# Transverse cracking of fibre bundle composites studied by acoustic emission and Weibull statistics—effects of postcuring and surface treatment

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Transverse failure in composite materials is a mechanism in the ultimate failure of the engineering composite. It is controlled by the strength of the fibre/matrix interface and improvement in the strength of this interface will improve the overall transverse strength. Transverse fibre bundle composites (TFBC) have been tested to failure, where the condition of the composite and the fibre/matrix interface have been modified. Progression to failure has been monitored using acoustic emission with the AE data analysed in a novel way using Weibull statistics. Although Weibull statistics have previously been used to characterise fibre bundle failure, where the concept of weakest link applies, this work extends this approach in an empirical way using an acoustic emission form of Weibull equations. The AE profile, when compared to stress/strain data, showed a "quiet-then-noisy" profile for room cured resin, which changed to "noisy-then-quiet" when the resin was post cured. Kevlar reinforced TFBC showed regular AE from low strains. The pattern of AE changed when specimens had been post cured and when the Kevlar fibres had been subjected to ultrasound treatment. Although individual AE events were highly variable, Weibull analysis of the AE parameters derived from a glass reinforced composite proved highly robust, with the AE ringdown count distributions moving to higher values for the more brittle, stronger post-cured resin. Measuring interfacial failure stress via the onset of AE, suggested the interface was weakened, but in a selective way, which did not necessarily show in the final failure stress of the composite. 

## 1. Introduction

The testing of composite materials with the use of acoustic emission (AE) has been undertaken for some decades. The main objectives when using acoustic emission are such things as the detection of micro-damage propagation, understanding the causes of damage by an indirect measurement, prediction of the serviceability and service life of materials and components, prediction of failure loads and strains and identification of failure mechanisms and the sequence of failure mechanisms.These aims have been achieved with varying degrees of success. All these objectives contribute to a main aim which is the quality control of the material.

The work reported here relates to the development and propagation of micro-damage during transverse failure of continuous fibre composites i.e. failure of the resin/fibre interface. When localised damage occurs during tensile testing of advanced composites, an acoustic emission system can be used to detect this low strain, transverse damage. Part of the strain energy involved in loading will be liberated in the form of elastic waves which travel through the material and are detected as AE at ultrasonic frequencies. This AE may be detected by means of resonant piezoelectric transducers attached to the specimen.

It is well known that the fibre/matrix interface plays an important role in achieving superior tensile properties of a composite [1]. The tensile strength of the composite is dependent on the ability of the composite to transfer the tensile load from the broken fibres to the surviving ones through the shear stresses at the fibre/matrix interface [2]. An AE event is indicative of some degradation in this system and an associated loss

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of material strength and this may be associated with effects such as fracture at the fibre/matrix interface.

The advantages of using an AE system to study materials degradation are significant in that AE is sensitive to all impulsive defect growth in brittle materials providing a real time, continuous, monitoring technique.

Structural composite materials fabricated from polyester resins and reinforced with glass or Kevlar fibres have become increasingly important because of their excellent performance characteristics in terms of their high specific strength, and high modulus. This study considers the evolution and characteristics of AE associated with the microfracture occurring at the interface of transverse resin-fibre samples as they proceed to failure.

## 2. Previous work and aims of this work

Our previous work has considered the evolution of damage and failure in a number of mechanical systems associate with finished composite materials, using acoustic emission to supplement and interpret failure data. Previous studies have been undertaken by us, studying fibre failure using acoustic emission, both during quasi-static testing [3] and during slow speed continuous testing [4]. Previous work has also sought to use acoustic emission to characterise damage growth in composite type materials around single fibre bundles and transverse fibre bundles [5].

In this study, transverse fibre bundle composites have been tested, the test specimens consisting of a single fibre bundle placed transverse in the centre of the waisted section of a dog-bone shaped specimen. Use has been made of a more sophisticated AE data acquisition system including the capture of full AE waveforms to enable microfracture related AE events to be characterised more effectively. The aim of the work has been to look at the effect of both post-curing of composites, ultrasonic surface treatment and associated modification of material properties and adhesion, on the microfracture, stress-strain and AE response of the specimens. The work has also included the use of Weibull statistics to characterise the fracturing material, where application of these statistical methods would be useful but perhaps less well justified from the view point of the basic statistics of fracture.

### 2.1. Weibull statistics and micro-fracture–general comments

Weibull statistics takes account of such features as the spread of fracture strengths for a range of material specimens under test. In the case of testing bundles of fibres used to reinforce composites, the spread of fibre strength can be monitored continuously, as the fibre bundle fracture proceeds, using acoustic emission to monitor the time of fracture of each individual fibre in the bundle. In this case, the stress and strain in the fibre bundle sample may be related via the stress ($\sigma$) and strain ($\epsilon$) equation [4], of the form:

$$\sigma = E_f \epsilon \ \exp[-L(\epsilon/\epsilon_0)^m] \qquad (1)$$

Associated with the stress/strain Weibull equation (Equation 1), is the fracture of the fibre population within the fibre bundle. The fracture of this population can be monitored using acoustic emission, with the number of fibres surviving, given by the expression:

$$N_s = N_0 \exp[-L(\epsilon/\epsilon_0)^m] \qquad (2)$$

where $L$ is the normalised length of the fibre bundle under test (in the case of a range of constant length tests, $L = 1$).

In the case of a transverse bundle composite, acoustic emission monitors the evolution of damage within the region of the transverse bundle. The origin, nature and propagation of the damage is likely to be highly variable, due to the variability of the manufacture of such a sample and the defect structure likely to be present within this transverse region.

The defect structure which evolves is likely to consist, firstly, of a large number of small defects, which are barely detectable using acoustic emission, with the defect population extending upwards in size with larger defects being progressively fewer in number. The increasing size (cross-sectional area) of any active defect and the associated strain is likely to be reflected in the size of the associated population of acoustic emission events [6]. If acoustic emission events from transverse fracture are arranged as a statistical distribution, then a form of the Weibull equation might be expected to describe this population. The shape of the Weibull function is controlled by the variables, $m$ (the shape parameter) and a second parameter which at this stage is labelled $x_0$.

If a distribution appears as a plot of $x$ against $y$, then the Weibull distribution which expresses this relationship is:

$$y = N_0 \exp[-(x/x_0)^m] \qquad (3)$$

where $N_0$ is the total number of acoustic emission events and associated microcrack movements.

The Weibull function, in the form shown in Equation 3, has the possibility to be linearised, using logarithmic functions, to determine $m$ and $x_0$, while, at the same time, having a form capable of approximating a range of likely distributions.

Fig. 1 shows the effect on the distribution of varying the parameters $x_0$ for a specific value of $m = 1.5$. If $x = \epsilon$ and $N_0 = E_f\epsilon$, then the distribution can represent the mechanical behaviour of a fibre bundle, where the fibre bundle strength has a Weibull distribution. If $N_0$, is the total number of fibres and $x = \epsilon$, then the distribution represents the diminution of the intact fibre population as strain increases (Equation 2 ). The value of $x_0$ controls the position of the distribution along the $x$ axis, and it may be useful to move this distribution along the $x$ axis to low values, as shown in Fig. 1, to characterise a distribution typical of AE events derived from the fracture of transverse fibre bundle composites. The value of $m$ controls the statistical spread of the distribution about the $x_0$ value.

