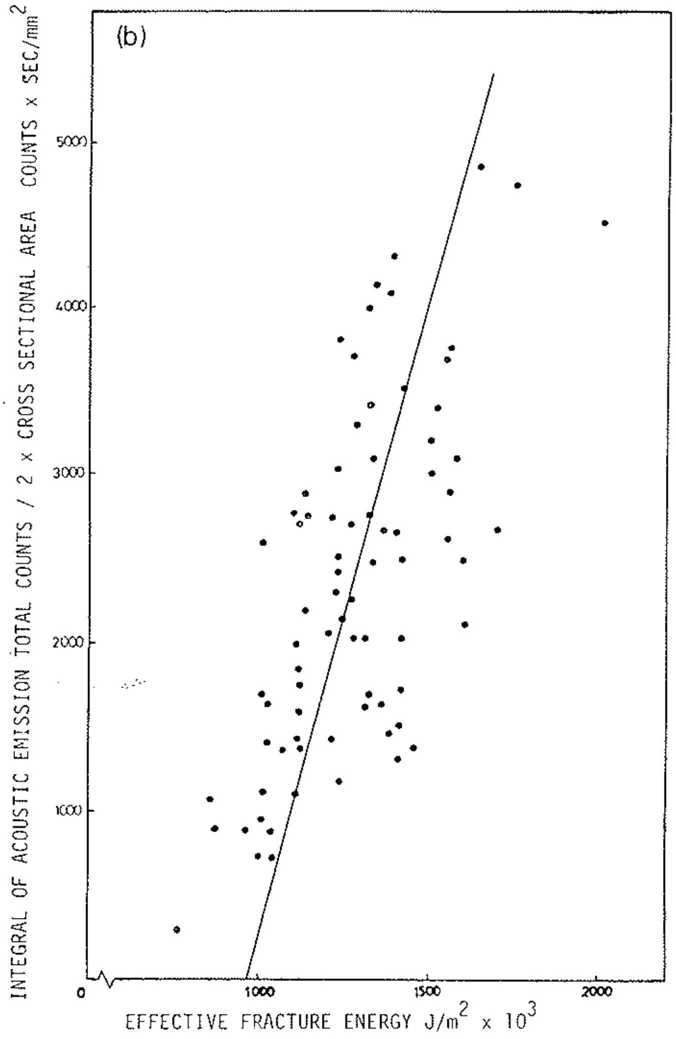


Figure 5 (a) Plot of total number of acoustic emission counts with corresponding fracture energy for a range of fiberising times (i.e. asbestos fibre bundle separation procedure)
(b) Approximate relationship between cumulative integral of acoustic emission and effective fracture energy. (Line drawn by simple regression analysis)

more closely to the fracture energy (Figure 5(b)) but does still not provide a sufficiently accurate correlation for reliable estimations of the effective fracture energy by simple acoustic emission monitoring procedures.

Using Dunegan/Endevco equipment, firstly, an attempt was made to discriminate amplitudes of the acoustic emission signals received. The amplitude detector characterises the acoustic emission signal according to peak amplitudes which could be stored in 100 separate segments of the distribution analyser. As mentioned in the preceding section, a comparison of the acoustic emission response on loading the plain specimens, with that received after the maximum load in the notched specimens should provide a means of separating the contribution from matrix cracking. Subsequent tests were arranged to change the relative proportion of fibre pull-out to fibre breakage by altering the fibre pre-processing treatment (larger diameter, longer fibre bundles having an increased potential for inter-fibre separation and breakage). However, comparison of the data received from a large number of tests, of which typical examples of the results for plain and notched specimens are given in Figure 6, indicates that very similar curves were obtained. Thus it appears that no matter how these data were subsequently processed or the system parameters varied no statistical pattern could be found for separating the various fracture modes according to emission amplitude.

A similar story was found when using the Brüel and Kjaer equipment. In this case, amplitude discrimination was performed by measurement of the time during which the acoustic emission signal exceeds four pre-set trigger levels having an amplitude relationship 1:2:4:8 (Figure 7). In essence, the acoustic emission count registered in each of the four channels contained in the pulse analyser is a measure of the area under the level — time curve of the acoustic emission signal (Figure 7). For each test carried out, the total acoustic emission pulse count was recorded in each of the four channels. A random selection of three test results for both plain and notched specimens, in the latter case the acoustic emission equipment again being activated only after maximum load, is shown in Figure 8. The data indicate that the reproducibility within a particular test series is

