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Determining the load-time history of fibre composite materials by acoustic emission

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Acoustic emission was monitored during the axial loading of unidirectional fibre composite tensile specimens. The material consisted of strong, brittle fibres (E glass) embedded in a viscoelastic matrix (epoxy). It was found that when the load was held constant the acoustic emission output continued, but at a decreasing rate with time at load. As the load level was increased, the acoustic emission output at load continued for a longer period. It is suggested that the acoustic emission under constant load is a result of fibre fracture which continues after loading ceases because of the viscoelastic nature of the matrix which allows stress redistribution with time. The experimental results from acoustic emission are compared with computer calculations for fibre fracture based on theoretical considerations. Good agreement is noted between the theoretical and experimental results.

1. Introduction

Advanced composite materials which are used today as structural materials usually consist of high strength, brittle, thin fibres embedded in a low strength ductile matrix. In order to achieve high efficiency, the fibres are oriented to sustain the load in their axial direction. Since the fibres are brittle, their strength has no unique value but is distributed around some average value. It was shown by Rosen [1] theoretically and experimentally that unidirectional fibre composites of this kind, when loaded in their axial direction, fail by progressive fracture of the fibres. Statistical strength theories were developed based on a distribution in the fibre fracture strength [2, 3, 4]. Because of this distribution, fibres begin to fail considerably below the average stress level. The total fracture occurs after accumulation of fibre fractures, when the remaining cross-section cannot sustain the external load. When fibres fracture, only part of the fibre's total strain energy is released by that part of the fibre which became ineffective, because the stress in the fibre ends is built up again by the interface shear stress between fibre and matrix. The length of this "ineffective" fibre is only a few times the diameter of the fibre, depending on the moduli of the fibres and the matrix, and the volume fraction of the fibres [1]. The energy released propagates from the source (the point of fracture) as an acoustic wave. By attaching a transducer to the material surface, it is possible to detect this energy release [5]. Since the rate of fibres fracture increases as the load approaches the ultimate strength, it is possible to predict the relative stress level to which the material is subjected [6].

2. Load-time effect

The mode of fracture of fibrous composite materials is very amenable to acoustic emission techniques, since the fracture of fibres releases a considerable amount of energy. Assuming a shear lag model [1] for the stress transfer at the vicinity of the fractured fibre, the energy released by the fracture would be:

$$U = 2\int_0^{l_c} \frac{\sigma_{f_0}{}^2 A}{2E_f}\,dx - 2\int_0^{l_c} \frac{\sigma_f{}^2 A}{2E_f}\,dx - 2\int_0^{l_c} \frac{\tau_m{}^2 A'}{2G_m}\,dx \qquad (1)$$

where U = the total energy released, σ_f = the axial stress in the fibre near the fracture, σ_{f_0} = the undisturbed axial stress in the fibre near the fracture, E_f = the extension modulus of the fibre, A = the cross-sectional area of the fibre, l_c = the ineffective length, τ_m = the shear stress in the matrix near the fractured fibre, G_m = the shear modulus of the matrix, A' = the cross-sectional area of the matrix surrounding one fibre.

The ineffective length, l_c, is defined by the shear lag model as [1]:

$$l_c = 1.15 d_f \left[\frac{E_f}{2G_m} \frac{1 - v_f^{1/2}}{v_f^{1/2}}\right]^{1/2} \qquad (2)$$