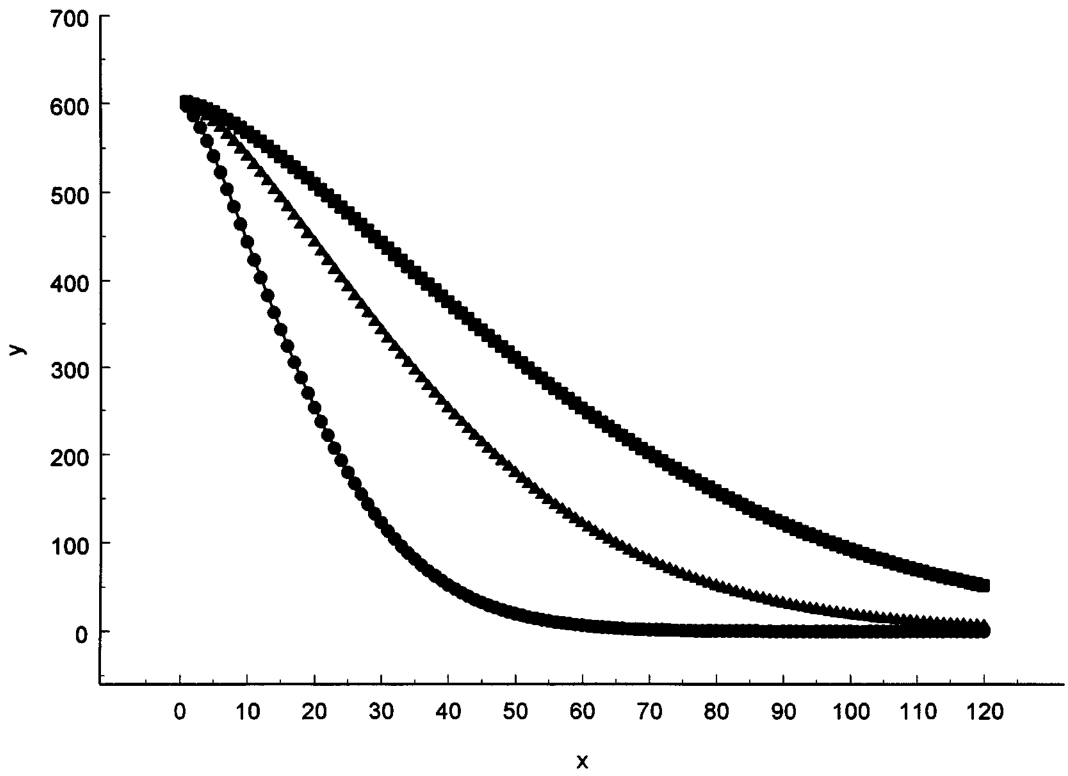


*Figure 1* Weibull Equation 3 plotted as an example, for $N_0 = 603$, $m = 1.5$ and $x_0 = 22, 44, 66$ for curves from left to right.

## 3. Experimental procedure—testing of transverse fibre bundle composites

Composite reinforcements used in this study include E-Glass (Fibre Glass (UK) Ltd, Equerove, Silane sized, ECB, 600 tex) of nominal diameter 10–12 $\mu$m and Kevlar-49 (Du Pont (UK) Ltd, tex 2400, 1000 filaments, finish free) of nominal diameter 14 $\mu$m. The matrix material used was Crystic Polyester 272 resin, supplied by Scott Bader (UK) Ltd.

### 3.1. Preparation of test specimens

The material preparation followed the recommended procedure: 100 parts Crystic Polyester 272 resin, 2 parts of Catalyst M (methyl ethyl ketone peroxide), 0.4–1.2 parts of cobalt Accelerator E in styrene. This resin was poured into a dog bone shaped mould of silicon rubber. In this study, two types of specimen were investigated using either glass or Kevlar fibre reinforcement. The test specimens fall into two batches. In the first batch are specimens which were cured for 7 days at room temperature and in the second, the specimens which were subjected to a further post-cure for periods of from 2–4 h at 80 °C in an oven.

The fibre bundle composites had a bundle of either fibre system centrally located with respect to the mould but oriented transversely to the longitudinal axis of the mould. All specimen gauge dimensions were 40 × 5 × 2.5 mm (Fig. 2).

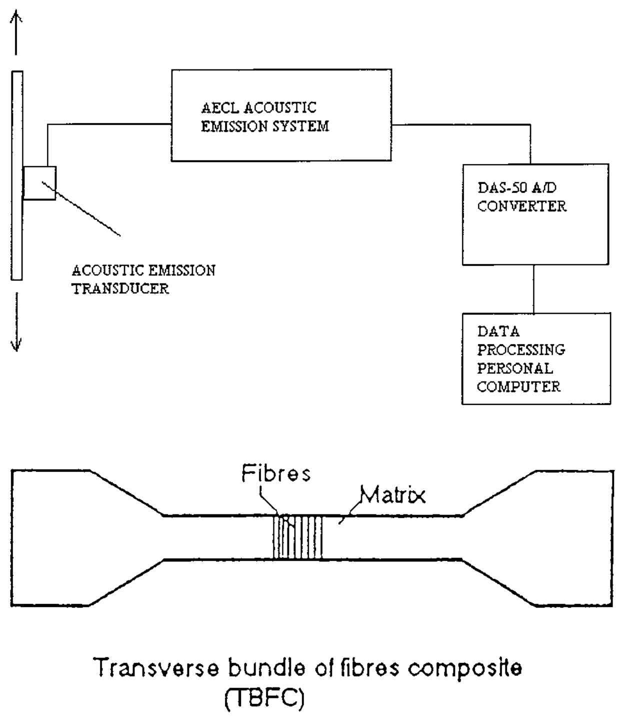


*Figure 2* Schematic diagram of the experimental system and a typical representation of a transverse bundle fibre composite specimen (TBFC). Gauge dimensions 40 × 5 × 2.5 mm.

### 3.2. Experimental test system

A schematic diagram of the experimental test system is shown in Fig. 2. Mechanical tensile tests were performed using a LLOYD-6000R tensile testing machine. The specimen were loaded at a constant speed of 0.5%/min (0.2 mm/min$^{-1}$), at a room temperature range of 20 ± 5 °C. The AE technique was employed during the tests for detecting material damage. The AE technique has previously been used by Hill *et al.* [3–5] to monitor fibre failures and their mode (singlets, doublets, triplets, etc.) during tensile testing of fibre bundles in air, yielding the combined stress-strain response and AE data. The previous work also considered testing of longitudinal and transverse bundle composites [5].

In this study, a commercial AE transducer (AC375L, resonant frequency 375 kHz, supplied by Acoustic Emission Technology Corporation) was utilised. The sensor was clamped in the middle of the specimen which was mounted in the bottom grip of the tensile machine. Silicon grease was used as a couplant to obtain acoustic coupling between the test material and the sensor.

The AE signals from the transducer, were preamplified by 60 dB (AECL 2100/PA, 208–530 kHz bandpass) and than processed using the AECL 2100 M Acoustic Emission system. The amplified/filtered signal was then sampled by an integral analogue to digital (A-D) DAS 50 board. This board, installed in a PC, accepts data from up to 4 single-ended channels, can operate in unipolar or bipolar mode with software selected input ranges of ±2.5 V, ±5 V, ±10 V, and has a maximum sample rate of $10^6$ samples/s. Data was processed under the control of VIEWDAC software package which acquires data from the DAS board.

The system settings were signal threshold 0.2 V and electronic dead time 0.2 msec. The former was chosen to minimise electronic background noise from the grips and from the tensile machine, thus ensuring that received signals were from the damage growth occurring in the composite being tested. There was no evidence of grip noise affecting the data.

## 4. Stress-strain and acoustic emission—testing of composite material

### 4.1. E-glass transverse fibre bundle composite

There is no simple relationship for predicting the transverse strength of a continuous fibre composite. Unlike the longitudinal tensile strength, which is determined almost entirely by a single factor (the fibre strength), the transverse strength is governed by many factors including the properties of the fibre matrix, the interfacial bond strength, the presence and distribution of voids, and the internal stress and strain distribution due to the interaction between fibres and voids.

