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ACOUSTIC EMISSION MONITORING DURING MECHANICAL - LOADING OF PAPER

STATE OF THE ART

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Acoustic Emission Monitoring During Mechanical Loading of Paper

State of the Art

by

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INTRODUCTION

It is known that paper, during mechanical loading, exhibits a number of different deformation and failure phenomena's e.g. plastic/viscoelastic deformation of the fibres, breaking of fibre to fibre bonds and fibre fracture.

In this report, some results from the literature aiming at the use of Acoustic Emission (AE) monitoring to detect some of the above phenomena's in paper, are reported. Though this specific use of AE is quite a new technique and hence the literature contains only a few references it is believed that this report should give some guide - lines for the abilities and limitations of the method as applied to paper.

A brief introduction to the monitoring of AE, is also given.

ACOUSTIC EMISSION MONITORING

During the straining of for example paper, the weakest fibre to fibre bond will break at some load level. During the fracturing of this bond (which will occur in the order of micro seconds), forces in the neighbourhood of the fracture site, will be redistributed. This redistribution will in general be transmitted through the material as a stress wave which can be recorded on the surface of the material, using an appropriate transducer. As the loading is increased, the number of broken bonds will increase and in a non - proportional way with respect to the load. At a later stage of the loading the fibres will also start to break and eventually the paper will suffer total failure.

A schematic setup for the Acoustic Emission (AE) monitoring is shown in figure 1:

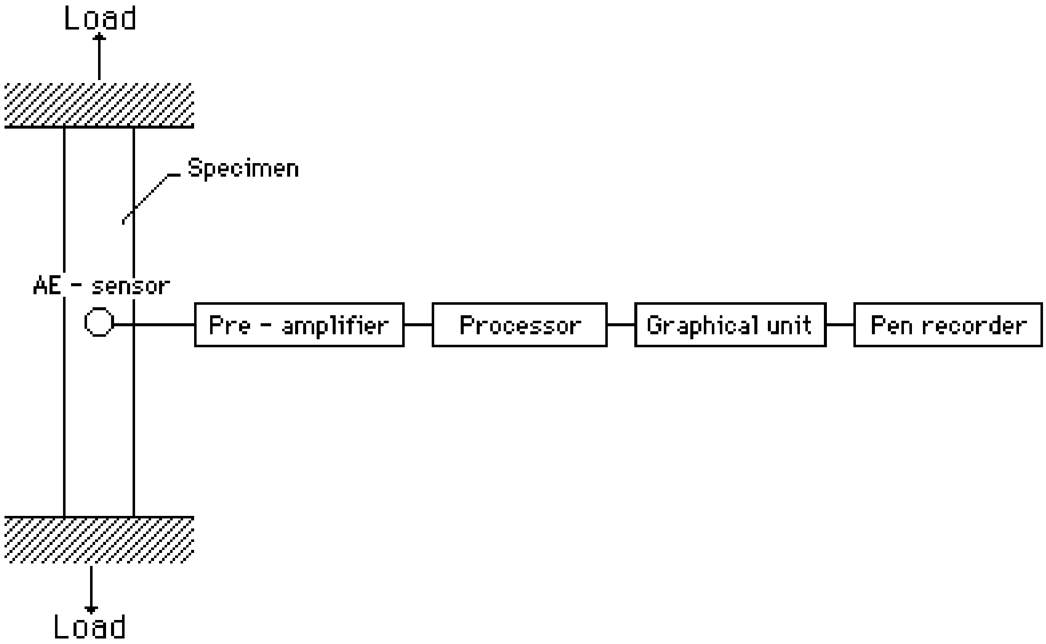

Fig. 1 Schematic setup for AE - monitoring

The pre - amplifier has typically an amplification of 40 or 60 dB_{AE} (to be defined later). A high pass filter is often used to eliminate low frequency noise.

In figure 2 is shown a typical amplified signal from a resonance frequency transducer (the most commonly used transducer) attached directly to a loaded paper sample. When hit by a stress wave, the transducer will ring like a bell and from figure 2 one can deduce that the resonance frequence of the transducer is about 150. kHz

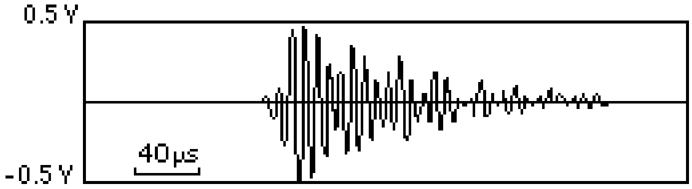

Fig. 2 Typical AE - signal from paper (from [1])

Since the stress wave, on its way from the fracture site to the transducer, will be reflected, converted to other wave types, suffer damping, dispersion etc and since the transducer will have a transfer function dominated by its resonance frequence it is in general impossible to say anything in detail about the process which caused the recorded AE - signal.

Figure 2 defines what in AE - terms is referred to as an event. The origin of such an event might be fibre to fibre bond failure, fibre rupture, external disturbances etc. Some parameters that are used to describe an AE - event are defined in figure 3 :

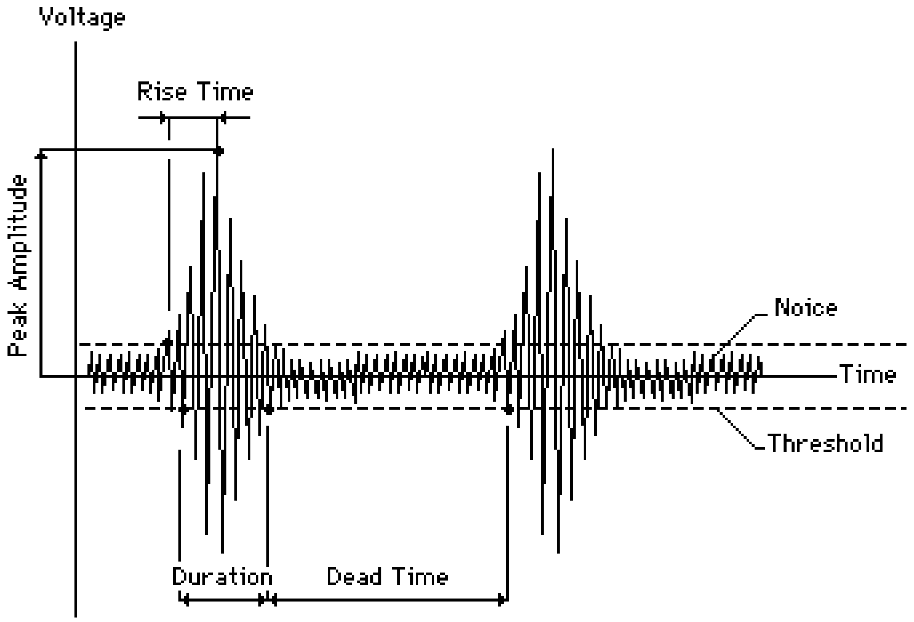

Fig. 3 AE - parameters

In order to exclude the mechanical and electronic noise that is, to some extent always present during an AE - monitoring, a threshold value for the output voltage can be defined as in figure 3. This means that every signal with an amplitude less than this threshold will be discarded. The threshold value and the peak amplitude is most commonly given in dB_{AE} defined as:

$$R\ [dB_{AE}] = 20 \log(V/V_{ref}) \qquad (1)$$

where R is the threshold value or the peak amplitude in $[dB_{AE}]$, V is the output voltage (peak amplitude or threshold value) from the sensor and V_{ref} is a reference voltage at the sensor taken as 1 mV.

On some AE - equipment the threshold is defined in volts with respect to the amplified signal so that a threshold voltage of say 0.1 V will, with a pre - amplification of 40 $[dB_{AE}]$ and an amplification in the process unit of 30 $[dB_{AE}]$, correspond to a threshold voltage of 31.62 mV at the sensor so that the threshold value in $[dB_{AE}]$ will be 30. In figure 3 is also shown a dead time which is introduced in order to define separate events i.e. the dead time is the time the signal should be below the threshold value in order to define the next wave train as a separate event.

