JOURNAL OF MATERIALS SCIENCE 26 (1991) 1301–1310

Testing E-glass fibre bundles using acoustic emission

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In tensile tests on lubricated bundles of a few hundred parallel E-glass fibres it is shown that individual fibre breaks, to the last fibre in the bundle, can be detected using acoustic emission (AE). By this means the single-fibre strength distribution is deduced. Relationships are obtained between some AE signal parameters and the fibre fracture stress which are consistent with theoretical expectations. Studies are made of the distribution of fibre break locations, the occurrences of multiple (stimulated) fibre breaks and the attenuation of the AE signals.

1. Introduction

In fibres of brittle materials, such as carbon or glass, the strength is normally limited by the most severe defect present and, for a set of apparently similar fibres, the strength distribution can often be represented by a two-parameter Weibull function [1]. For a large number, N_0, of fibres (perhaps in a bundle) the number of unfractured fibres when the stress in each is σ is given by

$$N = N_0 \exp\left[-\left(\frac{\sigma}{\sigma_0}\right)^m\right] \quad (1)$$

The scale parameter, σ_0, is proportional to $l^{-1/m}$, where l is the length of the fibres. It may be seen that σ_0 is the stress where $N = 0.368N_0$. The Weibull modulus, m, is a shape or flaw distribution parameter and is a constant of the fibre material: a large value of m indicates fibres with a uniform distribution of similar defects, while a small m describes fibres with a large variation in defect sizes. From Equation 1, if a Weibull distribution is an appropriate description of experimental data from a given set of fibres, then the data plotted as $\ln\ln(N_0/N)$ against $\ln\sigma$ will give a straight line whose slope yields m. The fracture stresses are usually found by testing large numbers of individual fibres; this process is tedious, time-consuming, and also entails a likelihood of contaminating or damaging the fibres (even breaking the weaker ones) by handling. However, Weibull parameters have not been found and reported in the literature by methods employing bundle tests, probably because of the difficulty of detecting fibre fractures in a bundle.

In this paper it is shown that acoustic emission (AE) monitoring of a lubricated bundle of E-glass fibres provides a convenient and relatively quick method of obtaining the Weibull or other parameters of single-fibre strength distribution. The fibres are tested in the form of a size-coated continuous tow as-received from the manufacturer, thus minimizing the amount of handling (and hence damage) in making the strength measurements. The principle of AE is that when cracking occurs in a brittle material the impulsive release of elastic energy generates a transient stress wave which travels through the material and may be detected by means of piezoelectric transducers attached to the specimen or component. As in most AE work to date, the AE signals are detected by resonant piezoelectric transducers whose output is not an electrical analogue of the stress impulse, but roughly resembles a decaying sine wave, Fig. 1. We shall show that monitoring such AE bursts ("events") provides a reliable means of identifying fibre fractures as they occur in a large bundle under tension, a detection capability which would be difficult to achieve by optical, load drop or strain measurements. While bundle testing to obtain the Weibull parameters of perfectly elastic fibres using a load–strain curve has recently been demonstrated [2, 3], the AE method employed herein is shown to be complementary; it can be used irrespective of whether a Weibull strength distribution applies or whether there is plasticity in the fibres, and yields additional information such as the fracture stress, time of fracture and fracture location for each fibre break in the bundle. The AE equipment for such bundle tests need not be sophisticated, so that the method we have developed appears to have the potential to be of general industrial use for routine monitoring of fibre strength distributions.

2. Theory

In the bundle test reported in this paper the stress, σ, for each fibre break is calculated assuming the applied load, F, to be shared equally among the N similar fibres surviving before the break, thus

$$\sigma = \frac{F}{NA} \quad (2)$$

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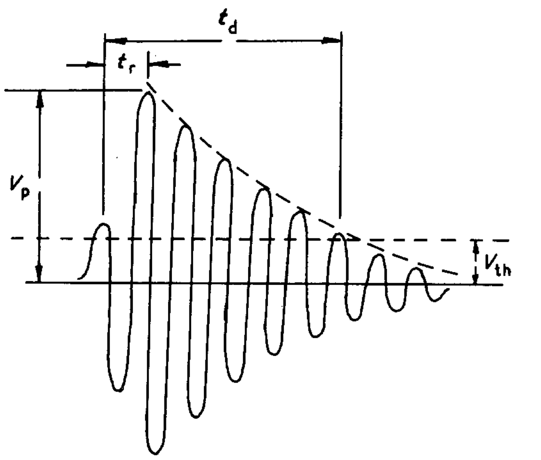

Figure 1 Acoustic emission parameters (peak amplitude, V_p, threshold voltage, V_{th}, risetime, t_r, event duration, t_d) extracted from an idealized decaying sine wave oscillation generated as a result of an impulsive AE source event. In this example the number of ringdown counts (positive threshold crossings), $R = 7$.

where A is the mean cross-sectional area of the fibres. From Equations 1 and 2 the bundle load is

$$F = N_0 A\sigma \exp\left[-\left(\frac{\sigma}{\sigma_0}\right)^m\right] \quad (3)$$

By putting $dF/d\sigma$ obtained from Equation 3 equal to zero and rearranging, the maximum value of the bundle load, F_{max}, is found to be given by

$$F_{max} = N_0\sigma_0 A(em)^{-1/m} \quad (4)$$

The corresponding stress at maximum bundle load is

$$\sigma^* = \sigma_0 m^{-1/m} \quad (5)$$

and the number of fibres surviving

$$N^* = N_0 e^{-1/m} \quad (6)$$

From Equation 6

$$m = \left(\ln\frac{N_0}{N^*}\right)^{-1} \quad (7)$$

Where a Weibull distribution of strengths applies, Equations 5 and 7 provide ways of obtaining σ_0 and m from a knowledge of the maximum bundle load and the corresponding number of surviving fibres [4].