where d_f = diameter of fibre, v_f = volume fraction of fibres. The energy released is calculated as the difference between the elastic energy stored in the fibre before the fracture and the elastic energy in the fibre and matrix after fracture. It was assumed that the matrix behaves in an elastic manner, but when the matrix is a polymeric material, its behaviour is really viscoelastic, which means that the shear modulus, G_m, is time dependent. The effect of this phenomenon will be discussed later. It has been found [7] that unidirectional elastic composite materials show a phenomenon very similar to the "Kaiser effect" in metals even though its nature is obviously entirely different. The "Kaiser effect" is the name given to experimental results of acoustic emission measurements which show that when a material is loaded to some stress level and then unloaded and reloaded again, there is no acoustic emission until the stress in the second cycle is higher than in the previous ones. For composite materials loaded in the fibre direction, there is no further fracturing of fibres in the second cycle until the first stress level is reached and, therefore, no acoustic emission. But when the matrix is viscoelastic there is some deviation from this behaviour. Because of the viscoelastic nature of the matrix, there is a stress redistribution in the material with time [8], which can cause fibres to fracture under constant external load. If the fibres themselves are sensitive to static fatigue, i.e. they will fracture after some time under constant fibre stress, we will have an additional source of acoustic emission which depends on time. We will develop our theory assuming that the fibres do not fracture with time under constant stress, so that all fractures occur as a result of stress redistribution because of the viscoelastic nature of the matrix.

Assume the matrix is viscoelastic and the fibres are not sensitive to static fatigue (stress rupture). When the specimen is loaded to some stress level and kept constant, we have at time, $t = 0$, some amount of fibre fracture. The stress in the fibres far away from the fracture is $\sigma_f(0)$, and the ineffective length is l_{c_0}. The relative amount of fractured fibres in the cross-section is $F[\sigma_f(0)]$. The detailed analysis can be found in [8]. After some time, T, the matrix relaxes, the ineffective length increases and the true stress in the fibres, $\sigma_f(T)$, increases. As a result, more fibres are fractured. After more time, the matrix continues to relax and more fibres fracture. The relative number of fractured fibres after time t is given by $F[\sigma_f(t)]$ which may be calculated from the equation,

$$\{1 - F[\sigma_f(t)]\}^{\beta} \ln\{1 - F[\sigma_f(t)]\} = -\frac{1}{\beta e}\left[\frac{\sigma_0}{\bar{\sigma}(1 - R(t))}\right]^{\beta}$$

where β = the parameter of the strength distribution of the fibres, σ_0 = the applied stress, $\bar{\sigma}$ = the most probable failure stress at $t = 0$ (elastic). $R(t)$ is a parameter which gives the amount of weakening of the composite due to the increase in the ineffective length, $R(t)$ is given by

$$R(t) = F[\sigma_f(0)]\left[\frac{l_c(t)}{l_c(0)} - 1\right] + \int_{F[\sigma_f(0)]}^{F[\sigma_f(t)]} \left[\frac{l_c(t - T)}{l_c(0)} - 1\right] \mathrm{d}F \qquad (4)$$

where $\sigma_f(t)$ is the stress in an effective fibre at time t. Equations 3 and 4 cannot be solved analytically since $\sigma_f(t)$ depends on $R(t)$ and numerical methods must be applied. The detailed procedure can be found in [8]. Fig. 1 shows the cumulative damage, or the summation of the relative number of fibres fractured as a function of time for a given stress level.

The effect of this phenomenon should be seen clearly with the aid of acoustic emission techniques, since the continuous fracture of fibres would be detected by the transducer. An experimental programme was planned to verify this phenomenon.

3. Experimental

The experimental programme was designed to measure the acoustic emission from unidirectional fibrous composites, under programmed tension cycles. Specimens made of E-glass fibres in an ERL 2256/ZZL 820 epoxy were fabricated into a unidirectional lamina by filament winding technique, cut to dimension and aluminium tabs were glued to them. The fibre volume fraction was 60%. The final specimen is shown in Fig. 2. The specimen was made wide enough to place the pick-up transducer on it. Special grips were