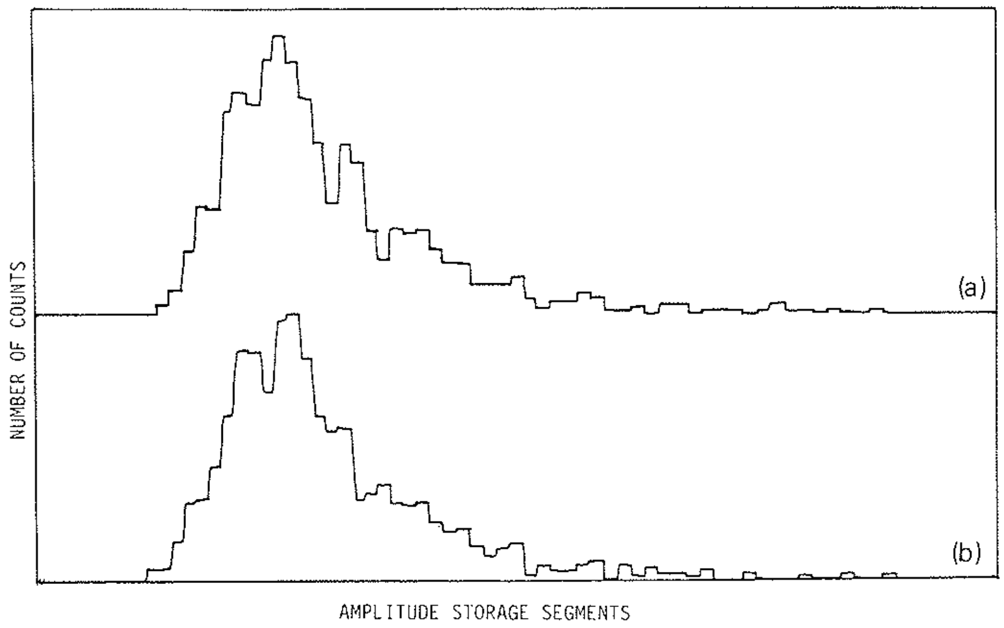


Figure 6
Typical amplitude discrimination results for the Dunegan/Endevco system for asbestos cement, a) plain flexure, b) notched (acoustic emission counting activated only after maximum load)

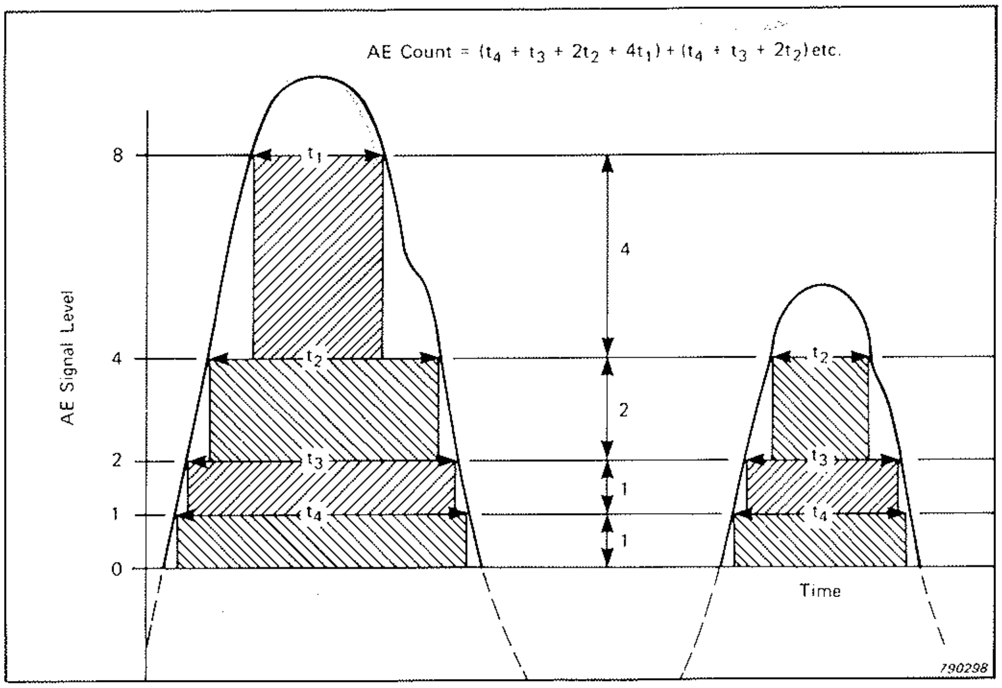


Figure 7
Brüel and Kjaer procedure for the measurement of the approximate area under the acoustic emission curve

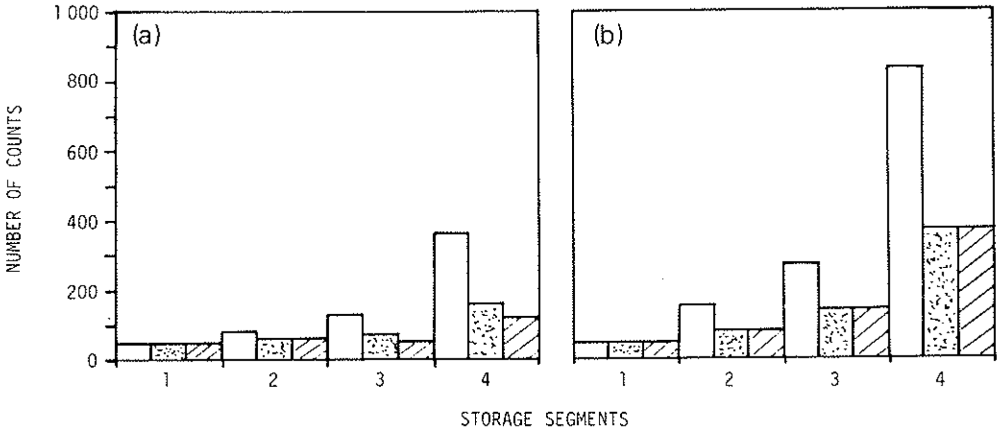


Figure 8
Normalised distribution of amplitudes in four separate storage channels, each channel showing the results for three tests, obtained from the Brüel and Kjaer pulse analyser, for a) plain flexure, b) notched

not good; further, the amplitude discrimination between the various failure mechanisms occurring is also not possible.

CONCLUSIONS

1. Acoustic emission instrumentation indicates that cracking in asbestos cement composites tested in flexure commences at about 30% of the maximum load. In notched specimens cracking can commence almost as soon as loading is applied.

2. Although there is a general trend in the relationship between acoustic emission parameters and effective fracture energy, this is not sufficiently precise to provide any correlation suitable for indirect assessment of composite toughness by acoustic emission procedures.

3. There is no basis whatsoever for using amplitude discrimination in acoustic emission monitoring for distinguishing between the various failure modes which occur in this material.

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