Parameters used to describe an AE - event are, with reference to figure 3, duration, rise time and peak amplitude. Among these, the peak amplitude is the most frequently used.

As output from an AE - monitoring, one can choose cumulative (or total) events versus load on and/or deformation of the specimen. In figure 4 is shown a typical cumulative events versus deformation curve.

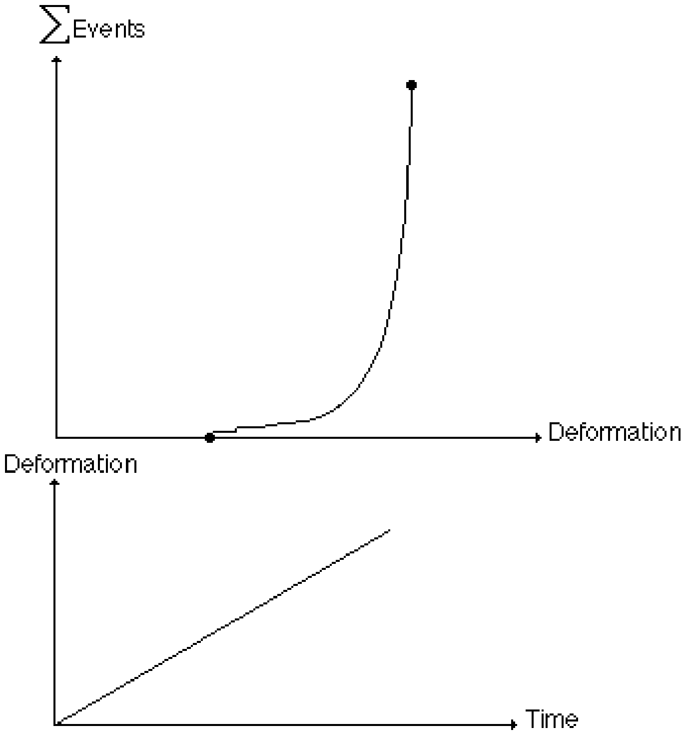

Fig. 4 Typical cumulative events versus deformation curve

Below a certain value of the deformation, the specimen is acoustically inactive. This deformation value is to some extent dependent on the threshold value. Increasing the deformation above the value for onset of AE, the cumulative number of events will increase in a progressive way and eventually the specimen will suffer total failure. From a curve as shown in figure 4, it is not possible to differentiate between different micro fracture phenomena's. To get an indication of the presence of different fracture phenomena's, the amplitude distribution can be used. The amplitude distribution gives the number of events with a peak amplitude in a certain interval. This is shown in figure 5:

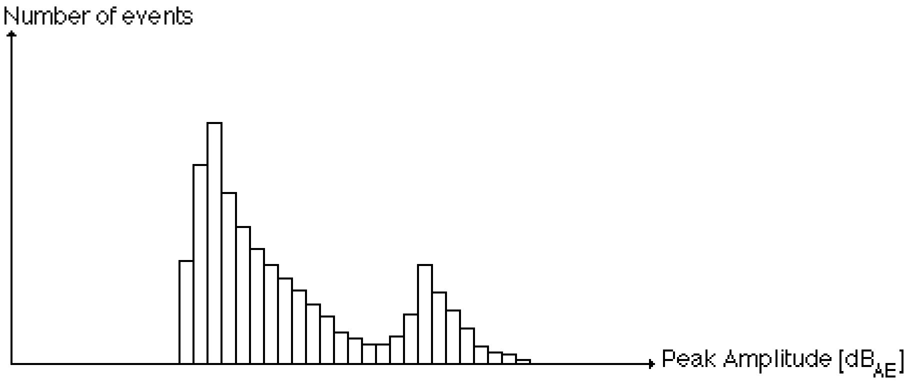

Fig. 5 Distribution by peak amplitude

The distribution in figure 5 shows two distinct distribution peaks, indicating that there are two different failure mechanisms. If the amplitude distribution is studied in real time during a test it is possible to estimate the strain for which the second failure mechanism is being activated.

It has been shown by various investigators that the cumulative amplitude distribution can be approximated by:

$$N = kA^m \tag{2}$$

where N is the number of events with a maximum amplitude larger than or equal to A, and k and m are constants. It has been claimed that m should be specific for a certain damage mechanism. In [7] it is shown that this exponent differs almost a factor two between the distributions for a tensile and a peel test, indicating different damage mechanisms for these particular situations.

Another general AE - parameter of interest is the so called Felicity Ratio (FR) which can be defined with reference to figure 6, where it is assumed that for example a paper sample is loaded by a given force.

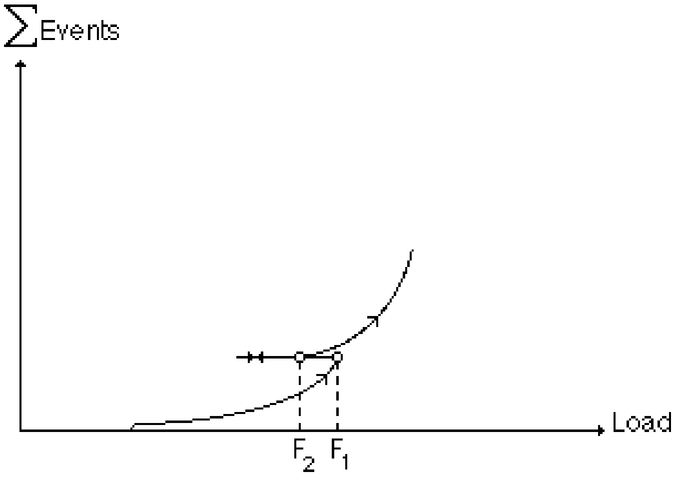

Fig. 6 Felicity Ratio

If, at some load level F_1, the sample is unloaded and reloaded again, so that the AE starts again at a load level F_2, then FR is defined according to:

$$FR = F_2/F_1 \tag{3}$$

A low value of FR in polymeric composites indicates severe structural damage. FR less then one has been found close to final failure of paper specimens (c.f. [1]).

WAVE PROPAGATION IN PAPER

In newer AE equipments it is possible to obtain, in addition to the parameters defined above, also information regarding the spectral distribution in an acoustic event. To obtain this distribution in an appropriate way, broad band sensors should be utilised.

Another option which is of a great value when determining e.g. arrival times for certain frequency components is the so called Wavelet Transform (c.f. [6]). This transform makes it possible to determine at which time at a certain sensor location, a specified spectral component appears. The needs for this will be motivated at the end of this section.
To be able to say anything about a possible source for a detected AE event, it is necessary to know something about how different waves propagate in a paper sample. In [8] is given a very thorough presentation of basic relations and different wave types, together with a description of a number of test methods involving ultrasonics.

In [9), the theory for bulk waves in anisotropic, linear elastic materials is reviewed and the results are used to construct plate wave solutions. By superposing bulk waves in a certain specified way it is possible to obtain a plane wave which satisfies the boundary conditions (see figure 7) $\square_z(x,\pm h, t) = \square_{xz}(x, \pm h, t) = 0$ for all x and times t.

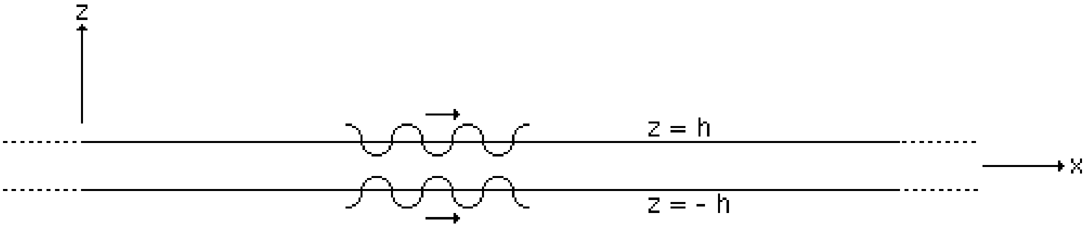

Fig. 7 Wave propagation in the positive x – direction

In general, a wave propagating in the positive x – direction can be written as: $u_i = f_i(z)e^{i(k_x x-\omega t)}$ where u_i (i = x, z) are the x and z components of the displacement vector, f_i (i = x, z) are some functions of z, k_x is a wave number and ω, is the frequency. It turns out that the displacements given above, will solve the problem only for certain functional relationships between k_x and ω. Every such functional relationship corresponds to a certain mode of propagation, witch is either symmetric or anti - symmetric with respect to the plane z = 0.