The so-called bundle strength, σ_b, based on the cross-sectional area of the original number of fibres, is given by Equation 4

$$\sigma_b = \frac{F_{max}}{N_0 A} = \sigma_0(em)^{-1/m} \quad (8)$$

while the median fracture stress, σ_{median}, is obtained by putting $N/N_0 = 0.5$ into Equation 1

$$\sigma_{median} = \sigma_0(\ln 2)^{1/m} \quad (9)$$

In tests on brittle fibres the bundle strength is often compared with the median strength

$$\frac{\sigma_b}{\sigma_{median}} = \frac{\sigma_0(em)^{-1/m}}{\sigma_0(\ln 2)^{1/m}} = (1.884\,m)^{-1/m} \quad (10)$$

This ratio depends only on the Weibull modulus, m, and hence on the degree of scatter of fibre strengths. However, a more usual indication of the dispersion of fibre strengths is the coefficient of variation, CV (ratio of strength standard deviation to mean). For values of m greater than about 5 a good approximation is [5]

$$\mathrm{CV} = \frac{1.2}{m} \quad (11)$$

If, as in glass fibres, the material is elastic up to fracture, with modulus of elasticity, E, the relationship between stress, σ, and strain, ε, is $\sigma = \varepsilon E$. Equations 1, 3, 4, and 5 may then be written in alternative form by putting $\varepsilon_0 = \sigma_0/E$ and are, respectively

$$N = N_0 \exp\left[-\left(\frac{\varepsilon}{\varepsilon_0}\right)^m\right] \quad (12)$$

$$F = \sigma AN = N_0 A\varepsilon E \exp\left[-\left(\frac{\varepsilon}{\varepsilon_0}\right)^m\right] \quad (13)$$

$$F_{max} = N_0 A\varepsilon_0 E(em)^{-1/m} \quad (14)$$

$$\varepsilon^* = \varepsilon_0 m^{-1/m} \quad (15)$$

The slope, S_0, of the load–strain curve of the fibre bundle at zero strain is

$$S_0 = \left.\frac{dF}{d\varepsilon}\right|_{\varepsilon=0} = N_0 AE \quad (16)$$

From Equations 12, 13 and 16 we then obtain

$$\frac{F}{S_0\varepsilon} = \frac{N}{N_0} = \exp\left[-\left(\frac{\varepsilon}{\varepsilon_0}\right)^m\right] \quad (17)$$

A plot of $\ln\ln(S_0\varepsilon/F)$ against $\ln\varepsilon$ will be linear with slope m if the test data follow a Weibull distribution. Equations 14 and 15 give

$$\frac{F_{max}}{\varepsilon^*} = N_0 AEe^{-1/m} = S_0 e^{-1/m} \quad (18)$$

or

$$m = \left[\ln\left(\frac{S_0\varepsilon^*}{F_{max}}\right)\right]^{-1} \quad (19)$$

Hence the Weibull modulus can be obtained from the initial slope and load and strain at maximum of the load–strain curve for the bundle. Equations 17 and 19 have been used to obtain values of m for carbon [2] and E-glass [3] fibres from the macroscopic mechanical properties of fibre bundles in tension.

3. Experimental procedure

E-glass fibre tow treated with "chrome" size was supplied by Owens Corning Fiberglas, UK. The mean fibre diameter (nominally 10 to 12 μm) and the number, N_0, of fibres in the tow were found from electron micrographs of sliced end-views of resin-embedded samples. N_0 could also be determined independently from the AE event print-out of the tested bundle.

The ends of a bundle specimen to be tested were cemented to aluminium plates using epoxy resin, taking care that the fibres were parallel. The free length of the bundles was 20 to 22 mm. The end-plates were mounted in the grips of an Instron 1195 machine. Resonant PZT transducers (Acoustic Emission Technology Corporation type AC375L: resonance frequency 375 kHz; bandwidth 200 kHz; nominal sensitivity -68 dB referred to $1\,\mathrm{V}\,\mu\mathrm{bar}^{-1}$) were clamped to the end-plates. Silicone grease was used as an acoustic couplant. AE signals from the transducers were preamplified by 40 dB and then processed using an AET 5000 A acoustic emission system. The overall system gain was 58 dB ($\times$ 800). A fixed threshold of 0.2 V was used, referred to the preamplifier output. A schematic drawing of the apparatus is shown in Fig. 2.

The AE event duration clock period was set at 250 nsec, which gave a "time-out" period between events of 64 μsec (= 256 clock periods). This resulted in dead-time losses of AE signals during bundle tests being negligible. The AE signal parameters available were energy, peak amplitude, ringdown counts, event duration, risetime and slope. Peak amplitudes, quoted in decibels, in terms of the preamplifier output voltage, V, are: $V_p(\mathrm{dB}) = 20\log_{10}(V/10^{-4})$. The linear location of each fibre fracture was obtained from time-of-arrival differences of AE signals at the two transducers. The speed of bundle loading and unloading was 0.05 mm min^{-1}.

After each fibre break, as detected by AE, the strain on the bundle was deliberately reduced by a small amount, about 5%, by movement of the cross-head, before being raised again to obtain the next break.

4. Results

4.1. General observations

In testing size-lubricated bundles of a few hundred parallel E-glass fibres in tension we have found that there was one distinctive AE burst for each fibre fracture: such AE events were, with rare exceptions,

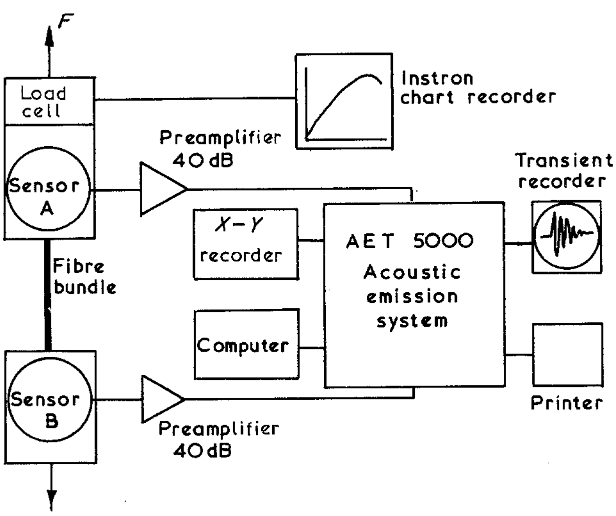

Figure 2 Experimental arrangement.

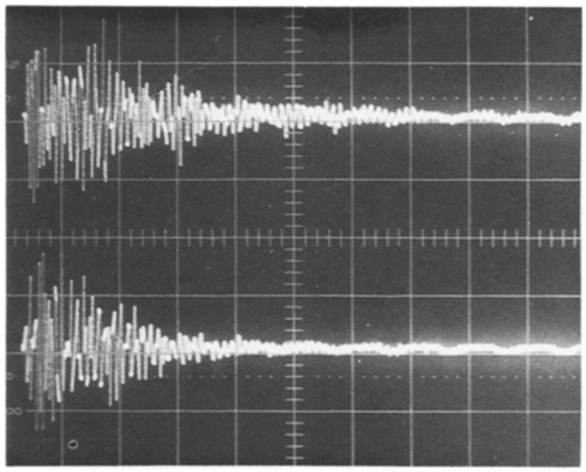

Figure 3 Typical AE signals in channels 1 and 2 resulting from a single fibre break. The vertical and horizontal scales per centimetre division are 2.0 V and 50 μsec. For the upper trace the measured AE parameters are risetime, $t_r = 17\,\mu$sec, event duration, $t_d = 190\,\mu$sec, ringdown counts, $R = 44$, peak amplitude (at preamplifier output, referred to 10^{-4} V), $V_p = 71$ dB. The threshold voltage $V_{th} = 0.2$ V and the overall system gain 58 dB.

received by both transducers and had peak amplitudes, as measured by either transducer, greater than about 60 dB. Fig. 3 shows typical fibre break AE signals.