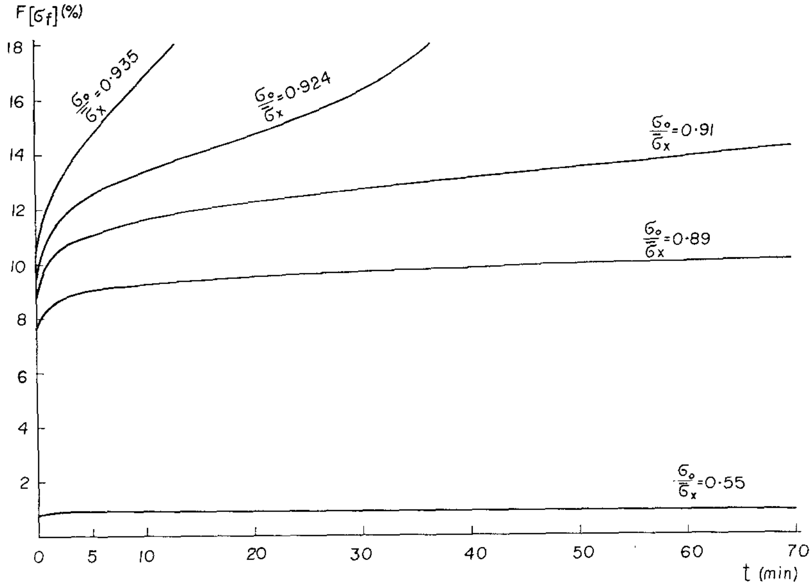

Figure 1 Accumulation of fibre fractures under constant stress.

made to grip the specimen and ensure that no slip occurred. Specimens were put in a tension machine and loaded through programmed cycles. The cross-head speed was 1 mm min^{-1} approximately. The load and the acoustic emission was recorded during the cycles.

3.1. Equipment

The glass-epoxy tensile specimens were pulled in a bench-type tensile testing machine (Hounsfield Tensometer) with a full scale load of 2000 kg. Cross-head motion in this machine is actuated by a belt drive without feedback control so that the cross-head speed is not accurately linear throughout the loading range. This factor was not considered significant for this investigation which was concerned with relaxation phenomena. The load in this machine is measured by means of a calibrated beam and hydraulic deflection measurement system using mercury. In order to obtain a record of the load, a strain gauge was attached to the beam and the output was amplified by a Sanborn transducer carrier amplifier, Model 311A. The analogue load output from the transducer amplifier was charted against acoustic emission data and also recorded on a 4-channel FM tape recorder in order to enable later processing and analysis. The block diagram of the system is shown in Fig. 3.

The acoustic emission pulses were detected by a PZT-5 differential transducer (Dunegan D-140-B) operating in the 100 to 300 kHz frequency range. By filtering to eliminate extraneous noise in the acoustic range, it was possible to conduct the tests without any special acoustic isolation of the test system. The differential input from the transducer also helped to eliminate external electrical noise pickup. The relatively high level of the acoustic emission pulses from the composite material (as compared

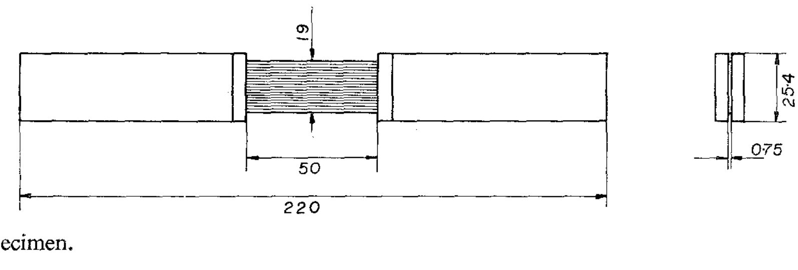

Figure 2 Test specimen.