By introducing the phase velocity $c = \omega/k_x$, it is possible to determine the relationship between the frequency and phase velocity which will give a travelling wave solution. In figure 8 is shown how the phase velocity depends on the frequency for a number of symmetric and anti - symmetric modes shown in figure 9.

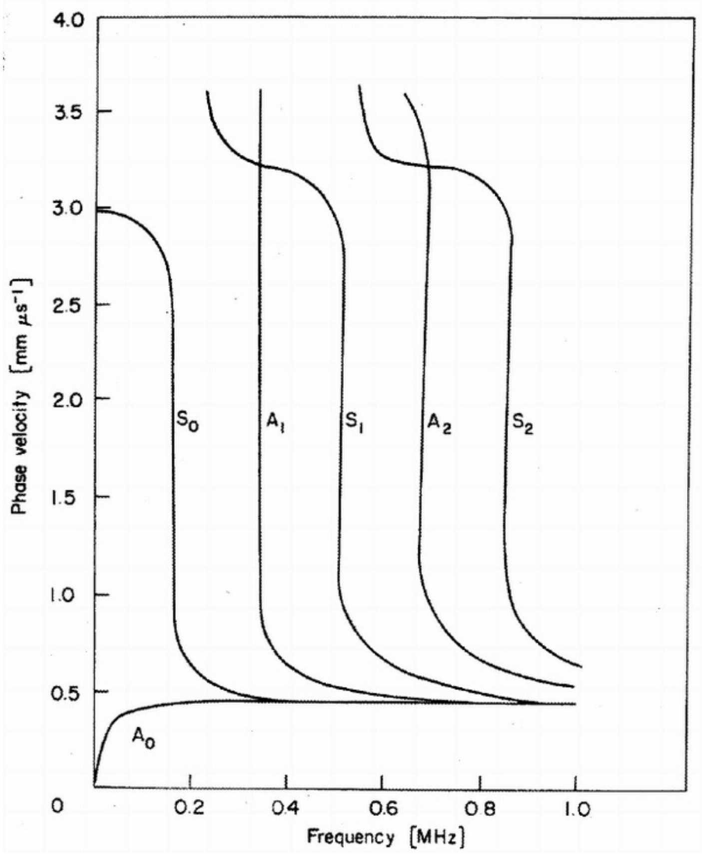

Fig. 8 Phase velocity versus frequency (from [9])

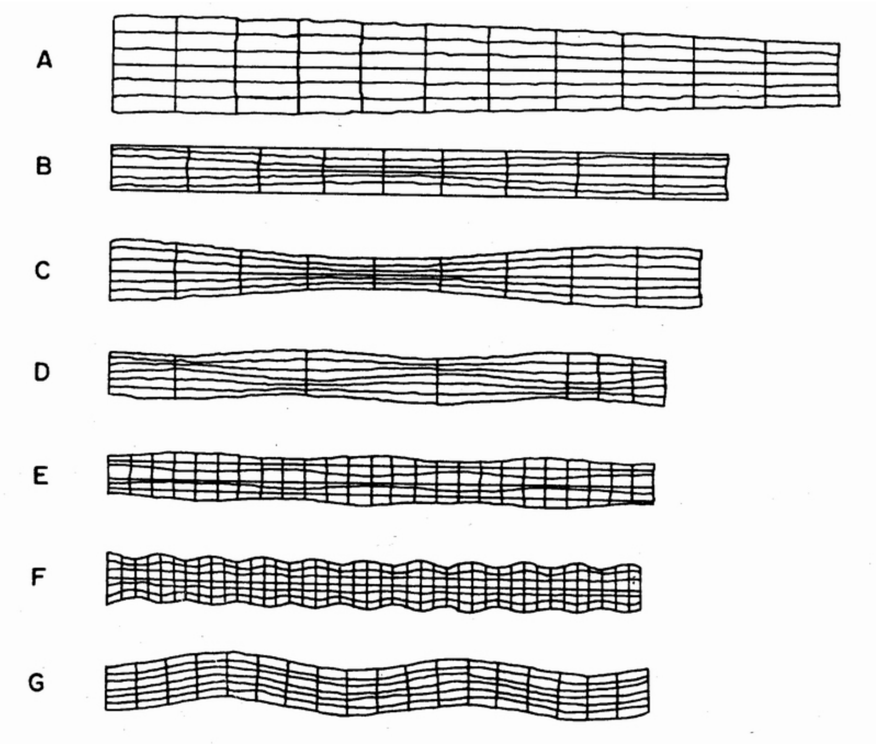

Fig. 9 Different propagation modes (from [9])

The fact that the propagation velocity is different for different spectral components causes problems when it comes to determining the arrival time for a certain disturbance since one can not in general be certain that it is the arrival of the same spectral components that is detected at two different sensor locations. Using wavelet transforms has proven an efficient means for determining at what time a certain spectral component appears.

ACOUSTIC EMISSION MONITORING APPLIED TO PAPER

In [1], [2] and [3] are given some results from Acoustic Emission (AE) monitoring of mechanically loaded paper samples, a review of which will be given here.

In general, the references [1], [2] and [3] lacks information about the number of samples involved in the tests i.e. whether the presented results are averages of a large number of specimens or if they are the outcome on tests on a single sample.

In [1] experiments on both glassine paper and hand - sheets of bleached softwood kraft pulp, were carried out. The effect of beating and basis weight was studied on the softwood kraft pulp.

To investigate the effect of stress history on the AE - behaviour, cyclic loading was applied to a paper sample taken from a hand - sheet formed from unbeaten pulp and with a basis weight of 120 g/m^2. The result is shown in figure 10:

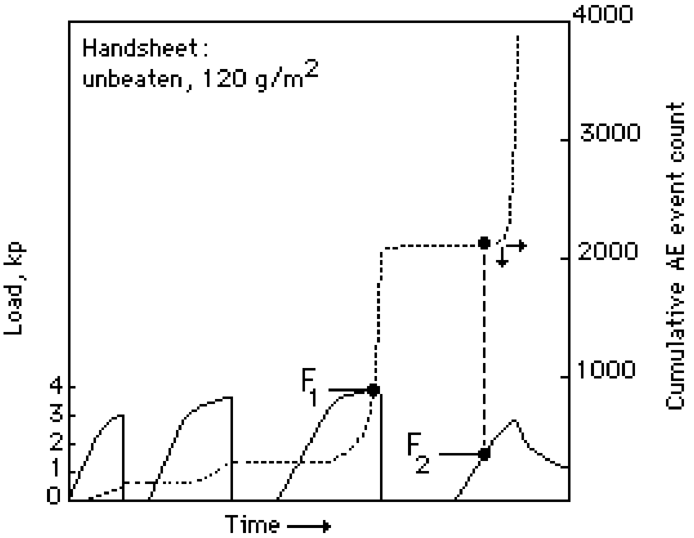

Fig. 10 Influence of stress history on the AE - behaviour (from [1])

The arrows in figure 10 indicates the point of total failure.