From the AE it was found that the fibre fractures mainly occurred singly. However, in each test there were a few instances where failure of a fibre induced one or more further fractures. To this extent the fibres were not independent of each other. "Primary" fibre fracture AE events were normally separated from each other by time intervals of many seconds. Hence there was no difficulty in identifying any stimulated fractures associated with a given primary, because AE signals in a "multiplet" event occurred within a few hundred milliseconds of each other. Multiplet fibre breaks seemed to appear sporadically in any particular test and did not conform to any recognizable pattern of occurrence when comparing one bundle test with another. Catastrophic collapse of the bundles did not occur, and the majority of fibres could be broken one-by-one to the last fibre. Agreement to within 2% was routinely obtained between the number of fibre break AE events to complete bundle failure and the direct fibre number counts obtained from microscopic examination.

Bundle testing generated a number of AE events of amplitude below about 55 dB. These "noise" events were not normally produced by fibre fracture, as was confirmed by the absence of an accompanying load drop. Load drop monitoring was not, however, a reliable method of determining the number of fibre fractures. It was found that the load could be taken from its current value to zero and back at any stage of the bundle test without incurring fibre breaks. Thus the so-called felicity ratio (defined [6] as the load at which "significant" AE (fibre fracture AE in the present case) begins on the $(n + 1)$th cycle divided by the highest load reached on the nth cycle) was $\mathrm{FR} \geqslant 1.0$ for $F < F_{max}$ and $\mathrm{FR} \simeq 1.0$ for $F \geqslant F_{max}$.

4.2. Results of a bundle test

Data are presented here for a test on a bundle of Owens Corning E-glass filaments of free length 22 ± 1 mm containing, according to a microscopic determination, 194 ± 2 fibres of mean diameter 12.0 μm. For this test the sequence of fibre break AE events by linear location is plotted in Fig. 4, and the histogram of linear locations is shown in Fig. 5. The parallel dashed lines in Figs 4 and 5 indicate the linear region of the sample within which 97% of the AE events were located and so are taken to represent approximately the ends of the 22 mm fibre bundle. The AE sensor nearest to the location of any particular fibre fracture first receives the AE signal and is thus the "first-hit" sensor for that AE event. From Fig. 5 it was deduced that 196 AE events occurred associated with fibre fractures; the occurrence of multiplet fibre breaks is indicated in Fig. 4.

The variation of the number of fibre failures, N_f, with load is plotted in Fig. 6. The maximum load sustained by the bundle was 27.0 ± 0.5 N and the corresponding number of fibre fractures at maximum load was 31 ± 3. The number of fibres surviving at maximum bundle load, N^*, was thus 163 ± 5. Load drops due to fibre breakage could usually be detected, but these are not shown in Fig. 6.

Fig. 7 shows the fraction of broken fibres, N_f/N_0, plotted against fracture stress. For the 196 fibres $\sigma_{mean} = 1.65$ GPa, $\sigma_{median} = 1.76$ Gpa, sample standard deviation, $s = 0.280$ GPa.

The fibre fracture stress histogram shown in Fig. 8 reveals the mode of the distribution (centre of the interval with the greatest frequency) to be 1.65 GPa.

Fig. 9 shows a plot of bundle load, F, against strain, ε, from which we obtain the initial slope, S_0, of 1.33 kN and the strain at maximum load, ε^*, of 2.37%. Hence fibre Young's modulus, $E(= S_0/N_0A)$ is 61 GPa.

The peak amplitudes, V_{P1} (first-hit sensor), and the differences $(V_{P1} - V_{P2})$ for each fibre break AE event are shown in Figs 10 and 11, respectively. These figures show that at any stage of the test the V_{P1} and $(V_{P1} - V_{P2})$ values are scattered over a similar range, namely, some 20 dB. The mean of all 196 values of $(V_{P1} - V_{P2})$ was found to be -0.23 dB.

Fig. 12 shows a histogram of the AE event durations, t_d, of the 196 fibre break AE signals, and it may be seen that the t_d are typically a few hundred microseconds. Fig. 13 shows a histogram of the time intervals, Δt, between adjacent AE signals in the multiplet fibre break events. The Δt are normally tens or hundreds of milliseconds. The shortest Δt recorded, a single value, was 10 m sec.

In Fig. 14 the mean number of ringdown counts per AE event, R, is plotted against $\ln \sigma$. Clearly R increases with increasing fracture stress, an effect which will be discussed in Section 6.

5. Analysis of fibre strength distribution

5.1. Graphical methods for m

Fig. 15 shows a plot of $\ln \ln N_0/N$ against $\ln \sigma$. From Equation 1 the linearity indicates that a Weibull treatment is appropriate and the slope of the graph yields $m = 6.0$. The few fibres breaking at low stresses do not fit well to the linear plot, because even a small number of additional breaks at low stresses produce a large increase in $\ln \ln N_0/N$.

Fig. 16 shows a plot of $\ln \ln S_0\varepsilon/F$ against $\ln \varepsilon$. From Equation 17 this linearity supports the proposition

