Acoustic Emission applied to mechanically loaded Paper

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Abstract
Acoustic Emission applied to mechanically loaded Paper (AEP) is a current European Union funded Fifth Framework project.

The overall objective of this project is to investigate the micro mechanics behind the behaviour of paper under mechanical loading, with a view to enabling the development of new and value added paper products with a better competitive edge in the global market. To achieve this, Acoustic Emission (AE) monitoring is used for detecting and recording damage on a scale ranging from a single fibre or fibre/fibre bond, to details on a macro level. This requires the development of methods by which it should be possible to identify which damage mechanism produces a specific acoustic event.

Another scientific objective is to investigate the applicability of Continuum Damage Mechanics (CDM) to describe the progress of damage and the influence of damage on the mechanical behaviour of paper, leading to a constitutive model that can account for damage and also for damage localisation.

The technological objective of the project is to specify and make available equipment suited for this purpose, which means both hardware; i.e. sensors, pre – amplifiers, etc., and software; i.e. routines for doing statistics, pattern recognition, etc., tailored for applications in paper physics, incorporating product design, and production. Another technological objective is the availability of a relevant damage constitutive model suitable for application in numerical routines, such as Finite Element codes.

Such work therefore, necessitates a multi-disciplinary team, comprising of four partners in the three relevant scientific fields; paper science, information technology (IT) and Acoustic Emission. These fields are somewhat disparate and this work offers the opportunity of stimulating future collaboration. This paper reports on the background and progress of the AEP project to date.

1. Introduction

The paper industry is one of the most rapidly changing industries today [2]. Driven by the pressures and demands of Information Technology, its products must meet ever greater demands placed upon it by the customer, involving new paper types and qualities, new requirements for physical properties and behaviour, etc. The problem is that more has to be understood about the complex physical and mechanical properties of paper and its constituents to enable new paper qualities and products to be “designed”.

Very little has been done regarding the use of Acoustic Emission (AE) as a tool for investigating internal deformation processes in paper. The first investigations to monitor the AE response of mechanically loaded paper specimens [4], [5] were concentrated mainly on the amount of AE during straining, although some attempts were made to try to distinguish different failure mechanisms. To achieve this, the amplitude distribution of the acoustical events was used, and this method has been much criticised.

AE [1] has also been utilised to investigate the behaviour of mechanically loaded LWC (Light Weight Coated Paper). Again, it was concluded here that nothing certain could be said about what kind of damage mechanism was active during loading of the paper.

Recently, new approaches to the problem of identifying damage mechanisms in composite materials have proved productive. These approaches include, among other things, the use of the frequency distribution (frequency content) of a single signal to identify the damage source. This approach has never been applied to paper. There has in fact, been very little done on the use of AE on paper in general, nor on the identification of damage sources on a micro level in particular.

Since it is yet an open question as to what the damage mechanisms in paper are, a method that can actually point out how a paper will degrade during mechanical loading will have a tremendous potential, inside both research and development of paper products. This hinges on the fact that in order to, for example, increase the strength of paper, one has to know the mechanism responsible for rupture. Another example could be the investigation of the mechanisms for stress redistribution due to damage in paper, which will be much helped by the use of AE.

Work carried out in Sweden [1] has shown that the way paper fractures can be followed by acoustic sensors and that the signals are closely related to the damage processes occurring within the paper’s structure. To mathematically model the influence of damage on the mechanical properties of paper, one needs a tool to include damage as a parameter in the constitutive relations. This tool is supplied by what is commonly referred to as Continuum Damage Mechanics (CDM). The use of CDM to describe the influence of damage on the mechanical properties of paper, is a completely novel approach. CDM ascribes different damage parameters to different damage mechanisms which mean that one must identify what specific damage mechanisms are active during the mechanical loading of paper. One way of achieving this is to identify what might be referred to as acoustic "fingerprints". These acoustic “fingerprints” can be anticipated to be complex in nature and time consuming to analyse manually.

2. AEP Project Objectives and Partnership

The overall objective of this project is to investigate the micro mechanics behind the behaviour of paper under mechanical loading with a view to enabling the development of new and value added paper products with a better competitive edge in the global market. To achieve this a technique for detecting and recording damage on a scale ranging from a single fibre or fibre/fibre bond to details on a macro level, will be used. This technique is the AE monitoring technique, which is an extremely sensitive way of detecting elastic stress waves originating from damage sites in a material.