It can be observed that for the fourth cycle, the FR is about 0.43 indicating the accumulation of damage during the preceding cycles. Since it is known that paper in general exhibits different behaviours in the Machine Direction (MD) and Cross Direction (CD), it is reason to believe that paper also will exhibit different AE -

performances in the two directions. To clarify this matter, glassine paper was loaded in both MD and CD and monitored with respect to AE. The results are shown in figure 11:

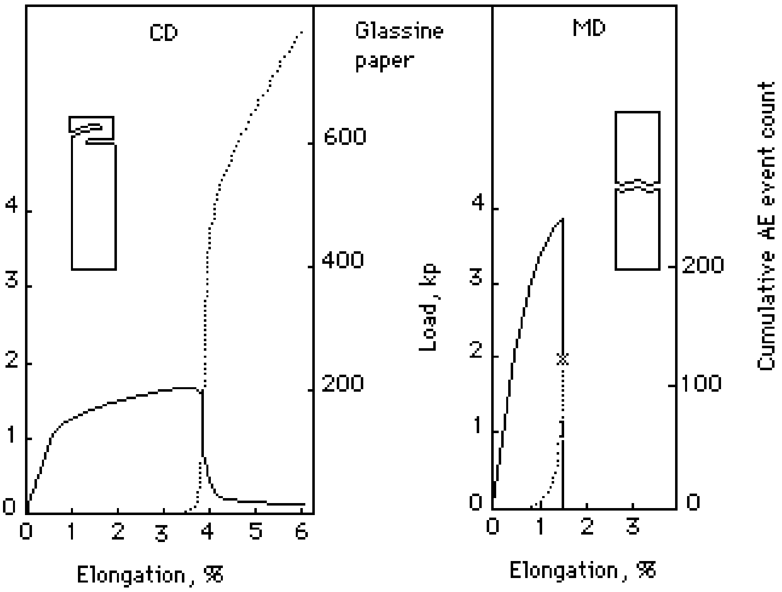

Fig. 11 AE - behaviour of glassine paper (from [1])

In figure 11 is also indicated the different fracture behaviours for the two directions. The fact that the CD sample is not completely separated is responsible for the large amount of emission after maximum load. It can be observed that AE for the CD specimen starts just before the maximum load is reached while it starts in the middle of the non - linear region for the MD specimen.

No amplitude distribution analysis was performed in [1] and it is therefore impossible to see whether there are different fracture mechanisms operative in the different directions.

The effect of beating degree was studied in that samples were taken out from hand - sheets of 60 g/m^2 made of pulp with different beating degrees. The results are shown in figure 12:

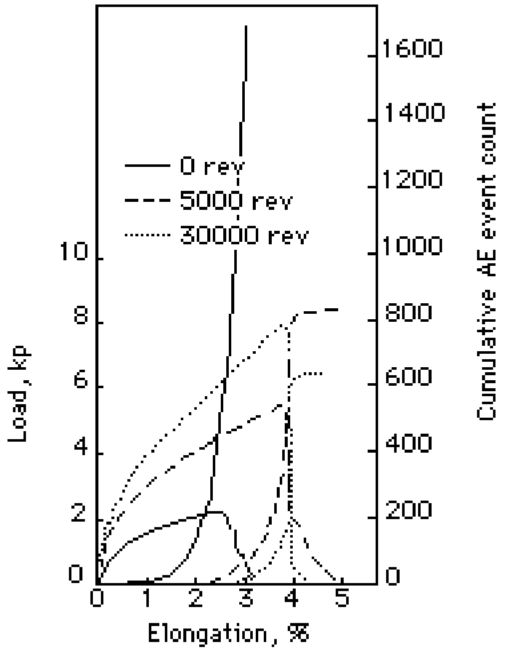

Fig. 12 Effect of beating on the AE - behaviour (from [1])

From the diagram in figure 12 the following result can be extracted, i.e. the strain for onset of AE versus the beating degree:

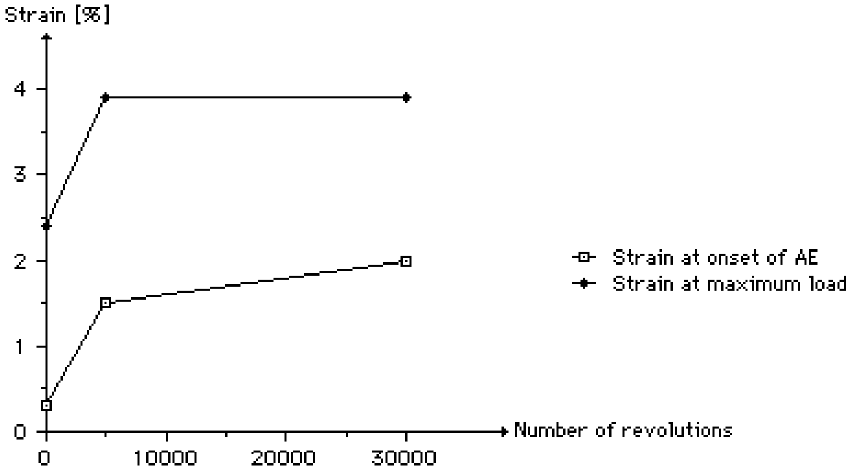

Fig. 13 The effect of beating degree on critical strains

It can be observed that there seem to be a correlation between the strain for onset of AE, strain at maximum load and the beating degree. Also, the total number of events at fracture decreases with increased beating.

The influence of basis weight on the total number of events at maximum load is shown in figure 14:

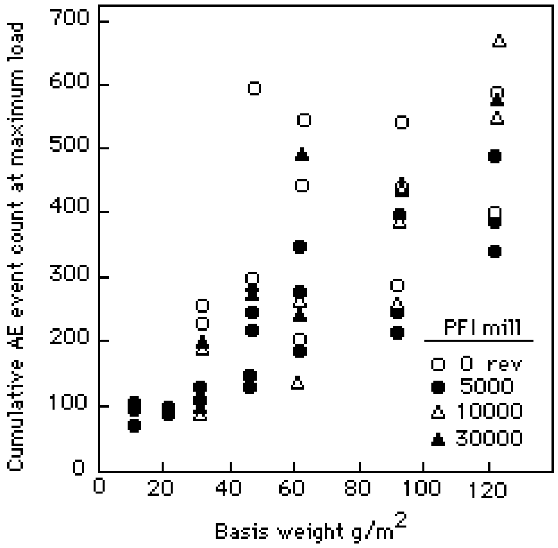

Fig. 14 Total number of events at maximum load versus base weight (from [1])

From figure 14 it can be concluded that except for the un - beaten pulp, the total number of events at maximum load, seem to be proportional to the basis weight. The different AE - behaviours between the un - beaten at the beaten pulps is explained in [1] with that for beaten pulps the AE occurs in a very localized area whereas in the unbeaten pulp, the AE occurs randomly in the whole specimen which would give little correlation between the basis weight and total number of events.

In [2] the different phenomena's, responsible for AE, are investigated. This is done by tensile testing of 70 by 15 mm paper samples with different moisture contents. The samples were taken out of hand - sheets with basis weight 60 g/m^2, made of bleached softwood kraft pulp which was beaten to different degrees using a PFI mill.

The moisture content was varied in order to investigate the role of the fibre to fibre bonds on the paper strength. In figure 15 is shown the effect of moisture content on the load - strain and AE curve.

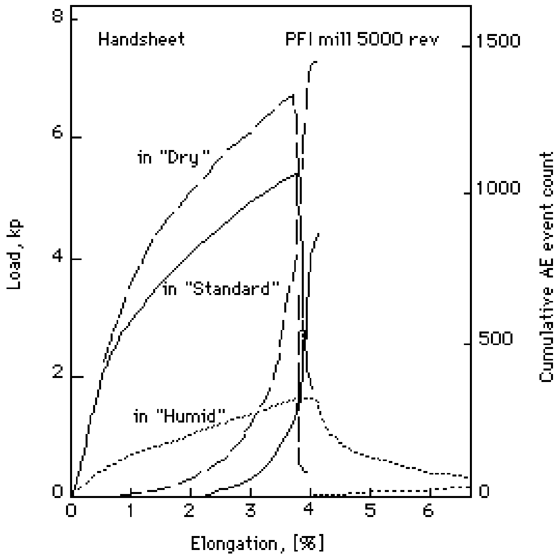

Fig. 15 Effect of moisture on the load - strain and AE curve (from [2])

From figure 15 it can be concluded that except for the dry samples, the AE started well into the plastic region. This means that a large part of the non - linearity does not come from the breaking of fibre to fibre bonds but more likely from the irreversible deformation of pulp fibres. The effect of an increased moisture content is to relax the fibre to fibre bonds which can be observed both as an increase in the strain for onset of AE but also as a decrease in the total number of events for the standard and humid curves.