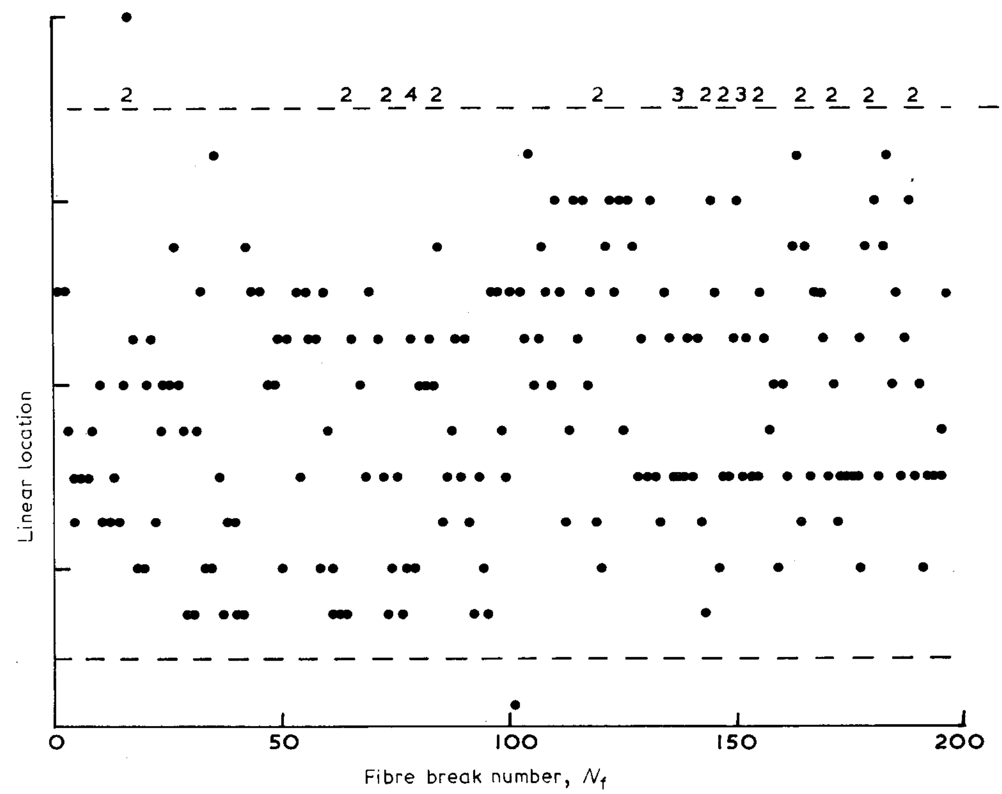

Figure 4 Sequence of E-glass fibre break linear locations in a bundle test. The dashed lines indicate the approximate locations of the bundle ends (see text). The numbers at the top of the diagram indicate the occurrences and multiplicity of multiplet fibre breaks.

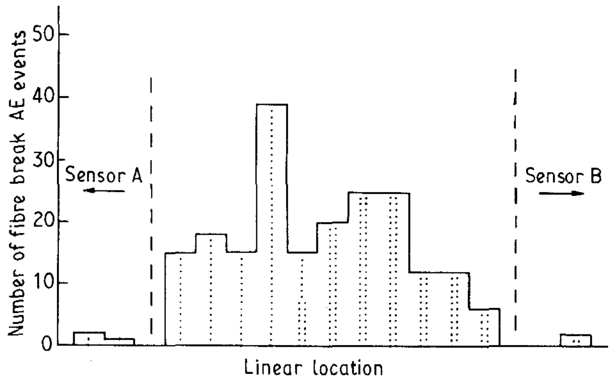

Figure 5 Histogram of E-glass fibre break linear locations in a bundle test. (•) Sensor A first hit, (••) sensor B first hit. (---) Approximate locations of the bundle ends (see text).

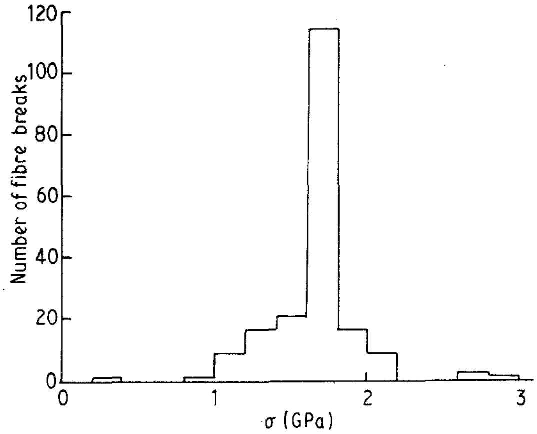

Figure 8 Histogram of E-glass fibre fracture stresses.

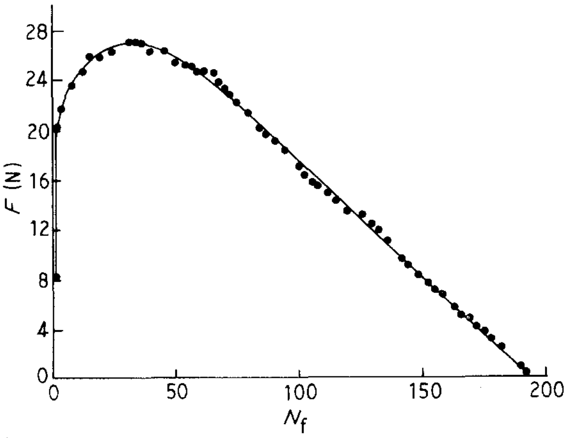

Figure 6 Variation of number of fractured fibres, N_f, with bundle load, F.

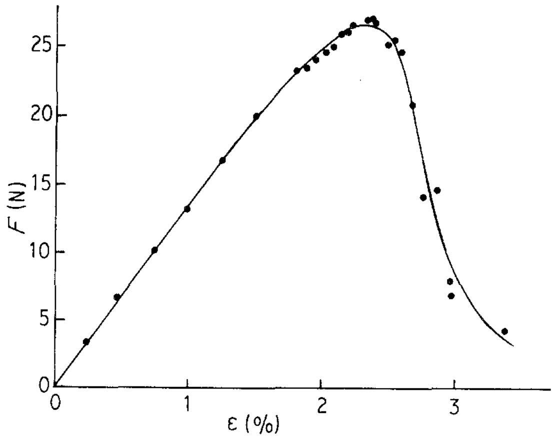

Figure 9 Plot of bundle load F against bundle strain, ε.

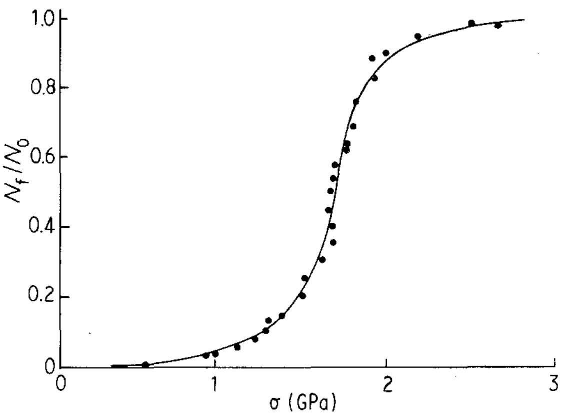

Figure 7 Fraction of broken fibres, N_f/N_0, plotted against fracture stress, σ.

of a Weibull distribution of fracture stresses, and the slope yields $m = 6.5$.

5.2. Use of maximum load points to obtain m and σ_0

From Fig. 6 we found $N^* = 163$ and $F_{max} = 27$ N. Substitution into Equation 7 gives $m = 5.8$, and into Equation 2 gives $\sigma^* = 1.47$ GPa, by using an A value obtained by microscopy of 1.13×10^{-10} m^2. Using this value of σ^* in Equation 5 gives $\sigma_0 = 1.98$ GPa.