Typical mechanical and AE test information for E-Glass cured and post-cured specimens embedded in polyester resin matrix are presented in Figs 3–6. These figures show the stress-strain response of the specimen and the AE ringdown counts per AE event respectively. In this study the AE amplitude was also acquired, which with ringdown counts, is ultimately related to the acoustic energy released by the transverse microfracture events.

Figs 3 and 4 show the characteristics of ringdown counts per event acquired from two similar E-glass reinforced samples where the resin is cured only (no post curing). These samples show a few early AE events (widely spaced peaks) with a second region of more rapid AE occurring beyond 2.75% strain. It should be noted that this strain value is not the true specimen strain since it needs correcting by 0.4% to allow for the early grip slip section. This grip slip data has been left in the data record to confirm the lack of AE from grip slip, since no attempt has been made to filter any grip noise (which experience has shown does not occur). In the case of post-cured transverse glass samples (Figs 5 and 6), the stress strain curve is more linear in shape, and AE occurs throughout the full strain range. The initial high level of AE activity during the early part of the test, drops toward failure, until the time just prior to failure, when it rises again. The two types of behaviour for the cured and post cured samples can be characterised as "quiet-then-noisy" and "noisy-then-quiet" respectively.

Table I shows the maximum stress, extension (%), and number of AE events for the cured (c) and post-cured (pc) E-Glass transverse fibre bundle composites.

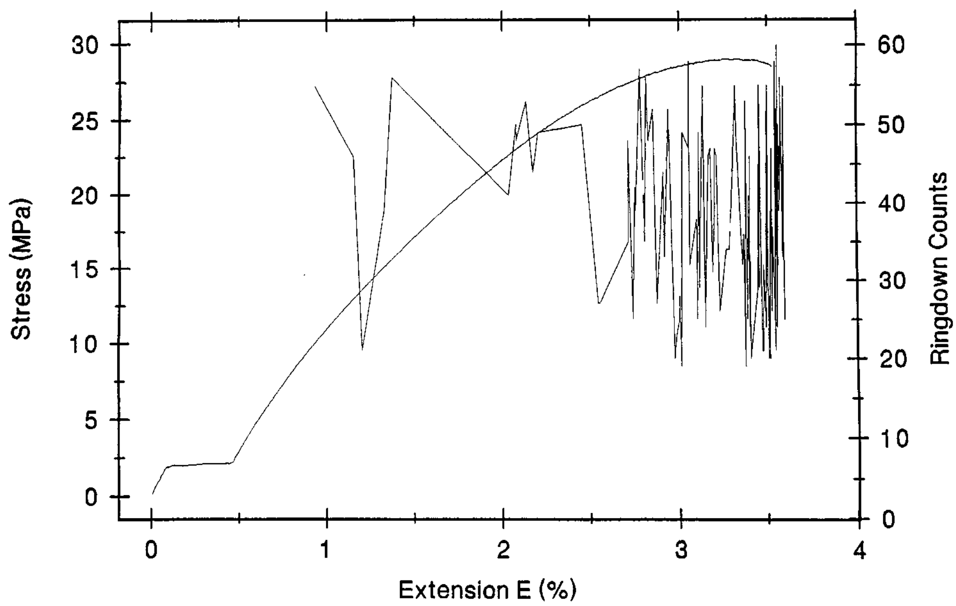


*Figure 3* Test data for stress-strain and acoustic emission ringdown counts per event for an E-Glass TBFC specimen subject to room temperature curing (example 1).

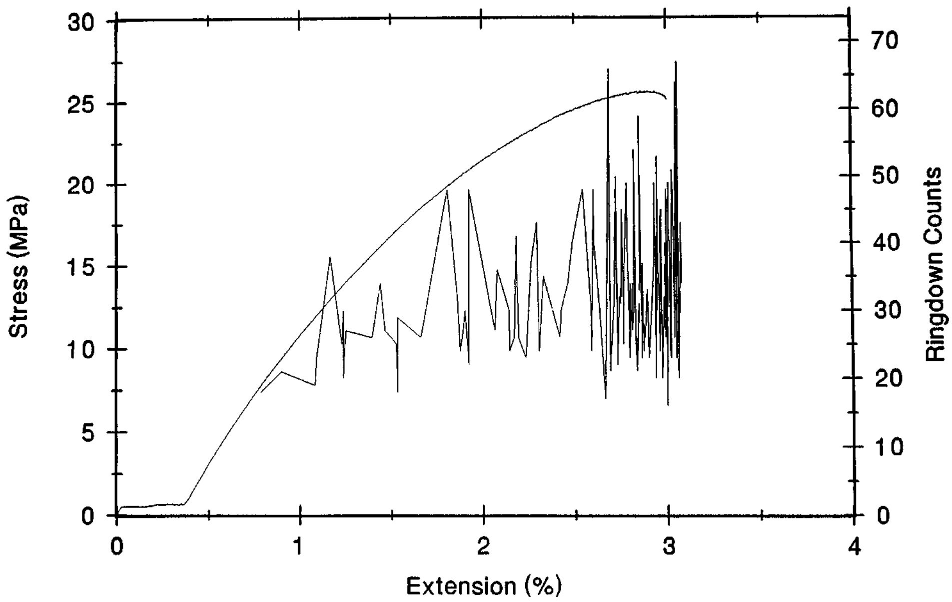


*Figure 4* Test data for stress-strain and acoustic emission ringdown counts per event for an E-Glass TBFC specimen subject to room temperature curing (example 2).

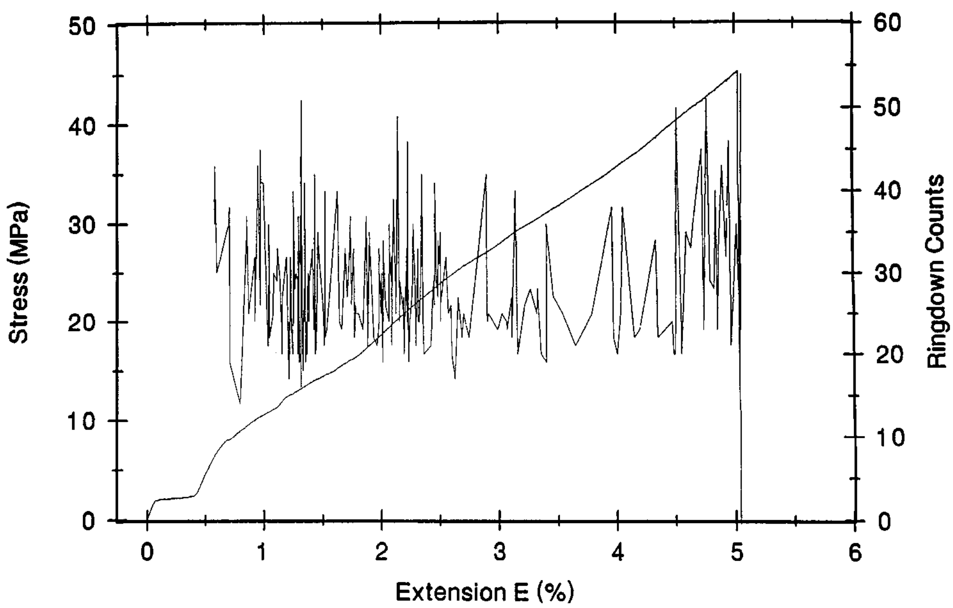


*Figure 5* Test data for stress-strain and acoustic emission ringdown counts per event for an E-Glass TBFC specimen subject to room temperature curing followed by post-curing (example 3).

It can be seen, from the maximum stress values, $\sigma_{max}$, that the effect of post-curing is to increase the maximum sustainable stress. Large fluctuations in the total number of AE events are seen, but with a clear higher AE average number of events for the post-cured samples. The elastic modulus for the specimens rises by some 17% on average for the post cured samples (1.5–1.77 GPa) with this value being largely dominated by the elastic response of the resin.