In figure 16 is shown the peak amplitude distribution for different load intervals (in connection with figures 16 and 17, it should be mentioned that the total amplification was 70 dB$_{AE}$). It is not stated in [2] for which moisture content, the monitoring was performed.

Up to about 90 % of the fracture load, the distribution peaks at approximately 0.1 V (30 dB$_{AE}$ with 70 dB$_{AE}$ amplification). As the load is increased, the distribution tends to flatten, indicating that events with larger peak amplitudes (e.g. fibre rupture) are present.

In figure 17, the peak amplitude for samples of different beating degrees is shown as an average amplitude in the following way: count 100 events, sum the peak amplitude for each event and divide by 100 to obtain an average amplitude. Sum the peak amplitudes for the next 100 events and calculate the average etc. The average amplitudes are then presented as a function of the number of events.

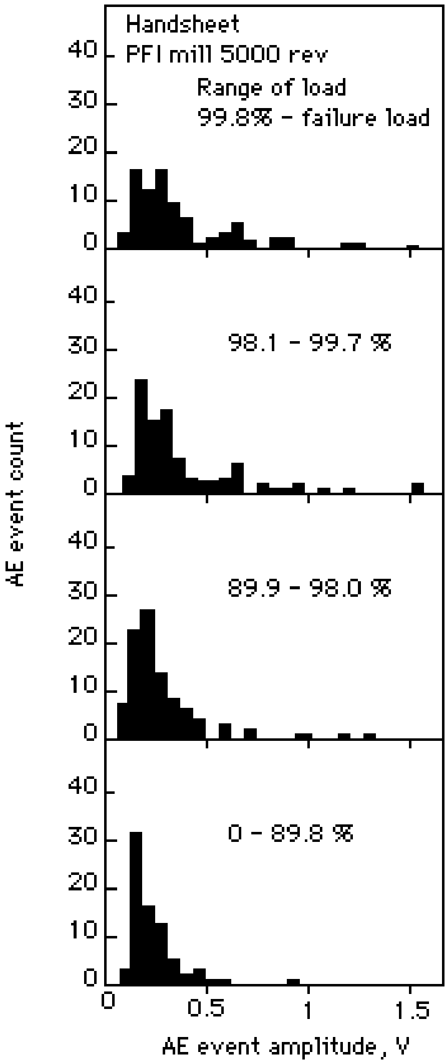

Fig. 16 Peak amplitude distribution for different load intervals (from [2])

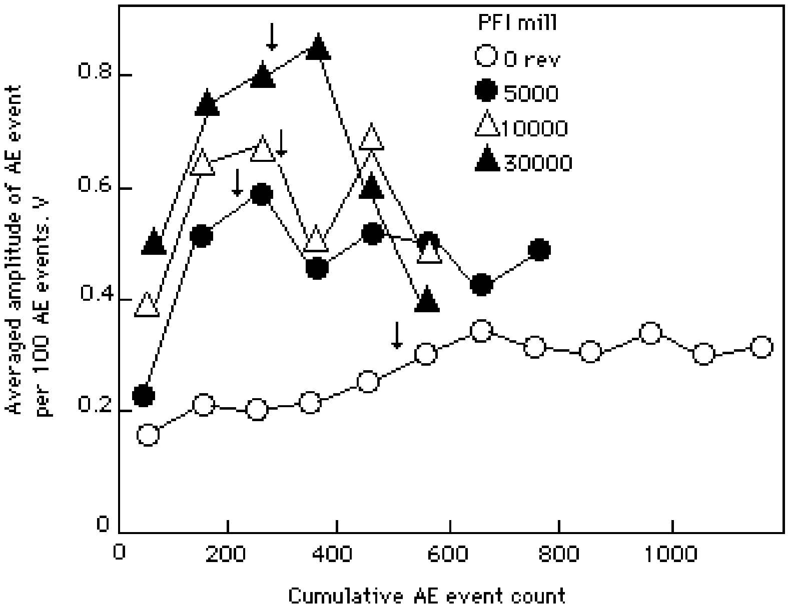

Fig. 17 Averaged peak amplitude versus the total number of events (from [2])

In figure 17, arrows indicate the maximum load (fracture point). One interesting observation is that the averaged peak amplitude increases with the beating degree which suggests that the fibre to fibre bond strength increases and/or that the number of ruptured fibres increases.

Finally the effect of Latex impregnation on the AE behaviour was investigated in [2]. The result is shown in figure 18:

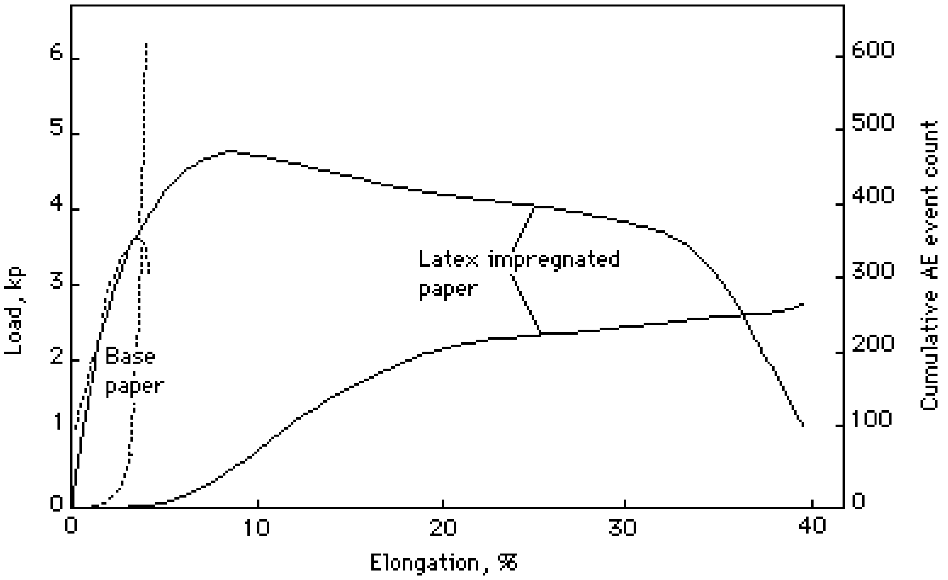

Fig. 18 The effect of Latex impregnation on the AE behaviour of paper (from [2])

It was first shown that the Latex was acoustically inactive so that the impregnation does not add any AE to the paper. From the curves in figure 18, it is seen that the total number of events decreases and both the strain for onset of AE and the fracture strain increases when the paper is impregnated. Two reasons for the decrease of the total number of events might be that the Latex layer damps the peak amplitudes of some events below the threshold value and also that the Latex "locks" a number of fibre to fibre bonds close to the surfaces of the sample. No information regarding the Latex content of the samples is given in [2].

In [3], tests on paper samples were performed both as conventional tensile tests and as zero span tensile tests (c.f. [4]). Zero span means that the gauge length of the paper sample is made approximately zero in order to make the fibre strength to have a greater influence on the total strength than it has in a conventional test. In the conventional tensile test, hand - sheets identical to those considered in [2] and with different beating degrees (0, 5000 and 30000 PFI mill rev) were tested with respect to there AE performance. The result was almost identical to those in figure (8). That is, AE began to occur immediately after the elastic deformation for the unbeaten pulp but not until half way through the plastic region in the load/strain curve for the beaten pulp.