Alternatively, using the values of S_0 and ε^* from Fig. 9 in Equation 19 we obtain $m = 6.4$ and, from Equation 15 $\varepsilon_0 = 0.032$, so that $\sigma_0 = \varepsilon_0 E = 1.95$ GPa.

5.3. Other methods for m

From Equation 8, $\sigma_b = 1.23$ GPa, then from Equation 10 we obtain $m = 6.7$. Alternatively from Equation 11, using the values of standard deviation and mean derived from Fig. 7, $m = 7.0$.

5.4. Summary

The values of m obtained for the fibre bundle by different methods are thus 6.0, 6.5, 5.8, 6.4, 6.7, 7.0, whilst those for σ_0 are 1.98 and 1.95 GPa.

6. Discussion

The mean stress to failure, $\sigma_{mean} = 1.67$ GPa for the E-glass fibres, deduced by AE monitoring, is in good agreement with manufacturer's data [7]. Referring to the range of values of m obtained by different methods, for accuracies of the m values obtained using the parameters at the maximum load points, we have $m = (\ln x)^{-1}$ where $x = N_0/N^*$ (Equation 7) or $x = S_0\varepsilon^*/F_{max}$ (Equation 19). It is readily shown from

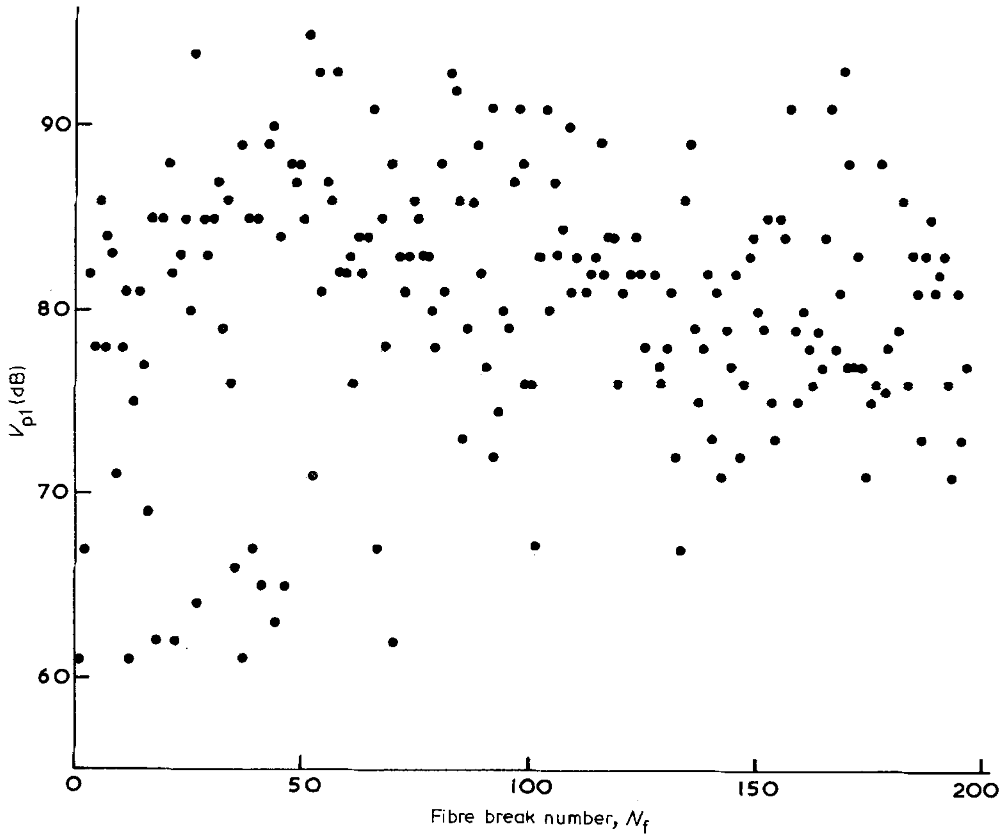

Figure 10 Sequence of peak amplitudes V_{p1} (first-hit sensor).

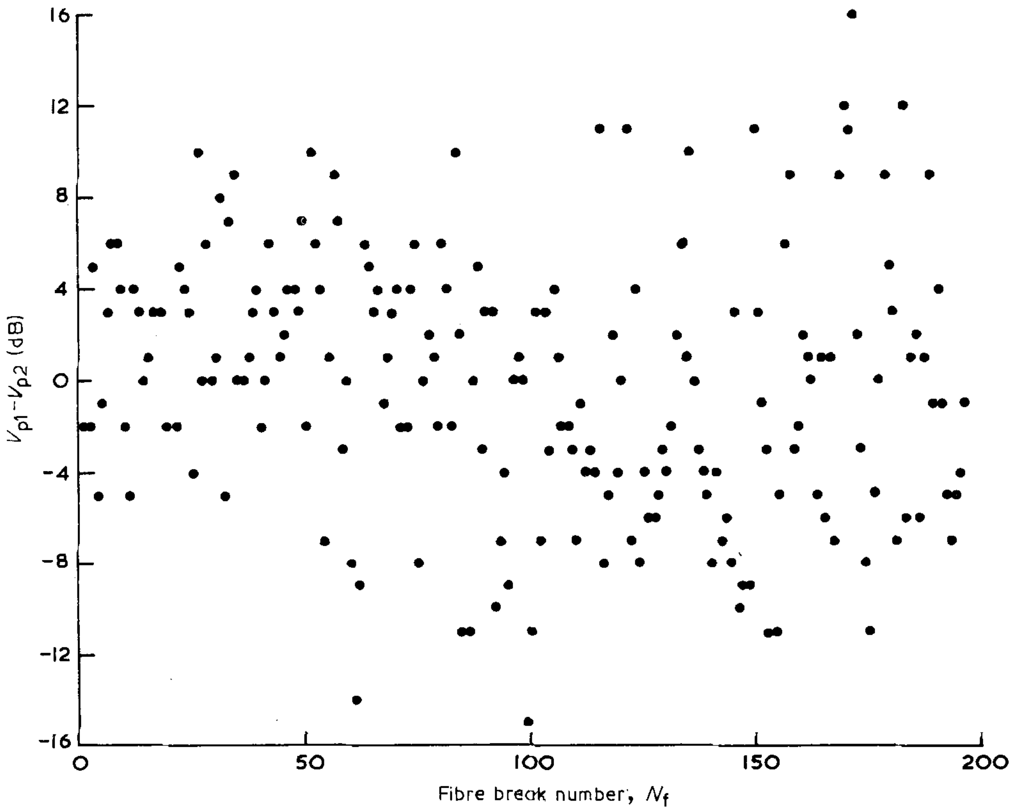

Figure 11 Sequence of AE peak amplitude differences: V_{p1} first-hit sensor, V_{p2} second-hit sensor.

this inverse logarithm that the fractional uncertainty, $\pm\,\delta m/m = \pm\, m(\delta x/x)$. For most brittle filaments $m \gg 1$, and hence large uncertainties may occur in m values derived from the parameters at maximum load. The graphical methods for m are to be preferred for accurate work.