Comparing Figs 3, 4 and Figs 5, 6, the effect of post-cure can also be seen to increase the maximum stress values. It is worth noting that the stress-strain curve for the cured sample is dominated by the polymeric deformation, with a strong curvature. AE data suggests that little defect activity is occurring in this case during the early part of the test, with late defect activity leading to transverse failure within the fibre bundle region. This response may arise as a result of a ductile matrix giving little matrix cracking at low strains and resin cracking or fibre/matrix debonding at high strains.

The post cured samples show linear type stress-strain response with some fluctuations. The majority of the AE is generated at low strains. The decrease in AE event rate in the middle of the test, shown by the greater spread of the peaks, suggests that limited defect growth is occurring. AE suggests some early fibre debonding or interfibre cracking has occurred with the transverse fibre bundle then held by the intact surrounding resin

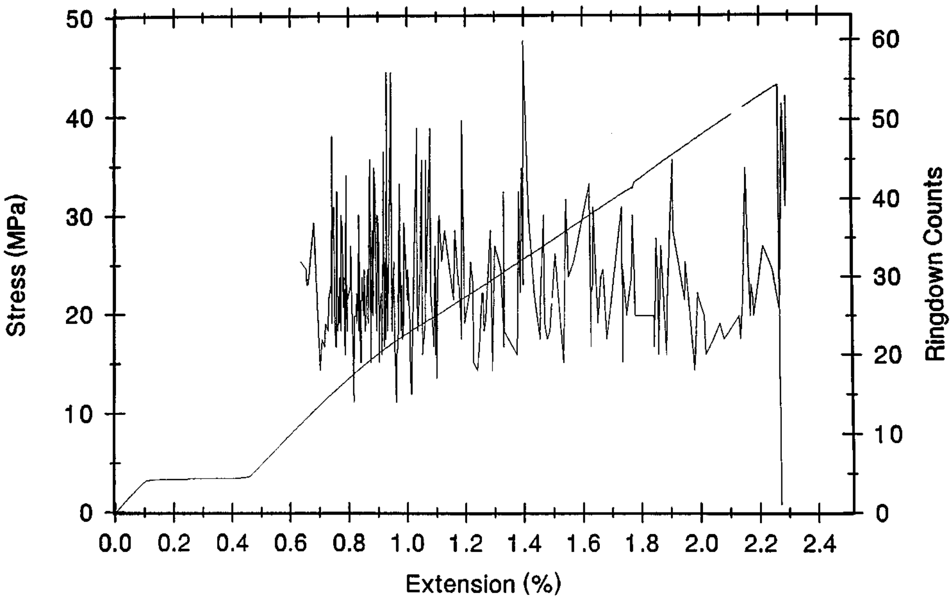


*Figure 6* Test data for stress-strain and acoustic emission ringdown counts per event for an E-Glass TBFC specimen subject to room temperature curing followed by post-curing (example 4).

TABLE I Tensile properties and acoustic emission events for transverse glass fibre reinforced composites-cured (c) and post-cured (pc) respectively (batches E1 and E2)

| Specimen no | Max stress MPa | Max extension (%) | No of AE events |
|---|---|---|---|
| E1-Glass ‘c’ | 28.28 | 2.93 | 178 |
| E1-Glass ‘c’ | 25.56 | 2.91 | 55 |
| E2-Glass ‘c’ | 26.42 | 2.82 | 118 |
| E2-Glass ‘c’ | 28.86 | 4.02 | 75 |
| E2-Glass ‘c’ | 28.88 | 3.34 | 121 |
| E1-Glass ‘pc’ | 40.01 | 3.42 | 31 |
| E1-Glass ‘pc’ | 41.44 | 1.90 | 89 |
| E1-Glass ‘pc’ | 46.62 | 3.34 | 91 |
| E2-Glass ‘pc’ | 45.22 | 5.03 | 260 |
| E2-Glass ‘pc’ | 30.00 | 4.03 | 370 |
| E2-Glass ‘pc’ | 42.40 | 2.27 | 271 |
| E2-Glass ‘pc’ | 40.41 | 4.27 | 97 |

(possibly due to regions of strong matrix/fibre adhesion) until final failure is approached. The AE suggests that interfibre cracking does occur in the early stages of deformation, but that post cure has created regions of resin which have the effect of either resisting further crack propagation and/or acting as resin ligaments firmly bonded to the fibre surface. These ligaments finally break, leading to late AE and final failure of the transverse sample.

Transverse matrix cracking is of much interest and importance because it is the first mode of damage that occurs in fibre composites under monotonic loading. The cracks in cross-ply composite cause stiffness degradation, which can be a lifetime limiting mechanism and which may lead to initiation of delamination [7]. It is clear from the data in Figs 3–6 that AE occurs earlier in the test (at lower strains) from transverse polyester-glass specimens which have been postcured, as compared to those without post-curing, although the absolute stress for AE onset, is roughly the same in each case ($\sim$10 MPa).

The post-cured specimens have a higher failure stress and greater resistance to final failure. From the AE and the stress-strain data, we assume that the initial stage of AE indicates that resin cracking or resin/fibre debonding is ocurring. In the case of the cured-only samples, the AE arising at the end of the test is assumed to be due to the propagation of larger microcracks. A factor in the quality of the adhesion may also be thermal compressive stresses which act on fibres due to postcuring, and which may have a role in improving interfacial adhesion. AE seems to identify better adhesion between polyester resin and glass fibres due to postcuring but in this case, this evidence has to be deduced not from the onset of AE as previously proposed [5], but from the different pattern of AE and the final fracture load. In the case of postcured material, it may be appropriate to ignore early AE and use the onset of rapid AE prior to fracture as a measure of adhesion quality.

Clearly the use of AE to characterise adhesion via transverse samples needs further investigation, but AE provides a useful insight into the progression of fracture in these transverse fibre bundle composites, and shows a marked change in response due to post-curing.

Since the AE techniques cannot differentiate between interfibre resin cracking and resin/fibre debonding a definitive interpretation is not possible. Conclusions can only be inferred from known information.

## 4.2. Kevlar 49 transverse fibre bundle composite

Further studies were carried out using Kevlar fibres in transverse samples, in order to compare the resin/fibre interaction for cured and post-cured specimens and also the effects of treating the surface of the Kevlar fibres with ultrasound prior to manufacture. Fibre surface treatment was considered since adhesion between Kevlar and polyester resin is known to be relatively poor, but the treatment was primarily aimed at investigating if the mode of specimen failure (and the AE) was sensitive to this treatment. The stress-strain and AE data for these specimens is presented in Figs 7–10. The specimens were dog-bone shaped and prepared as described in Section 3.1. The specimens were cured for 7 days at room temperature. Post-cured samples were subjected to a further post cure at 80 °C in an oven for 2 h and fibre bundles subjected to