It is agreed on that in paper, two fracture processes are dominating ie breaking of fibre to fibre bonds and fibre rupture. In a general situation both processes are active. In figure 19 is shown the peak amplitude distribution at maximum load for four different beating degrees, tested in normal conventional loading.

For the unbeaten pulp the distribution is narrow and peaks at about 50 dB_{AE} while the distribution tends to flatten as the beating degree increases. Since it can be assumed that breaking of fibre to fibre bonds is the dominant fracture process in conventional tensile loading a distribution peak at 50 dB_{AE} can be taken as a characteristic of fibre to fibre bond breakage. Note that the amplitude distribution broadens towards higher amplitudes with increasing beating degree, indicating that beating increases the fibre to fibre bond strength.

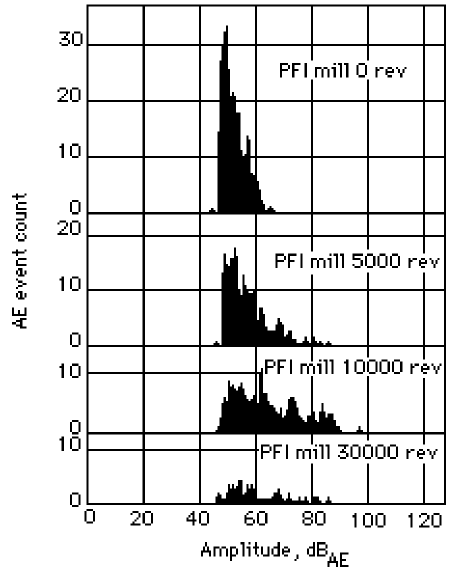

Fig. 19 Peak amplitude distribution for normal tensile loading (from [3])

In figure 20 is shown the amplitude distributions for the zero span test. Only two beating degrees were considered for this type of loading.

Figure 20 can for each beating degree be interpreted as consisting of two overlapping distributions peaking at 50 and 90 dB_{AE} respectively. The 50 dB_{AE} peak can be assumed to represent fibre to fibre bond breakage. Since in the zero span test, the possibility for fibre rupture has increased, the 90dB_{AE} peak can be taken to represent fibre rupture. This is an example of how to use the peak amplitude distribution to identify different fracture mechanisms.

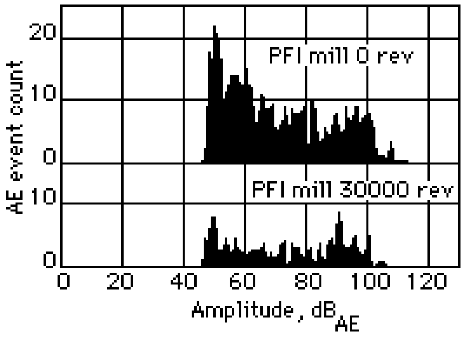

Fig. 20 Peak amplitude distribution for zero span loading (from [3])

In figure 21 is shown the amplitude distributions at all times up to final fracture for hand - sheets loaded in conventional tensile loading and for two beating degrees:

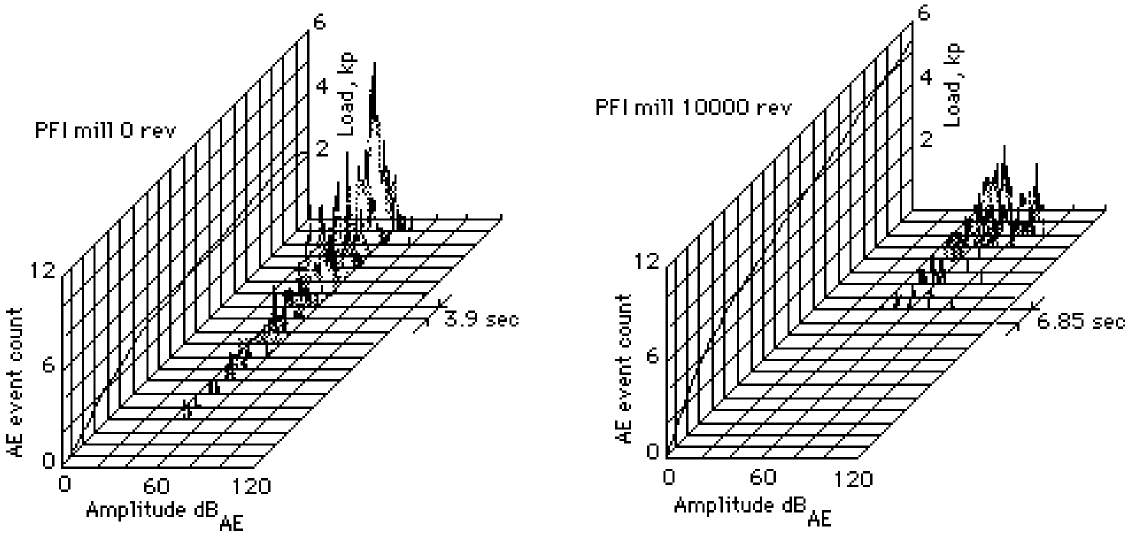

Fig. 21 Change of peak amplitude distribution during tensile testing (from [3])

From figure 21 it can be seen that for the unbeaten pulp, the AE starts quite early in the loading with a few, low amplitude events and that the distribution broadens somewhat during the test, peaking at about 50 dB_{AE}, at final fracture. For the beaten pulp, the AE starts later than for the unbeaten pulp and some AE with amplitude higher than 70 dB_{AE} occurs in an early stage of the loading. At final fracture, the distribution has broadened towards 100 dB_{AE}. The amplitude distribution for the beaten pulp seems to indicate that the fracture at almost all stages of the loading is a combination of fibre to fibre bond breaking and fibre rupture.

In [5] the effect of latex content in the coating colour, on the AE behaviour of coated paper is investigated. Specimens with a width of 18 mm and a gauge length of 120 mm were tested at either a constant deformation rate of 0.25 mm/min or loaded/unloaded according to a specific scheme at a loading/unloading rate of 5 N/min. The specimens were cut from sheets of machine made base paper, coated in the laboratory and finally loaded in the machine direction.

The base paper was a mixture of chemical pulp and thermo - mechanical pulp with tensile index 52.9 kNm/kg and 18.2 kNm/kg in the machine and cross machine direction respectively while the fracture strains in the same directions were 0.8 % and 2.3 % respectively.

The base paper with 10 parts and 20 parts of latex (by weight) respectively, were coated on both sides so that the surface weight of the coating layer was 10 grams/m^2 on each side

Two types of tests were carried out. The first type of test were carried out at a constant deformation rate of 0.25 mm/minute while in the second type of test the loading was according to figure 22:

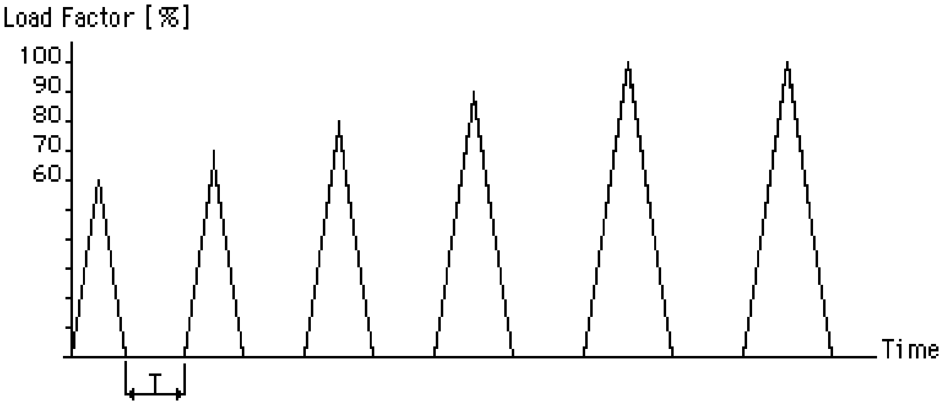

Fig. 22 Loading scheme

The hold time T was chosen to be 2 minutes and the loading/unloading rate to be 5N/min. The maximum load (100 %) varied for the base paper and 10 and 20 parts latex samples according to: 38, 44 and 44 [N].