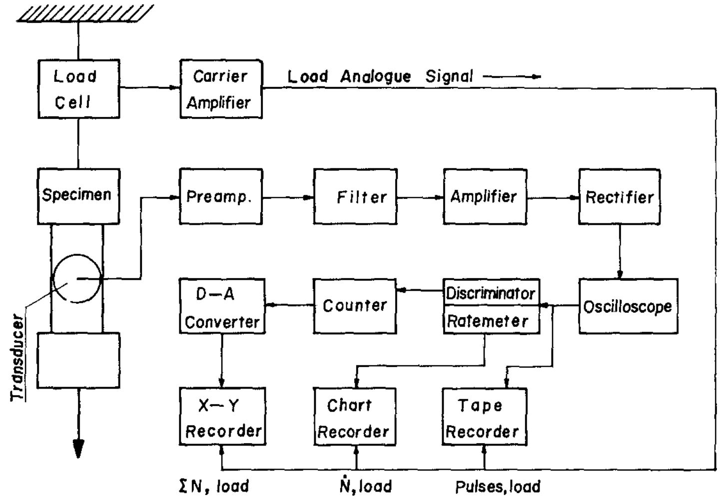

Figure 3 The experimental system.

to pulses from metals undergoing plastic deformation) gave a background pulse level that was essentially zero (more than − 80 dB).

The acoustic emission transducer was attached to the centre of the tensile specimen by a rubber band and coupled acoustically to it with a viscous resin (Dunegan A-9). The pulses from the transducer were amplified × 1000 in a preamplifier (Dunegan 802P-A), filtered to remove extraneous noise in a 300 kHz low pass filter and again in a 100 kHz-1 MHz bandpass amplifier, where the amplification could be adjusted from 20 to 60 dB (Brookdeal Model 432). The filtered and amplified pulses were then rectified in a full wave doubler to enable counting of individual pulses rather than the entire ring-down [9]. The rectified pulses were observed on an oscilloscope (Tektronik Model 564 with a 3A9 plug-in amplifier), filtered in the oscilloscope amplifier (100 Hz to 10 kHz) and then passed to processing and recording equipment. The pulses were recorded on the FM tape recorder at 15 in. sec^{-1} to allow playback later at an 8:1 speed reduction for greater resolution of transient events.

During the tensile tests, the load was recorded on one channel of a Sanborn oscillographic recorder (Model 322) and on the other channel the acoustic emission rate was recorded. The pulse rate was obtained by means of a discriminator-ratemeter (Elscint SCA-N-3). The discriminator lower level cut-off was adjusted to eliminate background noise and the upper level was set at maximum. The ratemeter provided a continuous analogue voltage proportional to the pulse input rate for recording on the chart and tape. At the same time, a logic output pulse was available from each acoustic emission pulse for summing the total number of pulses. The pulse total was summed on a Monsel 101B Minicounter and an analogue signal proportional to the total counts was obtained from a digital-to-analogue converter (Elron Model M-513) for plotting against load on an X-Y recorder.

The pulses, recorded during the test together with the load analogue voltage on the FM tape recorder, were later played back at an 8:1 speed reduction for better resolution.

4. Results and discussion

In the first group of tests, the specimen was tensioned at an approximately constant rate. The results are shown in Fig. 4. The stress-time curve is close to linear but the summation of counts and the rate of counts increases very quickly at the high stress level. Comparing with Fig. 5, where the relative number of fibre fractures versus the stress level is shown, we see that the behaviour is very similar. At the high stress levels, a small increase in the stress produces a large accumulation of pulse counts. On the other hand, at the low stress level, the same increase in the stress has very little effect on the number of fractures and the acoustic emission output. A significant acoustic emission output (over 1.6×10^3 counts per min) appears at a stress level which is 40% of the ultimate strength and, as can be seen in Fig. 5, the rate of fibre fracture also begins to be meaningful at that