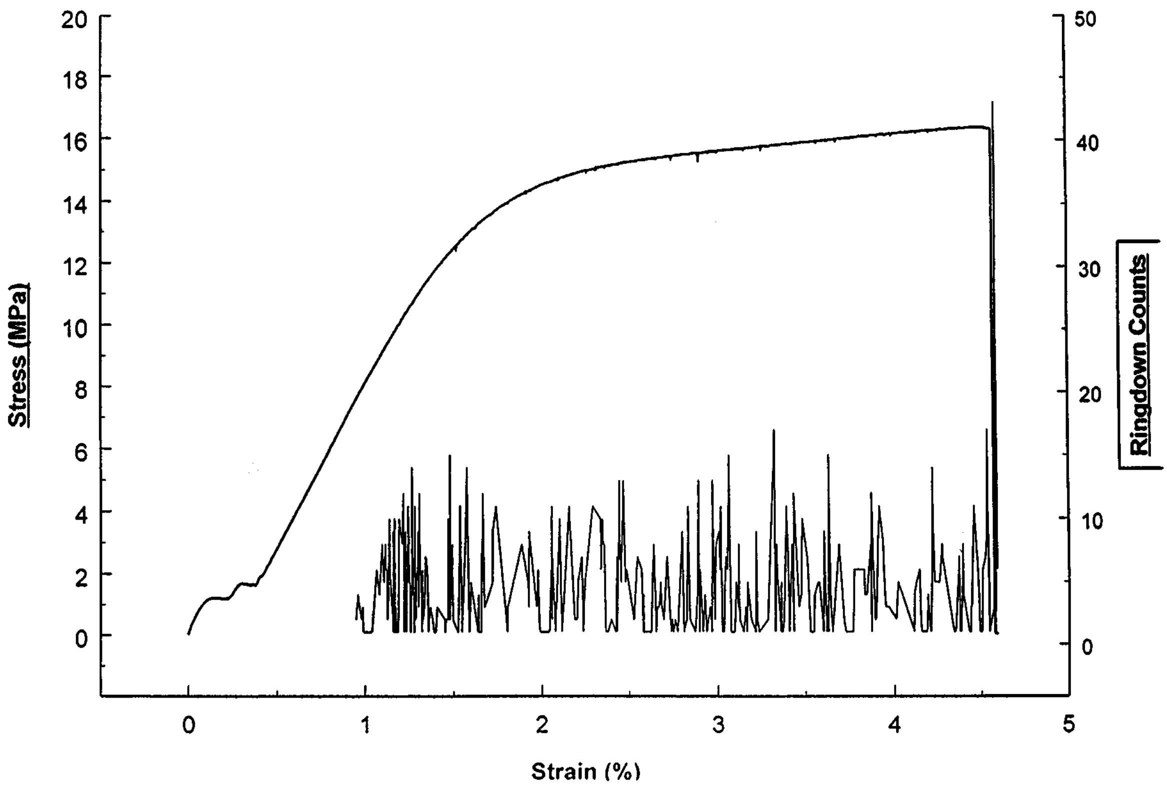


*Figure 7* Test data for stress-strain and acoustic emission ringdown counts per event for a Kevlar TBFC specimen subject to room temperature curing (Kevlar, "as received").

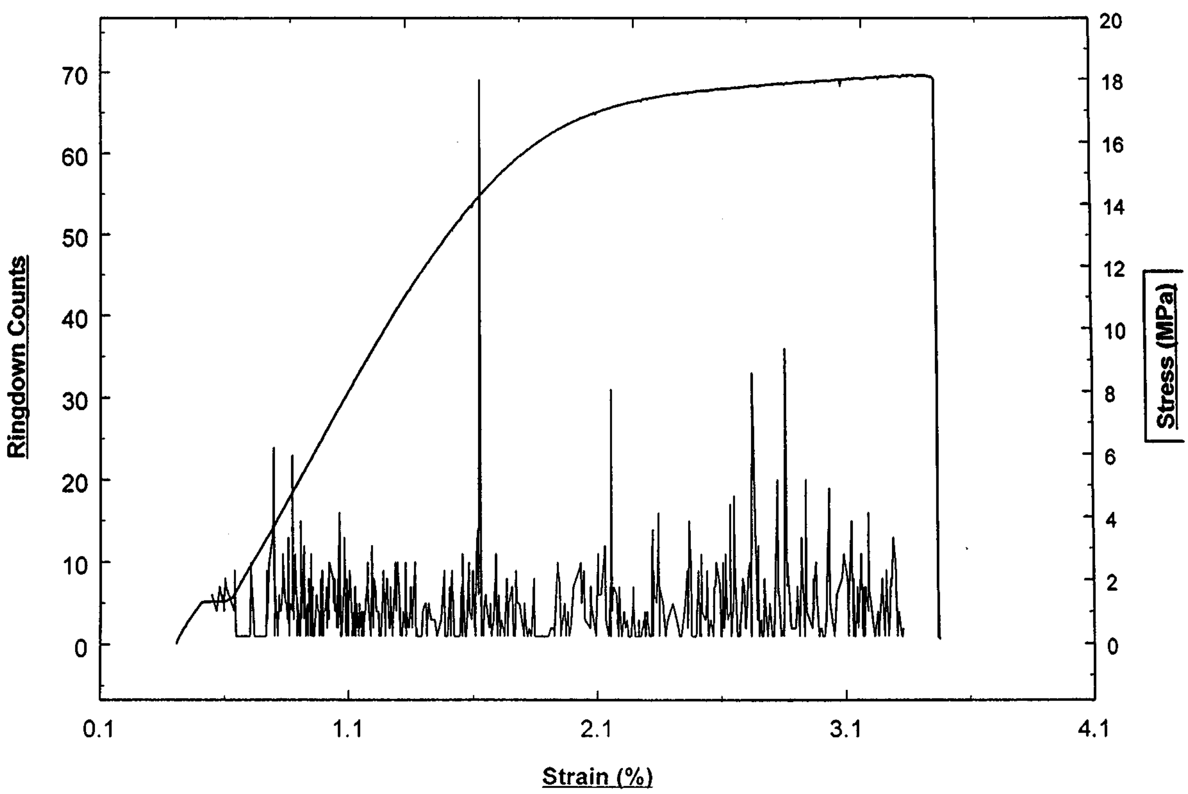


*Figure 8* Test data for stress-strain and acoustic emission ringdown counts per event for a Kevlar TBFC specimen subject to room temperature curing (Kevlar, subjected to ultrasound treatment prior to manufacture of the TBFC specimen).

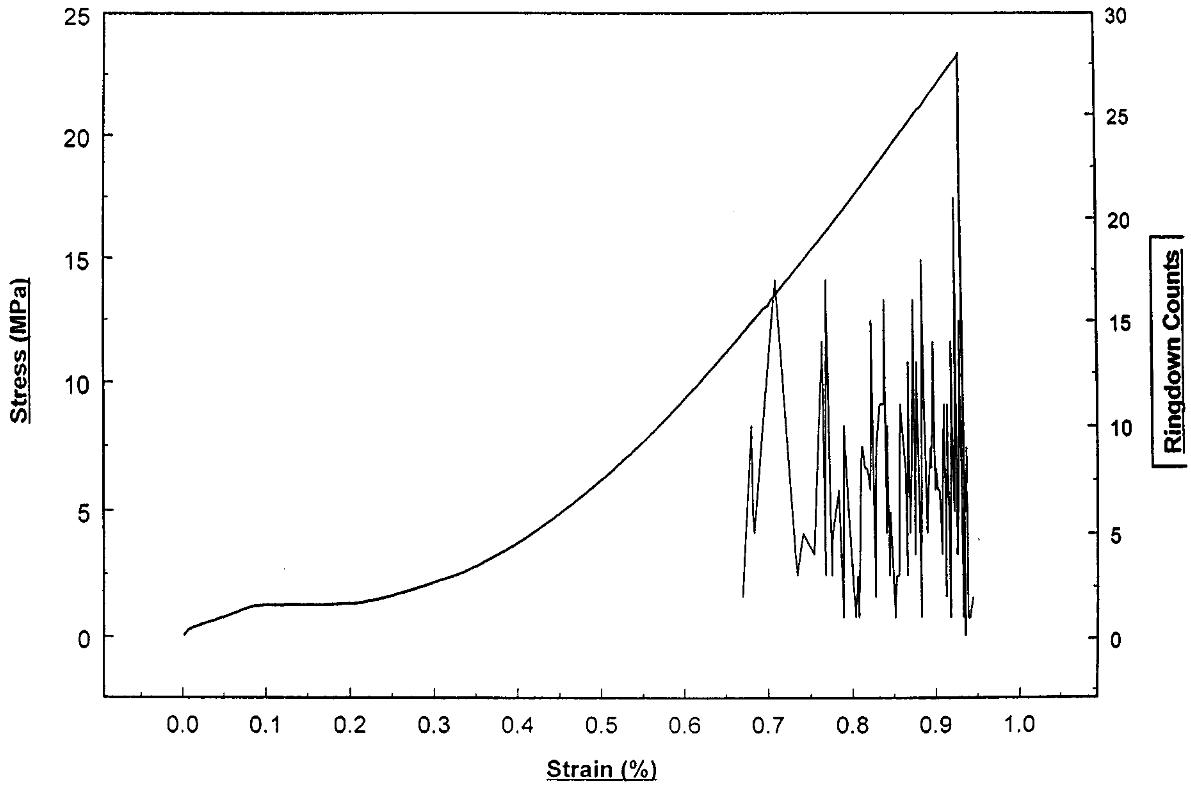


*Figure 9* Test data for stress-strain and acoustic emission ringdown counts per event for a Kevlar TBFC specimen subject to room temperature curing followed by post-curing (Kevlar, "as received").