The reason for using the above loading scheme was to determine the Felicity Ratio (FR), which is defined according to figure 6 and equation (3).

In figures 23 -25 is shown the total number of events versus tensile load for the three types of specimens i.e. base paper and base paper/10 and 20 parts of latex.

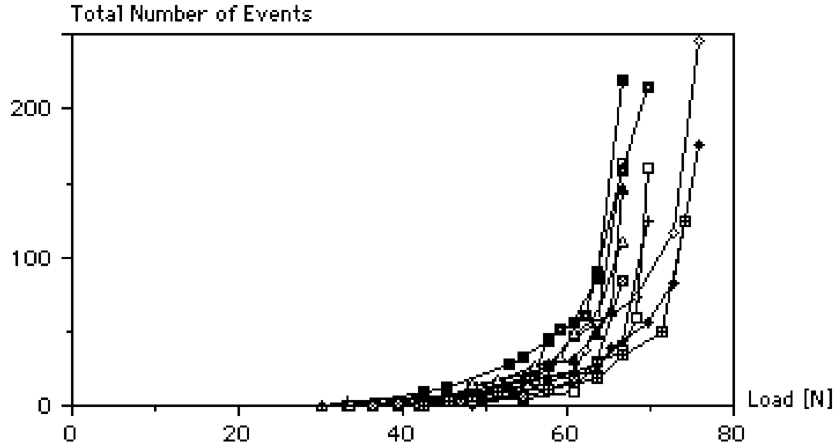

Fig. 23 Total number of events vs. load for base paper (from [5])

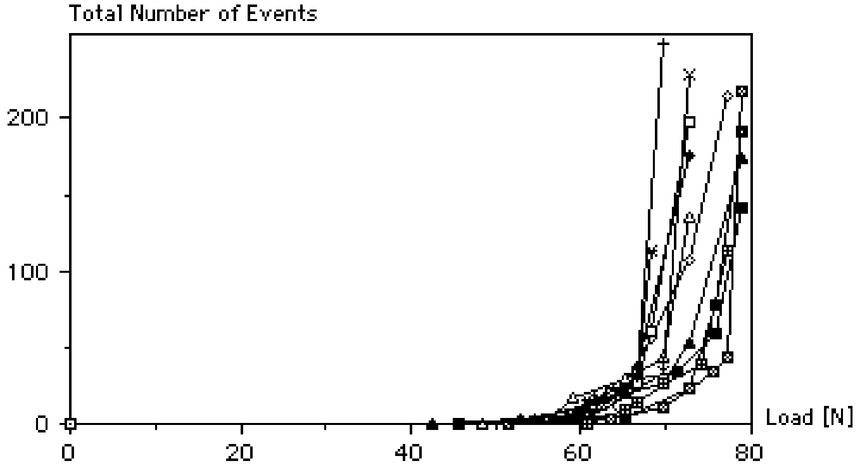

Fig. 24 Total number of events vs. load for base paper/10 parts latex (from [5])

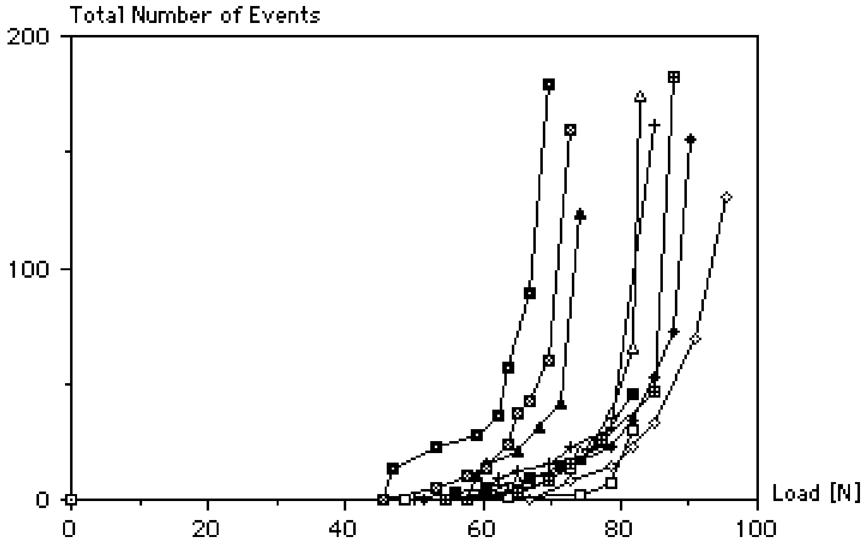

Fig. 25 Total number of events vs. load for base paper/20 parts latex (from [5])

It was concluded in [5] that an increasing latex content seemed to increase the scatter in the AE output.

Due to the scatter, the results were presented as the average plus and minus a standard deviation for a given number of events. This is shown in figures 26 – 28:

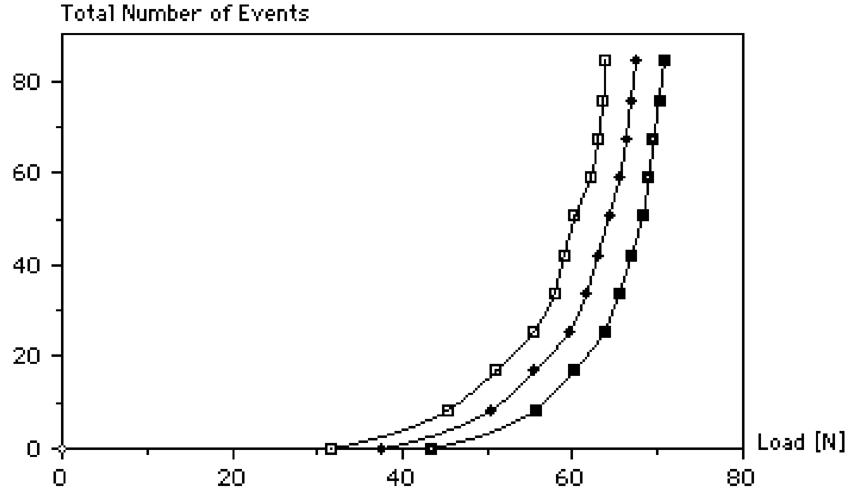

Fig. 26 Average data for base paper (from [5])

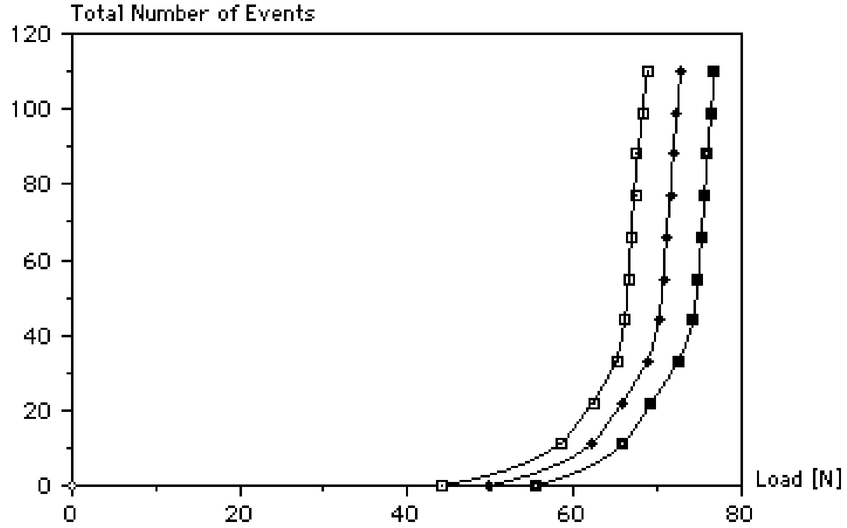

Fig. 27 Average data for base paper/10 parts latex (from [5])