A scientific objective of the project is to develop methods by which it should be possible to identify which damage mechanism produces a specific acoustic event. Another scientific objective is to investigate the applicability of CDM to describe the progress of damage and the influence of damage on the mechanical behaviour of paper. This will have its application on paper structures having strength as a limiting factor. In particular this should end up in a constitutive model that can account for damage and also for damage localisation.

The technological objective of the project is to specify and make available equipment suited for this purpose, which means both hardware i.e.; sensors, pre - amplifiers etc., and software i.e.; routines for doing statistics, pattern recognition etc., are tailored for applications in paper physics, incorporating product design, and production. Another technological objective is the availability of a relevant damage constitutive model suitable for application in numerical routines, such as Finite Element codes.

Such work therefore, necessitates a multi-disciplinary team, comprising of four partners in the three relevant scientific fields; paper science, information technology and Acoustic Emission.

A significant part of the research carried out concerns the fibre and fibre matrix properties of paper based products, with a view to the creation of new products with higher intrinsic technical value. This work is backed by expertise in materials properties, strength of materials and materials characterisation. Mid Sweden University, Sweden, is responsible for the AE properties of paper research within the project.

The University of Greenwich, School of Computing and Mathematical Sciences, U.K. is genuinely interdisciplinary involving applied mathematics, engineering science and computer science. The University of Greenwich is responsible for the IT aspects of the project, including the implementation of a data warehouse and pattern recognition software.

Norwegian Pulp and Paper Research Institute, PFI (Trondheim, Norway) is a research and service organisation assisting the pulp and paper industries in Norway. PFI was founded in 1923 by the Norwegian pulp and paper industry. PFI research covers the whole production chain all the way from the raw material wood to the end product paper and further to recycling and water treatment technologies. The core competencies of PFI include characterisation of fibre raw materials, paper physics, printability, white water chemistry and pitch problems. Research is particularly focused on wood containing printing papers as this is the most important product in Norway. Apart from industrial co-operative research, PFI undertakes contract R&D and material testing and provides expert consultancy in the overall paper field. PFI is responsible for the majority of the paper physics input to the project. They will provide the paper physics elements of the need specification, the majority of the failure mode analysis required to determine the levels of fibre/fibre bond failure in the testing carried out, and they will provide the objective assessment of the advance offered by AE in relation to standard paper physics tests.

Vallen-Systeme GmbH, Germany, has specialised since 1983 in developing and manufacturing state-of-the-art instrumentation for Acoustic Emission applications. It is the only independent manufacturer of AE equipment in the EU and has been involved in a number of national and international projects involving the specialised use of AE. The company is ISO 9001 certified for the development, production and sale of measurement systems. Vallen-System GmbH is responsible for much of the technical input, ensuring the commercial exploitability of the routines developed and the practical aspects associated with interfacing with the real world.

3. Approach

It is not realistic to achieve all necessary information about the specifics for all possible damage mechanisms, and to develop tools to evaluate the data obtained from mechanical testing. The approach taken here is to collect the raw data produced from Acoustic Emission tests and to employ techniques and tools to support Acoustic Emission Fingerprinting by using, enhancing, or creating, state-of-the-art data handling routines specifically for this task. The interpretation of these fingerprints is primarily the responsibility of the paper scientists. Fingerprinting will involve some mathematical modelling and an emphasis on mainly algorithmic solutions. It was envisaged that the project would use well-established software development methodologies, employing reliable algorithmic solutions and code for the core requirements, the embodiment of more state-of-the-art “intelligent” features, such as data mining and knowledge-based reasoning, was an additional desirable objective. Attention will also be paid to the human computer interaction (hci) issues, and the development of good user interfaces to some lesser degree.

Although Acoustic Emission as a tool for materials testing and qualification is well known when applied to, for example, complex composites [2 (section C)], very little work has been done in exploiting its potential in paper mechanics. Consequently, the necessary data handling routines for analysing the complex emissions emanating from paper have never been developed. This project aims to develop the analysis and data handling routines required to distinguish “fingerprints” in AE data for paper under mechanical loading. Another ingredient in the use of CDM is to determine the onset of damage (i.e. the onset of Acoustic Emission) in a general situation (e.g. bi - axial loading). Due to the observed large scatter in paper strength, advanced tools for statistical evaluation are needed here.