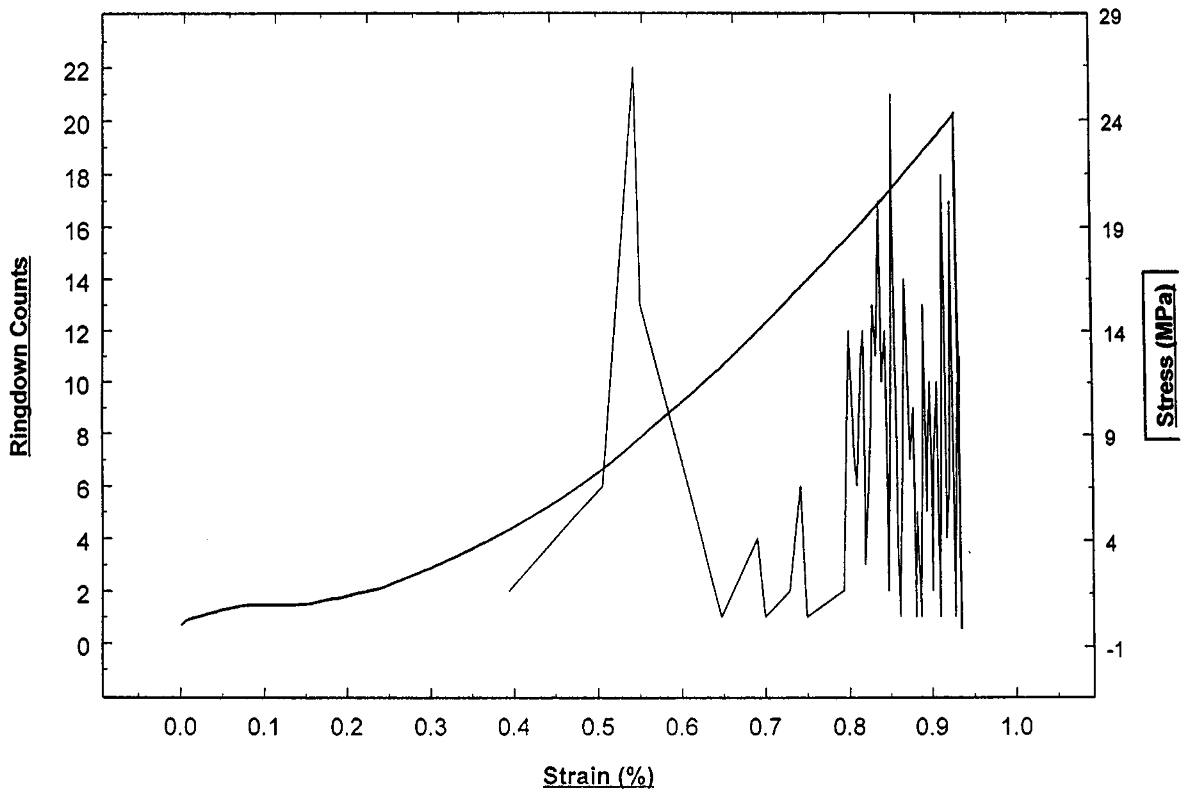


*Figure 10* Test data for stress-strain and acoustic emission ringdown counts per event for a Kevlar TBFC specimen subject to room temperature curing followed by post-curing (Kevlar, subjected to ultrasound treatment prior to manufacture of the TBFC specimen).

ultrasound, were treated for 15 min in an ultrasound bath containing distilled water prior to specimen preparation.The AE and stress-strain data shown in Fig. 7 is typical of a Kevlar transverse fibre bundle sample. The AE commences at approximately 0.7% specimen strain and at the end of the initial linear section of the stress-strain curve. Curvature is clearly, intimately associated with acoustic emission and microcrack growth within the transverse fibre bundle. The rate of AE activity appears a little higher at commencement, but then appears relatively constant right up to specimen failure. Adhesion between Kevlar and polyester resin is known to be weaker than between glass and polyester, from previous work [5 ] and this accounts for the early and relatively continuous AE throughout the test.

The AE events have lower ringdown count values than those from a glass fibre reinforced transverse composite (e.g. Fig. 3): i.e. less than 15 as opposed to those from glass being in the 50–60 range. This is partly associated with the higher applied stress for the glass fibre specimens. However, it is worth noting that the AE signals from Kevlar have a relatively constant value of ringdown count as stress rises in Fig. 7 suggesting it is more a question of localised adhesion failure. The AE events appear to be associated with smaller, less energetic source fracture events, due to adhesion failure.

These characteristics change dramatically when the Kevlar fibre bundle is exposed to ultrasound prior to specimen manufacture (Fig. 8). It appears that ultrasound has reduced fibre resin adhesion even further, providing a population of "defects" within the fibre bundle. AE commences almost immediately loading starts and the strain at failure is reduced. Several higher ringdown count AE events are also seen to occur. Resin-fibre adhesion is not arresting crack propagation in the same way as for the specimen shown in Fig. 7, which had no ultrasound treatment.

An example of the AE and stress-strain data for a post-cured sample using "as-received" fibres is shown in Fig. 9. As discussed earlier, the resin is strengthened and embrittled with the final fracture load enhanced. Early AE is not apparent, but this is in part an effect on the upward turning stress-strain curve causing the stress to rise less rapidly. Toward the end of the test, the AE appears to gather pace accompanied by the steepening stress-strain curve. It appears that the resin fibre interface has been improved by post-curing although this may be due to resin shrinkage and associated fibre clamping as mentioned earlier. The enhanced properties of the resin and improved adhesion appear to work together to keep the specimen intact until final failure occurs.

Transverse fibre composites using Kevlar fibres with the fibres subject to ultrasound treatment and post-cure show a suprising effect (Fig. 10). The stress-strain curve and AE show a similar pattern except, for a few early AE events. This must be interpreted as localised reduced resin-fibre adhesion due to ultrasound treatment of the fibre bundle. The relatively large AE amplitude, for these early AE events suggest a large debond area was produced.

Tables IIA and B summarise the test data for the transverse Kevlar fibre bundle composite specimens tested. The test specimens fall into batches which have been cured only (c), cured and post-cure (pc), cured with ultrasound treatment of the fibre bundle prior to manufacture (cu) and cured and post-cured with ultrasound treatment prior to manufacture (pcu).

Again it is clear that post-curing raises the failure stress significantly (Table IIB). Average values of interfacial failure stress (IFFS) deduced from the onset of AE [5] suggest that ultrasound has had a dramatic effect on initial damage generation, producing a reduction in the IFFS value. However, this reduction is not reflected in a dramatic reduction in the overall value of failure stress.