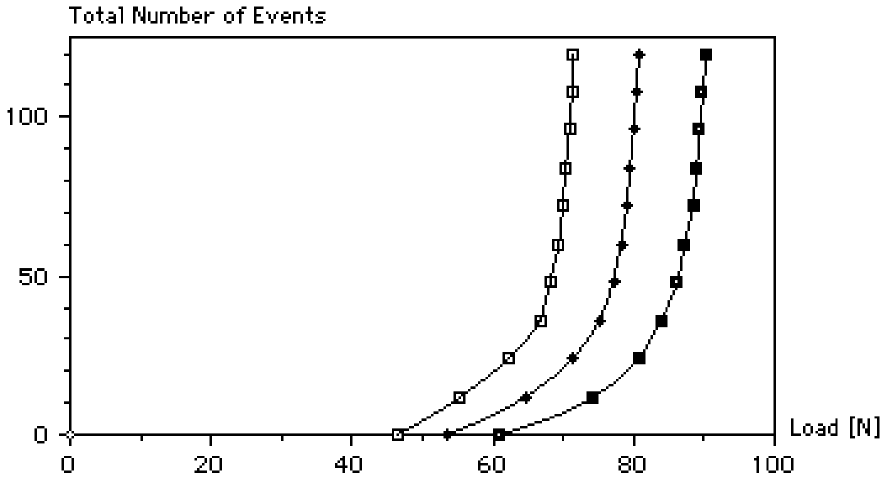

Fig. 28 Average data for base paper/20 parts latex (from [5])

In figure 29, a comparison between the three average curves, is shown:

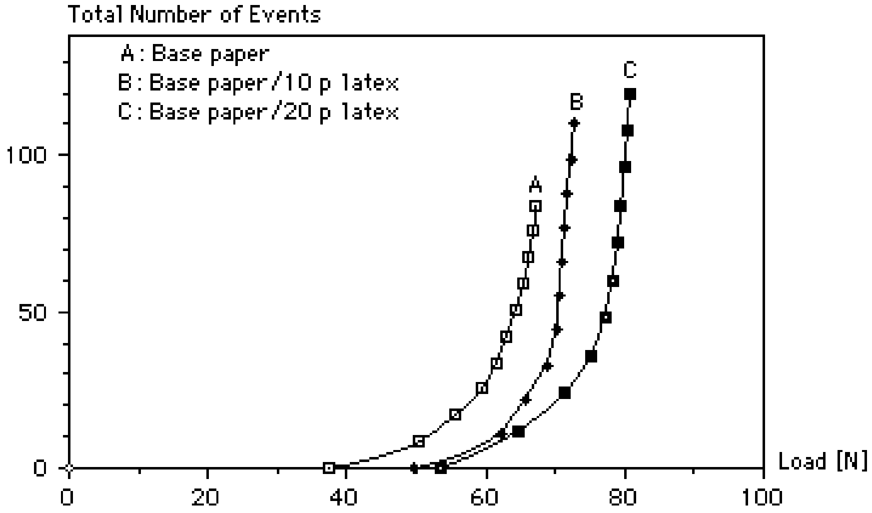

Fig. 29 Comparison of average data (from [5])

From figure 29 it was concluded that an increasing latex content resulted in an increased load level for the onset of AE. One explanation for this can be that the latex impregnates some of the critical fibre to fibre bonds so that the breaking of these bonds involves the rupturing of homogenous latex, a process which will (probably) not generate AE. Another explanation can be that the larger latex content will cause damping of some of the events so that they fall below the threshold value.

The Felicity Ratio (FR) versus the unloading load level for the three types of samples was also evaluated and the results are given in figures 30 – 33:

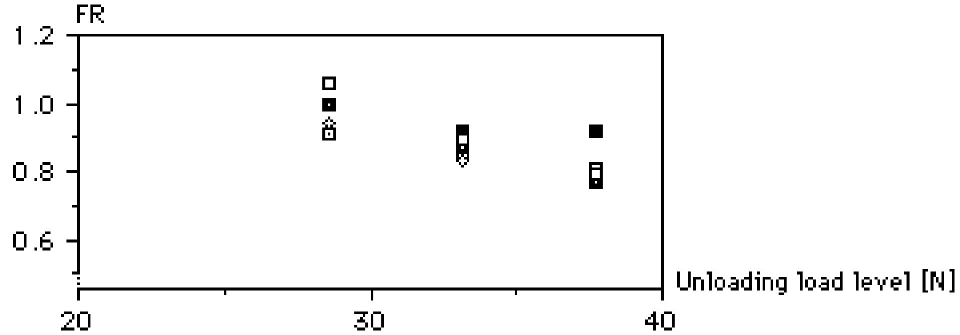

Fig. 30 FR vs. unloading load level for base paper (from [5])

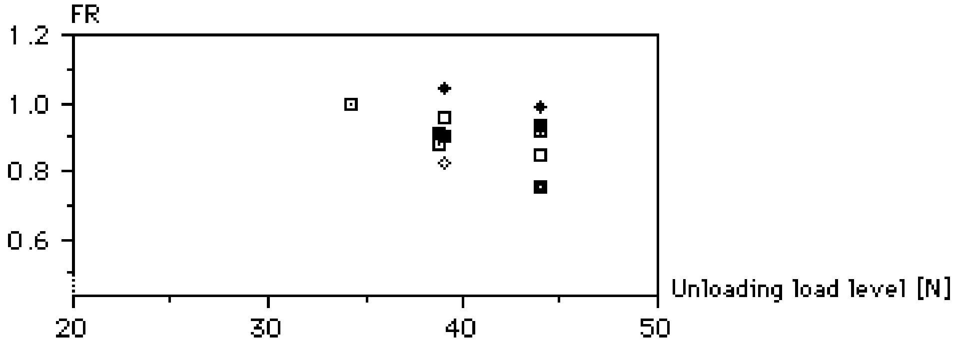

Fig. 31 FR vs. unloading load level for base paper/10 parts latex (from [5])

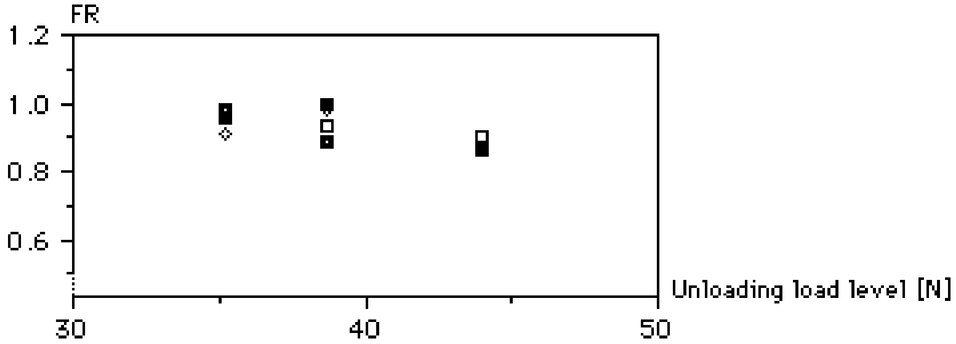

Fig. 32 FR vs. unloading load level for base paper/20 parts latex (from [5])

It appears as if the Felicity Ratio for the 20 parts latex samples is larger than the other two types of samples, again indicating some influence of an increasing latex content (a slower degradation) on the base paper.

CONCLUSIONS

It appears as if the Acoustic Emission monitoring technique is a sensitive tool for determining the onset and progression of damage in a paper structure. The technique has also proven to be of value when coupled to, what is often referred to as, continuum damage mechanics. In [10] is given some results from applying the continuum damage mechanics concept to paper.

However, much remains to be done when it comes to e.g. identifying specific types of damage, that is, to be able to see the difference in acoustic emission behaviour between for example a fibre fracture and a fibre/fibre bond failure.

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