If brittle fibres in a bundle are fractured in tension under dead loading, eventually catastrophic failure will occur when breakage of one more fibre reduces the cross-sectional area of those surviving below that which will support the current load. However, in the present quasi-static tests in the Instron machine the

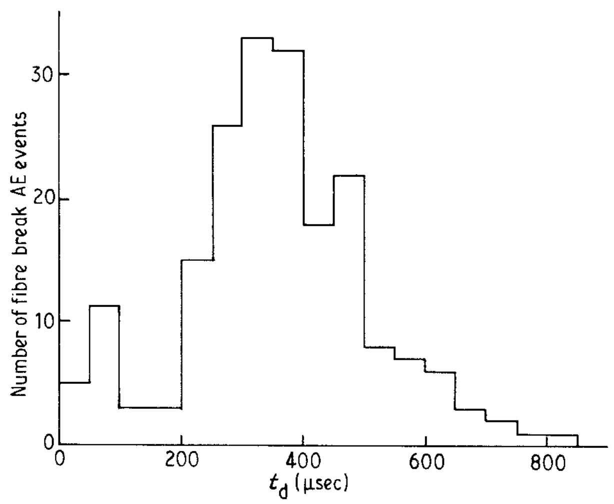

Figure 12 Histogram of E-glass fibre break AE event durations, t_d.

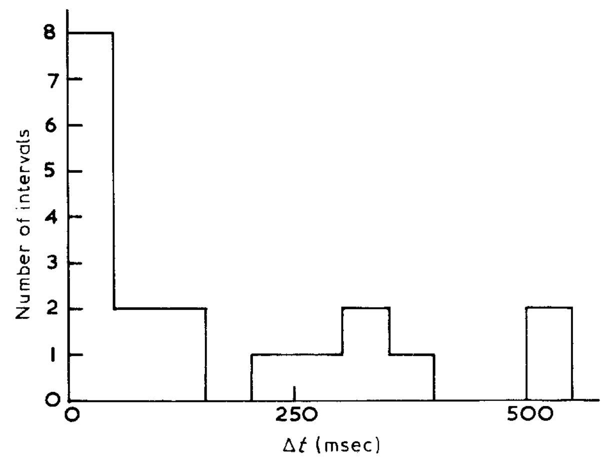

Figure 13 Histogram of time intervals, Δt, between consecutive AE events within the multiplet AE events.

bundle strain is essentially the same before and after any given fibre break and there is an accompanying load drop of magnitude $\delta F = -A\varepsilon E$. The static stress in the remaining fibres is unchanged as a result of the fibre break, and hence the multiple fractures we observe are presumed to be caused by transient load changes or other shock effects ensuing from a preceding fracture. It may be expected that these stimulated fibre fractures should occur at times within the duration, t_d, of the immediately preceding AE event, but this was not the case. For the bundle test of Section 4.2, Figs 12 and 13 show that usually $\Delta t \gg t_d$. The shortest Δt was 10 m sec and the longest t_d was 800 μ sec. Thus each stimulated AE event occurs long after the immediately preceding AE event which "caused" it. The Δt values are also much larger than the time (a few microseconds) for transverse or longitudinal waves to travel the length of the fibre bundle. The vibrations which stimulate additional fractures may be due to recoil of the suspension (grips, etc.).

Hamstad and Moore [8] have used AE to monitor filament breaks in tensile tests on bundles of loose Kevlar 49 fibres, and have observed multiple breaks. In one particular test on a bundle of 267 Kevlar filaments lubricated with silicone oil, there were 194 single-filament break events, 19 doublets, 9 triplets

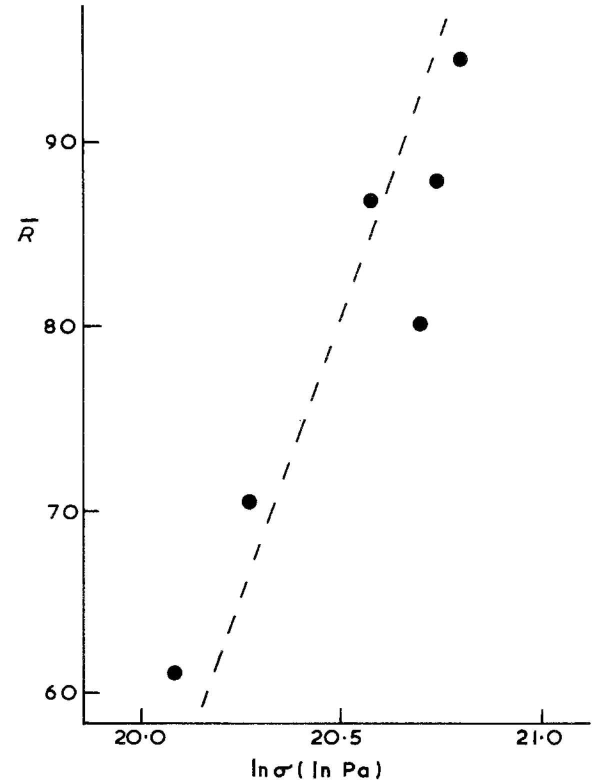

Figure 14 Mean number of ringdown counts, R, per fibre break AE event plotted against fracture stress, σ. The dashed line has numerical slope, 59, in accordance with Equation 27.