TABLE IIA Macroscopic measurements of the maximum stress and corresponding strain, maximum strain, interfacial failure stress (IFFS) and corresponding strain (IFFE) deduced from the macroscopic sample stress giving initial AE events, and total number of events emitted for four different types of Kevlar Fibre Reinforced Composites. c—room cured; pc—room cured and post-cured; cu—room cured, fibres exposed to ultrasound prior to specimen preparation; pcu—room cured and post cured with fibres exposed to ultrasound prior to specimen preparation

| Specimen number | Max $\sigma$(MPa)/ Max $\epsilon$(%) | Max strain (%) | IFFS (MPa)/ IFFE (%) | No of AE events |
|---|---|---|---|---|
| K1-Kevlar'c' | 10.92/4.00 | 4.00 | 7.34/1.425 | 62 |
| K1-Kevlar'c' | 16.34/4.52. | 4.59 | 7.52/0.95 | 338 |
| K1-Kevlar'c' | 25.24/2.03 | 2.76 | 8.91/0.71 | 723 |
| K1-Kevlar'c' | 13.35/5.40 | 5.40 | 7.09/1.10 | 522 |
| K2-Kevlar'pc' | 23.30/0.93 | 0.94 | 11.94/0.67 | 81 |
| K2-Kevlar'pc' | 24.34/0.90 | 0.91 | 2.88/0.28 | 87 |
| K2-Kevlar'pc' | 34.78/1.13 | 1.14 | 10.11/0.61 | 164 |
| K3-Kevlar'cu' | 19.66/2.71 | 3.07 | 4.66/0.58 | 169 |
| K3-Kevlar'cu' | 10.78/3.89 | 4.12 | 3.56/0.72 | 222 |
| K3-Kevlar'cu' | 18.13/3.22 | 3.22 | 4.73/0.92 | 332 |
| K4-Kev'pcu' | 24.23/0.93 | 0.94 | 1.35/0.12 | 59 |
| K4-Kev'pcu' | 34.73/1.13 | 1.14 | 2.80/0.35 | 213 |
| K4-Kev'pcu' | 28.93/1.01 | 1.02 | 4.55/0.39 | 99 |

TABLE IIB Average values for the maximum stress (MPa), corresponding strain ($\epsilon$), interfacial failure stress and corresponding failure strain for all the four type of transverse Kevlar-49 fibre bundle composite materials. 'c' signifies room temperature curing, 'pc' post-cured, and 'u' ultrasound treatment of the fibre bundle in distilled water for 15 min prior to specimen manufacture

| Sample type | Max $\sigma/\epsilon$ (MPa/%) | IFFS (MPa) | IFFE (%) |
|---|---|---|---|
| K1-Kevlar'c' | 16.46/3.98 | 7.70 | 1.04 |
| K2-Kevlar'pc' | 27.47/0.99 | 8.00 | 0.52 |
| K3-Kevlar'cu' | 16.19/3.27 | 4.30 | 0.74 |
| K4-Kevlar'pcu' | 29.30/1.02 | 2.90 | 0.28 |

The strength of the specimens in terms of final failure stress has been improved by post-curing with this being an effect due primarily to modification of resin properties. Some enhancement of adhesion is suggested, either by direct improvement of adhesion or by resin shrinkage and clamping of the fibre surface. Ultrasound surface treatment of the fibres has a dramatic effect on the IFFS without any dramatic reflection of this adhesion loss in the final failure stress values, in this case. In practical terms, interfacial failure might generate a situation of delamination, or a path for fluid penetration into the composite material, which would then, indirectly promote modification of material propeties and behaviour.

It can be seen that the total number of AE events varies for similar materials (Table IIA) and no attempt is made to interpret this information except to suggest that a large number of small AE events is equivalent to a small number of large events creating a similar final failure surface area.

## 5. Weibull statistics applied to the failure of glass fibre reinforced transverse composite specimens

The shape and nature of the Weibull distribution function has been described in general terms in Section 2.1. Here the distribution function is used in an empirical way to describe the distribution of acoustic emission parameters for each acoustic emission event in an attempt to quantify changes in material condition via the use of acoustic emission measurements.

Statistical techniques are often resorted to when dealing with materials that exhibit wide scatter in test data. One such techniques is the two parameter Weibull cumulative distribution function. Based upon theoretical and empirical justifications, it has become a popular statistical model in engineering applications. In the past the fibre strength distribution has been described using a two parameter Weibull distribution function [3, 8, 9]. In the present experiments the distribution of acoustic emission parameters was considered using a two parameter Weibull distribution function in the hope that this function would provide an adequate description of the changing nature of the microfracture mechanisms within the transverse fibre bundle composite material.

The Weibull equations have been modified to characterise the global distribution of acoustic emission parameters derived from each acoustic emission event, associated with each microfracture source active within the region of the tranverse fibre bundle.

Suppose that an AE event has a ringdown count value (RDC) and a voltage amplitude value (AMP), then number of events $N$ associate with this parametric value is given by the equations:

$$N_1 = N_0 \exp[-(\mathrm{RDC}/\mathrm{RDC}_0)^{m1}] \quad (4)$$

$$N_2 = N_0 \exp[-(\mathrm{AMP}/\mathrm{AMP}_0)^{m2}] \quad (5)$$

where $m$, $\mathrm{AMP}_0$ and $\mathrm{RDC}_0$ are the Weibull shape parameter and scale parameter respectively for each parametric distribution, $N_0$ is the total number of events for each distribution of the appropriate acoustic emission parameter, and shape parameter '$m$' is important for determining the breadth of the AE parameter distribution. A large value for $m$ signifies a narrow distribution. The value of $m$ is obtained from the slopes of the logarithmic Weibull plots produced in the form $\ln\ln(N_0/N)$ vs. $\ln(\mathrm{RDC})$ or $\ln\ln(N_0/N)$ vs. $\ln(\mathrm{AMP})$ derived from the acoustic emission data for a particular specimen under test. The intersection between the straight line from the graph and the $Y$ axis is represented by $y_1 = -m \ln(\mathrm{RDC}_0)$ when analysing AE ringdown counts and $y_2 = -m \ln(\mathrm{AMP}_0)$ when analysing AE amplitude. It should be noted that in describing the ringdown count and amplitude distributions using Weibull parameters, no direct equivalence is expected between the Weibull parameters for each sample.

The linearity of such Weibull plots over the strain range indicate that a Weibull treatment is applicable.

From Equations 4 and 5 the values for Weibull parameters were obtained for the 7 days cured and 2 h post cured transverse glass fibre bundle composites. The Weibull parameters were obtained using composite fracture data below maximum stress, after which saturation of the acoustic emission data can occur which would have distorted Weibull parameters obtained. The Weibull parameters for transverse fibre bundle glass fibre composites are summarised in Table III for the specimens tested. Since the AE distributions extend from a peak at low AE parameter values, the Weibull parameters obtained have low values. The $m$ value for the ringdown count distribution is (Table IIIB), on average 1.28 with an $\mathrm{RDC}_0$ value of 20.55 counts. Postcuring has the expected effect of moving the $\mathrm{AMP}_0$ and $\mathrm{RDC}_0$ values higher since the fracture sites are expected to be acoustically more energetic for the more brittle post-cured material. The brittle post-cured specimens also show a narrower spread of the AE parameters as signified by the increase in the Weibull $m$ parameter (from 1.28 to 1.68 for ringdown counts).