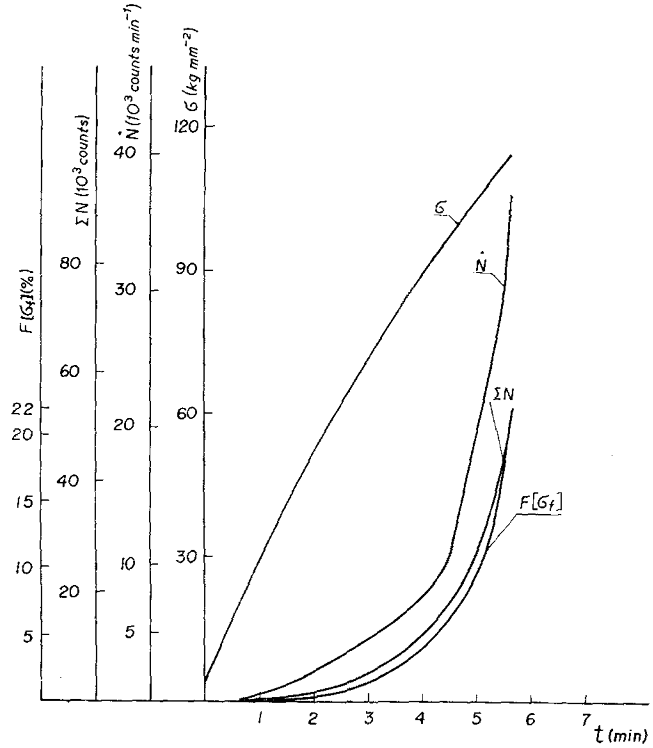

Figure 4 Stress, total counts, and rate versus time for constant rate of axial tension of unidirectional fibre composite. The theoretical relative number of fractures is also shown.

stress level. For comparison, the data of Fig. 5 are plotted also on Fig. 4 to show the similar behaviour of the total counts and the total relative number of fractures. In the next test, the loading was stopped for a short time and remained at a constant stress level for half a minute and then continued again at the same rate as before. It is seen in Fig. 6 that the counting rate decreases immediately, and as the loading begins again, it reaches the same value as before. This phenomenon has been discussed elsewhere [7] on the application of the "Kaiser effect" to composite materials. It is important to note that the rate of acoustic emission as well as the rate of fibre fracture are both a function of the stress level.

The experiments which were programmed to show the time effect consist of loading the specimen to some stress level and maintaining this stress level for some time, after which it was unloaded and reloaded again to another stress level and again kept there for some period of time. The results of such experiments are shown in Figs. 7 and 8. Fig. 7 shows the results of an experiment where at first the specimen was loaded to 56% of its ultimate strength and kept at this stress level. It is seen that the acoustic emission counting rate decreases very rapidly and, after 3 min, there was no meaningful counting at all. This is in good correlation with the behaviour of the fibre fracture under low stress levels, as can be seen readily from Fig. 1.

After unloading and reloading again, acoustic emission begins only after passing the previous stress level, which emphasizes again the "Kaiser effect". The load was raised to 93.5% of the ultimate strength and again kept constant. This time, because of the high stress level, the acoustic emission pulses continue for a much longer time with a considerably higher counting rate. The theoretical cumulative fibre fractures from Fig. 1 are also plotted here for reference, for that part of time which is relevant. After 9 min, the specimen was unloaded and removed from the tension machine. Some time later it was loaded again to 84% of its strength without any acoustic emisson being noted. In the experiment described in Fig. 8 there is again a verification of the

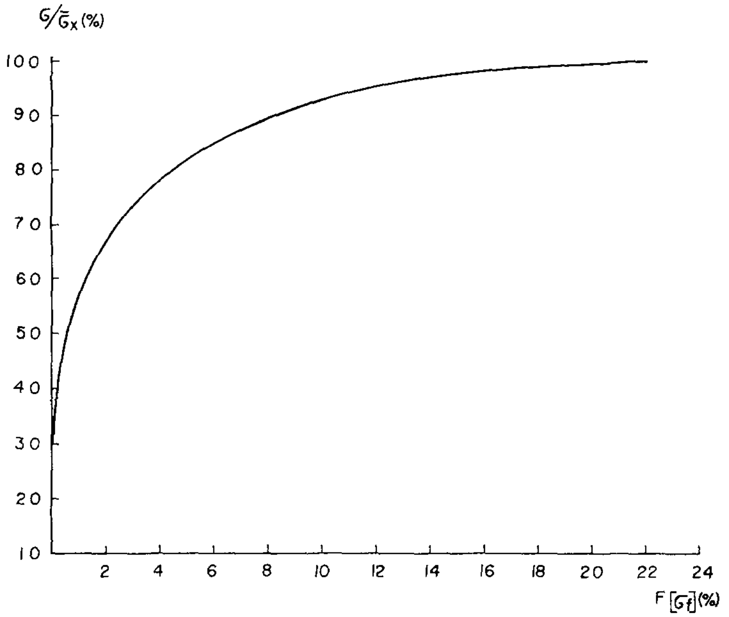

Figure 5 Relative number of fibre fractures versus relative stress level, for E-glass/epoxy.