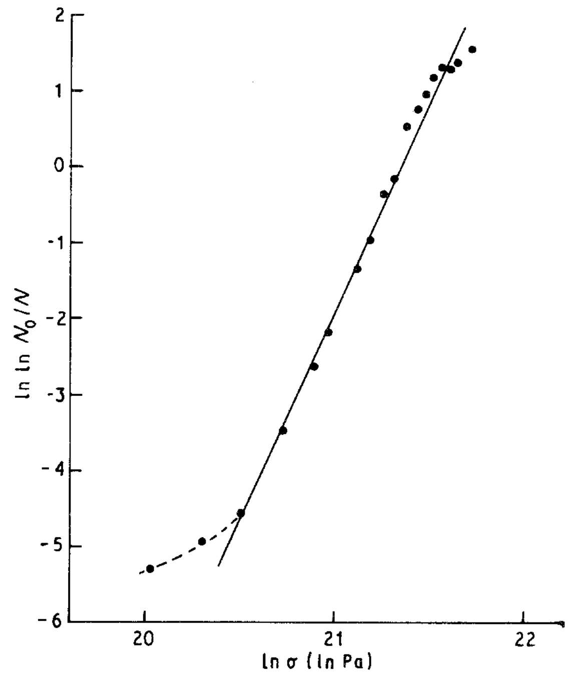

Figure 15 Plot of ln ln N_0/N against ln σ.

and 1 quintiplet. When testing dry bundles of Kevlar fibres, Hamstad and Moore found that the fibres fractured mainly one at a time up to the peak load, but then the bundle collapsed catastrophically. This was attributed to concentrations of stress in the dry bundle, due to the macroscopic effects of friction. Multiple fibre breaks in uniaxial bundle tests have also been observed by Chi *et al.* [2] in carbon fibres and by Fuwa *et al.* [9] in glass and carbon fibres. In the present experiments we note that although Fig. 4

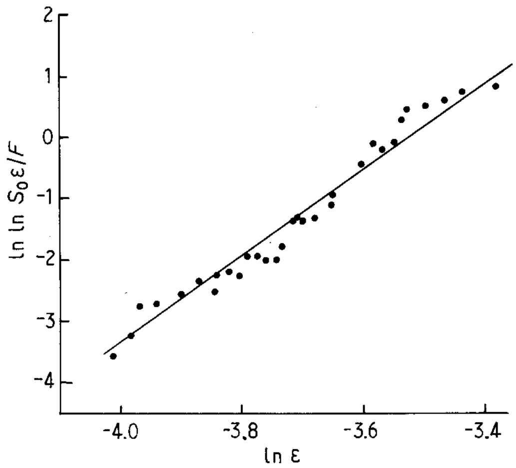

Figure 16 Plot of ln ln $S_o\varepsilon/F$ against ln ε.

reveals some short runs of fibre break AE sources with similar locations, these do not indicate significant amounts of concentrated bundle damage.

An objective of the present bundle tests was to find whether the fracture stress of a fibre or group of fibres could be correlated with some characteristic of the associated AE signals. A central difficulty here is that AE signals from similar source phenomena, such as fibre fracture at a given stress or stress intensity, are commonly found to have a wide scatter of amplitude, duration, etc. Even if an AE stress wave has energy proportional to the energy released at source there are, in general, losses such as plastic deformation, heating effects, creation of new surfaces, internal friction, attenuation, and reflection at interfaces and boundaries.

In the present experiments if we have glass fibres of length l, cross-section A, modulus of elasticity E fracturing at stress σ the elastic energy released in fracture is $U_f = \sigma^2 Al/2E$, and for each fibre a similar fraction of this energy is used at source in creating a fracture surface; the remainder presumably appears in some form of wave energy. If each AE signal were to propagate in a similar acoustic mode, or mixture of modes, and be similarly attenuated in transit to the measuring sensor then we expect the electrical energy output by the AE transducer, U_{AE}, to be directly proportional to U_f. Supposing the transducer output to be similar, as in Fig. 1, to an oscillatory voltage of frequency ω(ω is the resonant frequency of the transducer) which decays exponentially with decay constant α from a peak value V_p at $t = 0$. Then

$$V(t) \simeq V_p e^{-\alpha t} \sin \omega t \qquad (20)$$

Beattie has shown [10] that the energy in such a signal is

$$U_{AE} = \frac{1}{r}\int_0^\infty V^2(t)\,dt = \frac{1}{r}\frac{V_p^2}{4\alpha}\left[\frac{1}{1+\alpha^2/\omega^2}\right] \qquad (21)$$

where r is the resistance of the transducer. If r is constant then $U_{AE} \propto V_p^2$ and then we expect $V_p \propto \sigma$: Fig. 17 shows that the variation of mean peak AE amplitude, V_p, with stress, σ, is consistent with such a

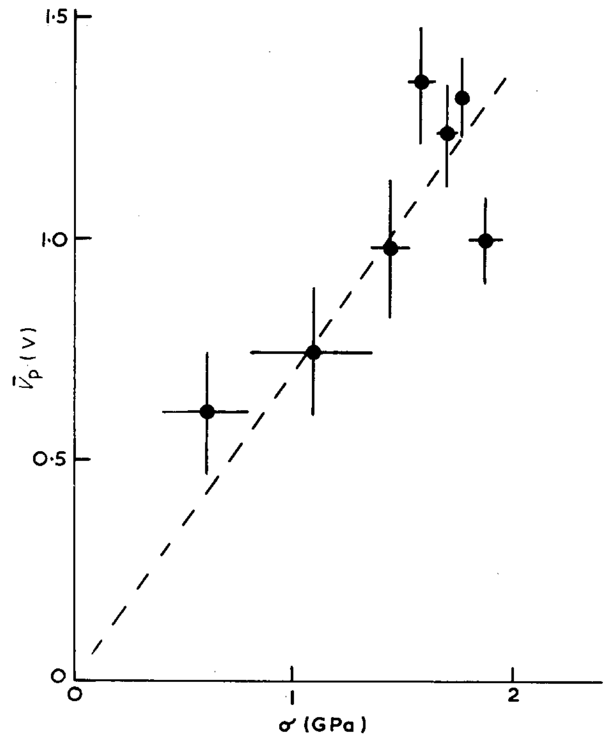

Figure 17 Mean peak amplitude $\bar{V}_p$ of the E-glass fibre fracture AE signals plotted against fracture stress, σ.

relationship. The result of Fig. 17 may be compared with the finding of Kumosa *et al.* [11] that for stress corrosion cracking in an aligned glass fibre/polyester composite, high-amplitude AE signals, originating from parallel glass fibres fracturing singly, have mean peak amplitudes which are proportional to the applied stress intensity, K_I. The large scatter of V_p values would appear to preclude their use as a reliable indicator of the fracture stress of individual fibres, whether in a loose bundle or in a matrix.