TABLE IIIA Weibull strength distribution parameters for transverse-E-glass fibre reinforced composites-obtained from AE amplitude and ringdown count distributions for batches 1 and 2 together with the percentage regression for each of the specimen when undertaking a straight line fit to data

| Specimen no. | $m$ AMP | Regression (%) | $m$ RDC | Regression (%) | $\mathrm{AMP}_0$ | $\mathrm{RDC}_0$ |
|---|---|---|---|---|---|---|
| E1-c | 0.627 | 85.2 | 1.41 | 85.8 | 0.581 | 23.47 |
| E1-c | 0.528 | 69.1 | 0.484 | 47.0 | 0.524 | 6.84 |
| E1-pc | 0.276 | 64.6 | 1.64 | 82.5 | 0.100 | 28.96 |
| E1-pc | 0.727 | 76.7 | 1.81 | 99.2 | 0.730 | 26.09 |
| E1-pc | 0.739 | 67.3 | 1.61 | 91.7 | 0.773 | 23.46 |
| E2-c | 0.566 | 64.0 | 1.46 | 89.9 | 0.495 | 22.10 |
| E2-c | 0.531 | 61.3 | 0.985 | 78.7 | 0.408 | 16.10 |
| E2-c | 0.398 | 48.0 | — | — | 0.215 | — |
| E2-pc | 0.699 | 71.8 | 1.71 | 98.9 | 0.612 | 23.66 |
| E2-pc | 0.774 | 84.8 | 1.28 | 94.6 | 0.710 | 17.45 |
| E2-pc | 0.813 | 74.6 | 1.71 | 95 | 0.773 | 23.94 |
| E2-pc | 0.723 | 56.1 | 1.96 | 98.5 | 0.667 | 27.14 |

"c" signifies room cured and "pc" signifies postcured specimens for batches E1 and E2.

TABLE IIIB Average values derived from the Weibull statistical data for cured and post-cured samples. '$m$ (AMP)' and '$m$ (RDC)' are derived from the AE amplitude and ringdown count data correspondingly

| Type of sample | $m$-AMP | Regression (%) | $m$-RDC | Regression (%) | $\mathrm{AMP}_0$ | $\mathrm{RDC}_0$ |
|---|---|---|---|---|---|---|
| E-Gc | 0.56 | 70 | 1.28 | 84.8 | 0.50 | 20.55 |
| E-Gpc | 0.75 | 72 | 1.68 | 96.3 | 0.71 | 24.54 |

Fig. 11 shows an example using the Weibull parameters derived from the logarithmic plots, with the parameters used to fit the Weibull distribution equation to a real AE parametric distribution. The fit between experimental data and the theoretical curve can be seen to be good.

It is not self evident that Weibull statistical methods are applicable to transverse cracking. However the use of these methods in an empirical way shows that the Weibull analysis of the statistical distributions of AE parameters is sensitive to changes in the micromechanics and mechanisms of fracture. Weibull analysis yields two parameters which describe the distribution and indirectly describe the changes in the evolution

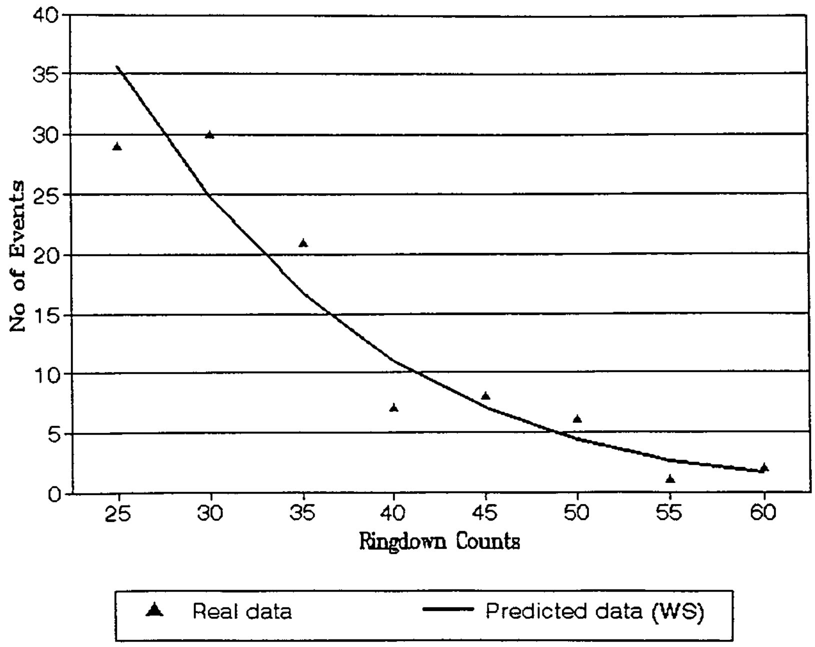


*Figure 11* Fit of a Weibull acoustic emission equation (in RDC form) to AE data from a glass fibre transverse fibre bundle composite.

of microscopic damage in the material. Since the signature of individual acoustic emission events carries highly specific information related to a point of emission within the sample, and these point events are highly variable, it is pleasing to find that movements of the value of Weibull parameters are sensitive to material condition, even in the light of this localised variability.

Under normal circumstances, when testing composite materials, some variability is inherent in acoustic path from AE source to the transducer, but in the case of these transverse bundle tests, since the fracture occurs in the localised area of the single fibre bundle, this variability is minimised.

## 6. Conclusions

Acoustic emission has been used to monitor the evolution of damage in E-Glass and Kevlar-49 transverse fibre bundle composite materials during tensile testing, using instrumentation which captures the full AE waveform. Results have been compared for 7 days cured and 2–4 h further post-cured composite using stress-strain, AE amplitude and AE ringdown count information.

AE provides a useful insight into the microfracture processes occurring during transverse microfracture damage growth and allows indirect interpretation of damage evolution in terms of changes in adhesion and resin mechanical characteristics.

It is clear that specimens made from post-cured resin can sustain much higher stress levels associated with improved resin strength and improved resin/fibre adhesion.

Transverse fibre bundle composites reinforced with glass show a characteristic "quiet-then-noisy" AE pattern associated with approaching failure. Post curing of these specimens results in enhanced resin elastic modulus and failure stress. For these specimens AE adopts a pattern which is "noisy-then-quiet" suggesting that initial microcrack generation is arrested by resin ligaments or other features suggesting improved resin/fibre adhesion.

Adhesion between Kevlar and polyester resin is known to be less effective. AE shows a pattern which starts early and is distributed throughout the time of the transverse test. The lower amplitude of AE events suggests the growth of smaller cracks with each AE event, on average, having lower acoustic energy. Post-curing of the Kevlar reinforced transverse bundle composites results in a change in the stress-strain curve, with increased resin failure stress. The pattern of AE becomes more concentrated towards the end of the test, but now with higher ringdown-count values. Treating the surface of Kevlar fibres in an ultrasound bath clearly modifies the adhesion with, for instance, a few early large AE events (in the case of post-cured specimens) suggesting adhesion has been made worse by the treatment.

Weibull statistics have previously been used by us to characterise fibre systems used in composite materials with AE used to identify the pattern of fibre failure [4]. In this work, the Weibull equations have been modified, in an empirical way, to describe the distribution of AE parameters associated with each AE event. The method has been applied to damage evolution in the glass reinforced transverse fibre bundle composites. The distribution of AE ringdown counts adopts a right-hand tail form (Fig. 11) and the Weibull parameters have values which reflect this. Although the AE data shows much higher statistical spread, due to the more complex nature of crack propagation in a transverse fibre bundle composite, (as compared to a fracturing fibre bundle), the Weibull parameters still change, reflecting the changing failure mechanisms within post-cured specimens, in comparison to those without any post-curing. This is encouraging and suggests the Weibull statistical methods can be combined with acoustic emission, used in an empirical way, to characterise changes in the mechanisms of microcrack growth within a material system, which may or may not be reflected in the short term fracture behaviour of the material.

The use of acoustic emission to monitor the growth of damage in transverse fibre bundle composites, provides a sensitive method of monitoring hidden changes in the mechanisms of transverse damage growth associated with resin condition and material interactions at the resin/fibre interface. However, it must be said that this work is not an attempt to provide any kind of global interpretation of failure in all material systems of this type, but provide a methodology which reveals more information about material failure in each case. To provide definitive information about material failure in a particular material system then material production methods and quality control need attention. Acoustic emission is sensitive to fine changes in material condition and clearly able to help in this respect, which would lead to optimisation in material behaviour not necessarily apparent from stress-strain or final fracture stress/strain information alone.

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