Paper, being a composite material, has strength properties that are dominated by two separate mechanisms, which, acting together, give the material, its unique properties. These mechanisms are fibre failure strength and fibre/fibre bond fracture strength. Critical to the usefulness of any investigative tool for paper is the ability to discriminate between these two failure types. This project will devise a series of mechanical tests producing predominantly one failure type or the other.

The specific cases to be considered are presented below:

In the zero span test, a tensile test is performed using a very short span according to figure 1:

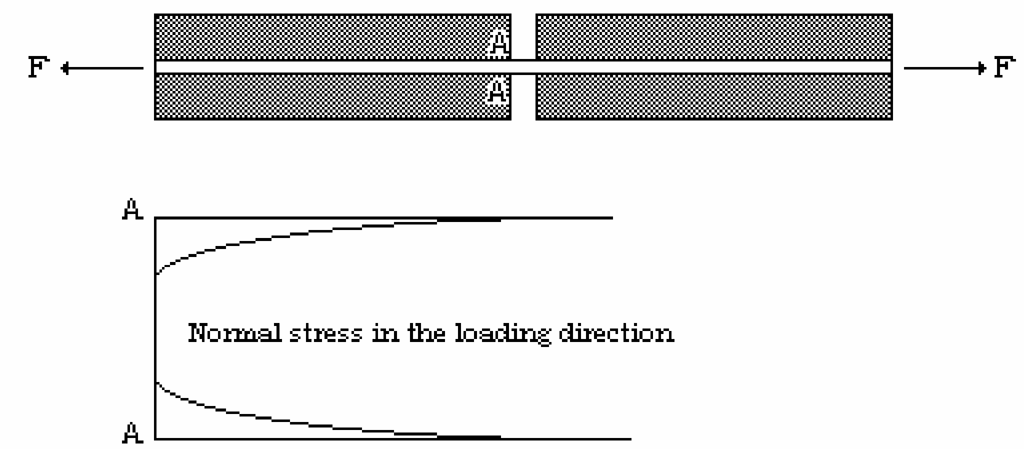

Fig. 1 Zero span test

In figure 1 is also shown schematically, the stress distribution over the cross section A - A, indicating very high stresses in the upper and lower surface of the sample. If the span is much less than the average fibre length, it is reasonable to assume that fibre fracture in the vicinity of points A will be the dominating damage mechanism and by recording the AE signals it will be possible to study the characteristic features of fibre fracture.

To study fibre/fibre bond fracture, two experiments will be utilised according to figure 2:

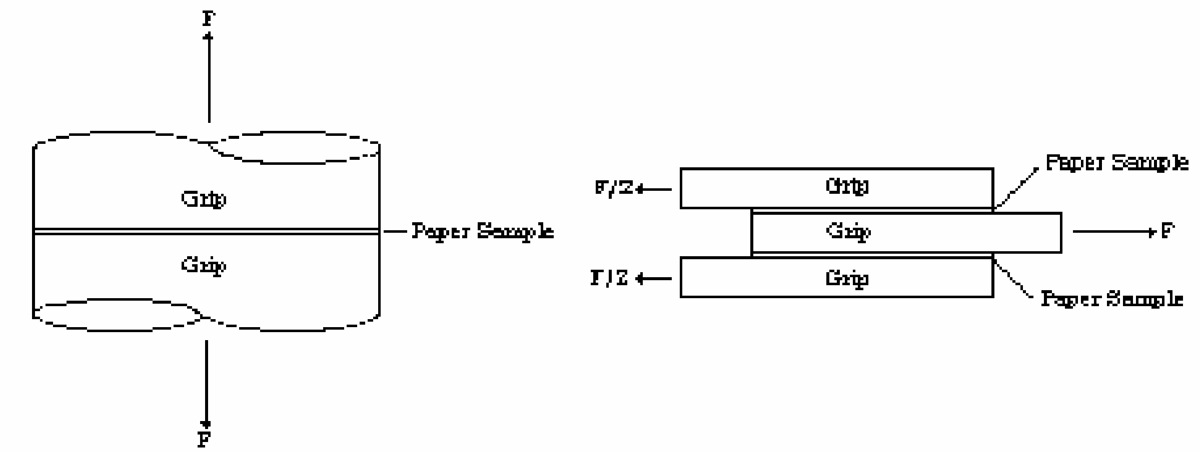

Fig. 2 Bond failure testing

In both situations shown in figure 2, fibre/fibre bond failure will (provided that the fibres are oriented in the plane of the paper) be the dominating damage mechanism and the corresponding AE signals will show the characteristic features for bond failure.