A further basic AE characteristic which we have attempted to correlate with the fracture stress of the glass fibres is that of ringdown counts, R, defined as the number of times per AE event that the oscillatory waveform of period T crosses the preset threshold, V_{th}. From Fig. 1 and Equation 20

$$V_{th} = V_p \exp[-\alpha(t_d - t_r)] \qquad (22)$$

or

$$\ln V_p - \ln V_{th} = \alpha(t_d - t_r) \qquad (23)$$

A plot of $\ln V_p$ against $(t_d - t_r)$ should have slope equal to α, the decay constant. Fig. 18 shows such a plot for the first 40 fibre break AE events of the bundle test. There is a considerable scatter of points on Fig. 18 so that it cannot be treated as conclusive. However, there is a general trend as indicated, and from the slope of this line we tentatively obtain a value of $\alpha = 6200\ \text{sec}^{-1}$. The intercept on the $\ln V_p = 0$ axis in Fig. 18 indicates an effective $V_{th} \simeq 0.15$ V, somewhat lower than the set value of 0.2 V.

Referring to Fig. 1, the ringdown count, R, for the model AE signal is given by

$$R \simeq \frac{t_d - t_r}{T} \qquad (24)$$

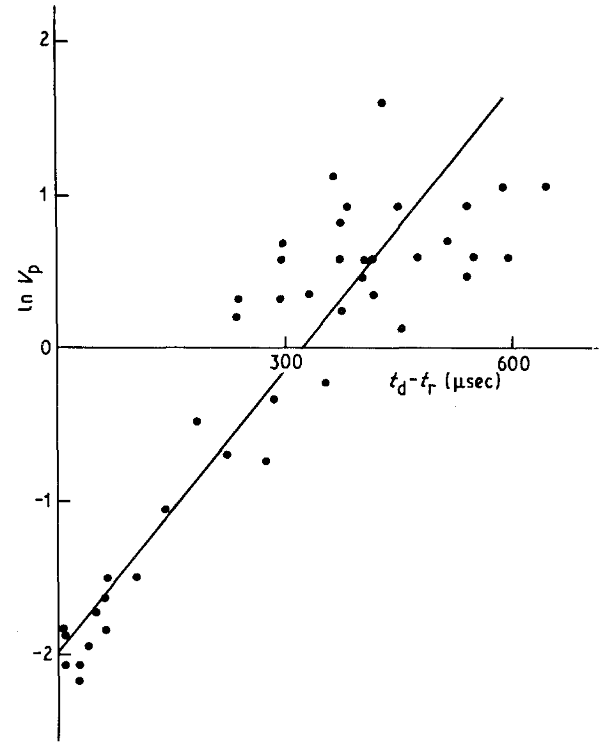

Figure 18 Plot of ln V_p (ln V) against $(t_d - t_r)$ for the first 40 fibre break AE events of the bundle test.

in which we have used the approximation $t_d \gg t_r$. Hence from Equations 23 and 24

$$R = \frac{1}{\alpha T}(\ln V_p - \ln V_{th}) \quad (25)$$

If $V_p \propto \sigma$ then

$$R = \frac{1}{\alpha T}\ln \sigma + C \quad (26)$$

where C is a constant. Fig. 14 shows the mean ringdown counts per event, R, plotted against $\ln \sigma$, and confirms that R increases with increasing fracture stress at a rate which is consistent with

$$\frac{d(\bar{R})}{d(\ln \sigma)} = \frac{1}{\alpha T} = 59 \quad (27)$$

where we have used $T = 2.67$ μsec and the tentative value for $\alpha = 6200\ \text{sec}^{-1}$.

The wide scatter of V_{p1} values (Fig. 10) or the means $(V_{p1} + V_{p2})/2$ (from Figs 10 and 11) which cover a range of about 20 dB at any stage of the bundle test, indicate that energies U_{AE} of the received AE signals from fibre break sources of similar energy, U_f, vary by a factor up to ~ 100. The question then arises whether this scatter of received AE signal characteristics is due to (a) variations in stress wave intensity, in the AE waveband, output by the source, or (b) the transmission losses mentioned earlier. In fact, the data of Fig. 11 show that the mean

$$\overline{V_{p1} - V_{p2}} = \frac{1}{196}\sum_{N_f=1}^{196}(V_{p1} - V_{p2})_{N_f} = -0.23\ \text{dB} \quad (28)$$

which differs negligibly from zero when compared with the scatter of $(V_{p1} - V_{p2})$ values. On average, therefore, the first-hit transducer (nearest the source) does not record a higher peak amplitude than the second hit. Because the fibre breaks occur at all bundle locations we conclude that attenuation in the bundle itself is a negligible effect; this, and also the fact that V_{p1}, $V_{p1} - V_{p2}$ and $(V_{p1} + V_{p2})/2$ all exhibit similar intrinsic scatter, suggests that the wide variation in measured AE intensity is principally due to variation in the AE intensity output at the source, i.e. at the point of fracture. Hamstad and Moore [8] who also obtained a wide scatter of V_p values (about 8 dB at any stress value) in testing bundles of Kevlar fibres, have suggested that the explanation may be that the energy in the acoustic wave at AE frequencies will be dependent on the rate at which the stored elastic energy is released in the fracture process.

7. Conclusions

Acoustic emission (AE) monitoring of E-glass fibre bundles under tension has enabled the time of occurrence and linear location of each fibre fracture to be determined. There was little, if any, departure from a random sequence of fibre break locations. Fibre breaks mainly occurred singly, but a small number of multiplets occurred, where fractures were evidently triggered by the shock of an earlier fibre fracture; this may ultimately be due to shaking of the suspension following fibre break, because there was no instance of a stimulated fibre break occurring within the AE event duration of the preceding break which caused it.

The values of the Weibull modulus obtained from AE monitoring of a test fibre bundle are consistent among themselves and with the values obtained here using the load–strain methods devised by Chi *et al.* [2]: in contrast with such a macroscopic bundle test, the AE method has the advantage that it will give the strength distribution of the fibres whether or not the strengths fit a Weibull, or other analytical expression. Also, the AE method does not depend on the fibres being perfectly elastic. We consider that these features, together with the information yielded on time-of-break, break location for each fibre and bundle integrity make this apparently uncomplicated application of AE event counting, which we have developed, a useful technique in fibre science.

Experimental relationships obtained between (a) mean AE peak amplitude and fibre fracture stress, (b) mean AE ringdown counts per event and fibre fracture stress are consistent with theoretical expectations, based on an idealized AE waveform. However, the wide spread of AE signal parameters arising from similar fibre break events would appear to preclude the use of AE to determine fracture stresses of individual fibres.

The large scatter of measured AE parameters for fibre fractures of similar energy probably originates at the AE source, and there is comparatively negligible attenuation of AE in the fibre bundle itself.

The AE bundle testing technique developed in this work provides a quick, convenient and apparently reliable means of determining the fracture stress distribution of glass fibres, while also avoiding the many problems associated with measurements on single fibres. It is probable that the technique could also be used for tests on a variety of other fibres.

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Received 17 May 1989
and accepted 28 March 1990