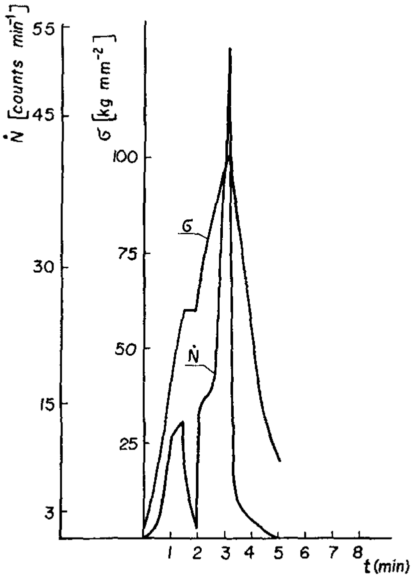

Figure 6 Effect of a pause in loading on the counting rate.

"Kaiser effect". At the beginning of the test, two stages of loading and unloading were applied without keeping the specimen under constant stress. The first cycle was to 54% of the ultimate strength and the second to 89%. Again, there was no acoustic emission on the second cycle before the first cycle's highest stress was exceeded. On the third cycle, it was loaded again to the same stress level as in the second cycle, and held at this stress level. It can be noted that there was acoustic emission output at this stress even though the previous cycle stress level was not exceeded. This is in contrast with the usual behaviour of the "Kaiser effect" and it is a result of the accumulation of fibre fractures during the constant stress level. The specimen was kept under this stress level until no meaningful acoustic emission output was recorded. During this time, a considerable number of counts accumulated because of the high stress level. Therefore, the time effect takes place even when there is a pause in the loading of the material, and its nature is cumulative and depends on the viscoelastic nature of the matrix. At this stress level it took 13 min until the fibre fractures reduced to a slow rate. After that time, the specimen was unloaded and reloaded again to the same stress level. Because of the high stress level, relaxation of stresses in the matrix occurred during this unloading cycle, and as a result, some acoustic emission with counting rate a little higher than before unloading occurred, but the relaxation phenomena is cumulative and therefore there is no counting as in the second cycle. We see that the viscoelastic matrix has some influence on the "Kaiser effect" as well.