To confirm the actual form of failure for each of the above testing modes, electron microscopy examinations will be performed on suitable samples taken from tested materials.

Having obtained experimental data for the two different damage mechanisms, a number of experiments where it is likely that both damage mechanisms are active, will be performed. This will be used later on to see whether the damage mode can be identified. Here use will again be made of microscopy to determine the type of damage occurring in the test samples over an appropriate range of test conditions. Two examples of such experiments are shown in figure 3:

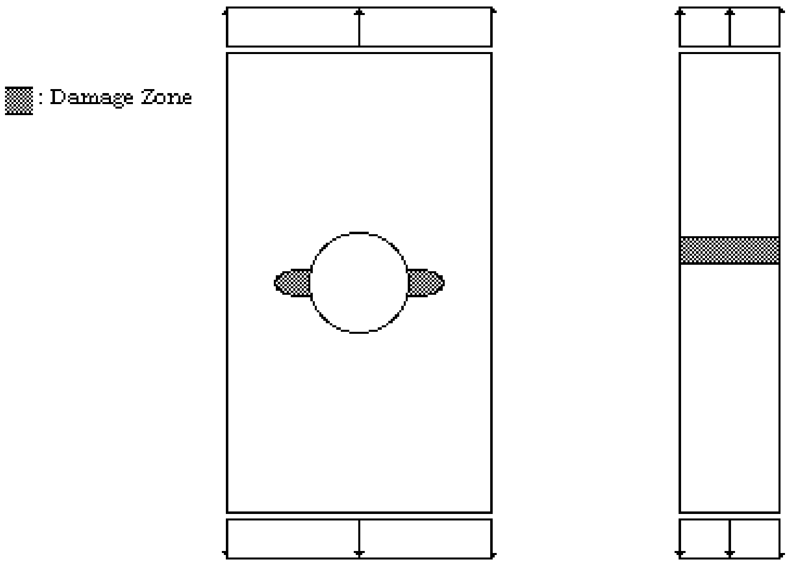

Fig. 3 Verification experiment

To investigate the conditions for onset of damage (i.e. onset of AE) a number of load cases have to be considered. One of these cases is shown in figure 3, i.e. uni - axial tension. Another case would be tensile loading of a specimen with a very large width to height ratio. A third case is shown in figure 4:

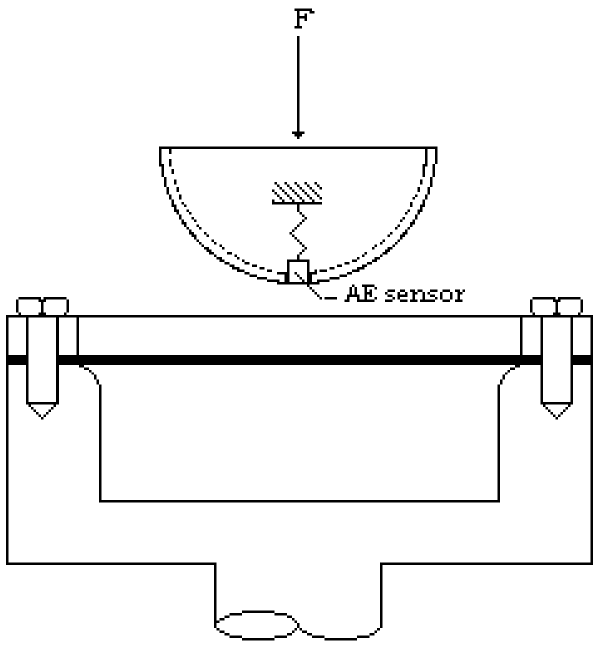

Fig. 4 Bi - axial loading

By loading a circular paper sample by contacting it with a sphere, it is possible to create a bi - axial stress state. Through the tests described above, it should be possible to get a picture of the stress states that are critical with respect to onset of damage.

4. Preliminary findings and future work

In summary, the overall objectives of this project are:

- to use Acoustic Emission techniques in the identification of "fingerprints" for determining damage mechanisms in paper
- to investigate conditions for the onset of damage in paper for a general loading situation
- to develop procedures and routines for the statistical evaluation of acoustic emission data to identify acoustic "fingerprints".

The first stage was to bring together the three key disciplines involved, AE measurement technology, data handling (IT) expertise and paper physics expertise to define a realistic need specification. The preliminary specification has been defined and the current range of commercial data handling routines examined with a view to their use or adaptation to meet the specification. Alongside this survey, the AE experiments required to examine the basic proposition, that AE can discriminate between fibre and fibre bond failure, have been defined. These are now available, and testing can begin on the range of paper qualities required to be representative, together with a microscopic examination of the tested samples to establish which type of failure is actually present.

Commercial data handling routines which *fully* encompass all the requirements were not available, so suitable routines are being developed using well-established software development methodologies and reliable algorithmic solutions and code for the core requirements, together with state-of-the-art "intelligent" features, such as data mining and pattern recognition. Completion of these routines and the availability of test data will lead to the beginning of the test and verification stage. Commercial routines are available for data mining, and some adaptation is likely to be needed.

The completion of this stage and data input from the test and verify stages, will enable the investigation of alternative test methods to more simply achieve the same result. Whilst it is believed, at the current state of the art, that AE is the route most likely to provide success, alternative methods will not be overlooked. It should be realised that no similar analysis of the failure mechanisms has been performed and the results could well show results of an unexpected nature. Simultaneously, the AE test methods will be similarly examined to see if simplifications can be made here.

The results output also enable the refining of the need specification, eliminating unneeded features and strengthening those found important. This provides for a similar refining of the data handling routines to produce the β-test version suitable for the exploitation stage.

Dissemination and exploitation will take place via two routes. The first is open publication of the findings of the research; the microscopy analyses, the AE fingerprinting results, the comparison with "traditional" testing, the analysis of standard test methods in the light of the failure modes actually present, etc. The second is "on site" exploitation within the paper industry. The paper industry is notoriously conservative and effective exploitation of the results requires a hands-on approach. This will be achieved through Vallen-Systeme GmbH offering to supply a working AE equipment package to appropriate companies within the paper industry, including trade institutes, on loan for a limited period. This will enable the industry to investigate the advantages of including AE in their testing arsenal and to provide the required feedback of the behaviour of the β-test version of the data handling routines under production testing conditions. This is deemed to be the most rapid method of disseminating the results in the production environment as well as providing the environment for the industrial partner to break new ground in this market.

5. Discussion

The project [2] tackles one of the principal stumbling blocks to the development of new products in the paper industry; the limited understanding of the basic mechanical properties of the wood fibre composite that is paper. New qualities and types of paper, and even new paper based products require a deeper understanding of the basic mechanical properties and strength of the fibre matrix making up the structure of paper. This knowledge requires a reliable method for determining the actual failure mechanism in paper's fibre composite, something that is poorly understood at the state of the art in paper science today. To achieve this, the project will investigate and develop the technique of Acoustic Emission monitoring, a method well accepted in the field of metals and polymer composites, and its application to the characterisation of the failure mechanisms in paper.

The principal socio-economic impact of this project is on long-term employment. The forests constitute one of Europe's key renewable resources and pulpwood answers for a high proportion of forest usage (approx 30%). The "paperless revolution" has resulted in increased demand for paper, but paper of an ever-increasing technical quality. The decline in certain paper qualities, particularly newsprint, although offset somewhat by the increase in office paper usage, threatens the livelihoods of forest owners in the longer term. Since a stand of trees takes many decades to mature, this threat, to them, is an immediate one. To mitigate this problem, new product outlets must be found for forest pulpwood products. These products must be competitive in the global market and thus must involve a technical added value quite different from the overproduced, "bread and butter" products of today. This added value can only come from the design of products based on a better understanding of the properties and constructional capabilities of the natural fibre composite making up paper.

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