5. Conclusions

It was shown experimentally that there is an

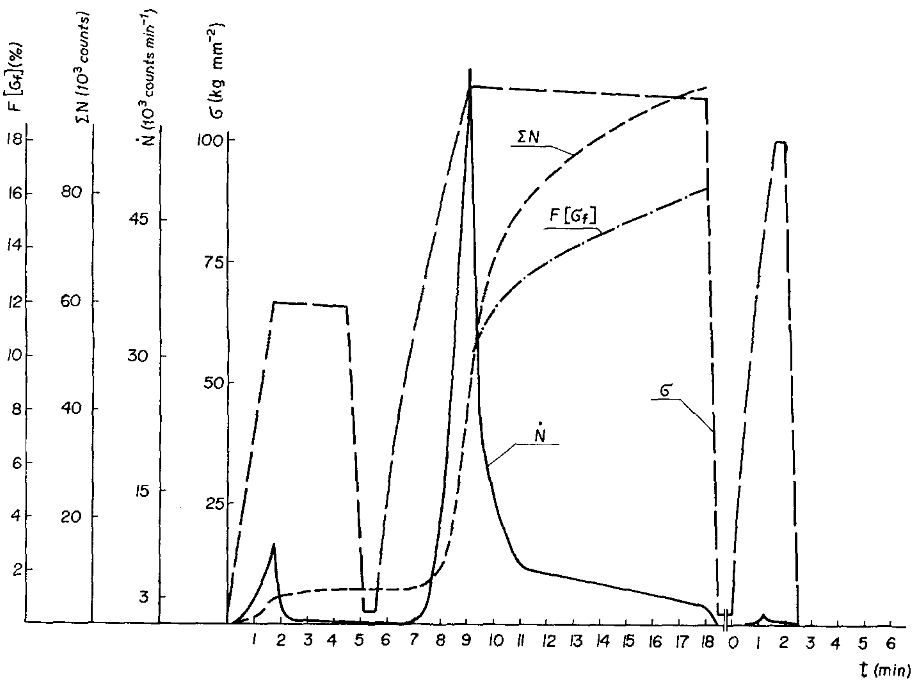

Figure 7 Load-time effect-continuous counting of acoustice mission with constant load applied.

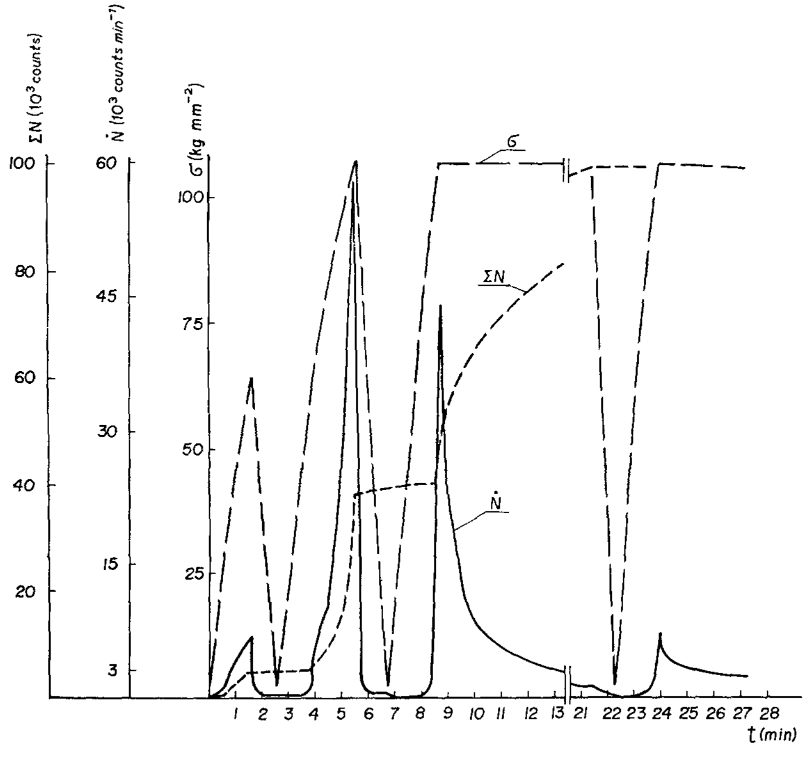

Figure 8 Time effect and the "Kaiser effect". In the second cycle – continuous counting; on third – no counting.

acoustic emission output when a unidirectional fibre composite material with viscoelastic matrix is held at a constant high stress level. The rate of the acoustic emission output decreases with time until there is no meaningful output. These phenomena are indicative of events which occur in the material when it is under a constant load. It is suggested that the acoustic emission output is a result of fibre fractures during the static load. The results from the theory of fibre fractures is in good agreement with the data gathered by acoustic emission detection.

It is concluded that the material fails by the accumulation of fibre fractures which can be monitored by the acoustic emission technique. Thus by unloading and reloading again, no further fractures occur until the fibre stress is higher than in the first cycle, since all the weak fibres break in the first cycle. Because of the visco-elastic matrix, there is a relaxation of stress within the material which causes redistribution of loads among the fibres and, therefore, further fracture of fibres, which can be detected by an acoustic emission transducer.

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