INVESTIGATION OF THE THROUGH-THE-THICKNESS STRENGTH PROPERTIES OF PAPER BY ACOUSTIC EMISSION MONITORING

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Abstract

In the quality assessment of paper, a standard test referred to as the Z-test is often utilized. It consists in gluing a piece of paper between two circular metallic grips and loading it with a tensile load in the thickness direction of the paper. The fracture load or rather the maximum load the paper specimen can withstand is then taken as a measure of the through-the-thickness (Z-) strength of the paper tested. The interpretation of the results and how to use the results has been and still is, a question of some controversy. To shed some light over the deformation or damage processes active when a paper is loaded in the thickness direction, specially designed grips were developed and manufactured. The grips are designed in such a way that they admit that acoustic emission (AE) sensors are mounted in the grips. In this paper, the method is presented together with a simple analytical model, relevant for the Z-test. Some experimental results are given and it is concluded that the analytical model can, at least in a qualitative way, predict not only the load vs. displacement behavior but also the total number of AE events vs. displacement relation.

Introduction

In the papermaking field, a number of testing methods exist, the results from which are believed to say something about the quality of the paper. For instance, when a paper is printed on, or when a paper is coated with color, the paper delaminates due to simultaneous sticking of the printing ink or coating color to the paper and a roller in a roller nip, causing out-of-plane loading of the paper. One testing method, which is believed to give a measure of the sensitivity to delamination is the Z-strength test [1]. In essence, the test consists in that a quadratic paper specimen is glued between grips with a circular cross section (with a diameter less than the side length of the paper specimen) and loaded in the thickness direction. The maximum force divided by the grip area is defined as the Z-strength. This test is not free from criticism since it is obvious that the stress field in the paper specimen is far from being homogenous and the stresses in the thickness direction are large in a region close to the circular grip boundary. Since paper is not a homogenous material, the paper will start to degrade at weak points from the high stresses, leading to a real crack that initiates and grows across the grip area. The maximum load and the start of crack growth probably coincide. Since local conditions are responsible for the fracture of the specimen, it is questionable to define an average measure of the strength. To gain further insight into the delamination process, it would be of particular interest to be able to determine at which load the damage growth starts to initiate and also to study how the damage progresses up to the point and after crack formation. Therefore, in an attempt to extract more information from a traditional Z-strength test, acoustic emission (AE) was monitored to record the breaking of fiber/fiber bonds.

AE Monitoring and Testing

AE monitoring of the breaking of a fiber/fiber bond in paper has been used (c.f. [2-5]), but these were only in connection with ordinary tensile tests. To use AE in a Z-strength test, the grips used in the Z-strength test were modified so that an AE sensor can be attached to each of the two grips. While not ideal, it was possible to detect AE signals from the loaded paper specimen using Vallen Systeme AMSY-4 together with the sensors (Vallen Systeme PROTO 410) and the pre
amplifiers (Vallen Systeme AEP 4H - 10 k) with an amplification of 34 dB. A threshold value of 40 dB was used in all tests.

First, a large paper sample was covered with a double-sided adhesive tape on both sides and cut into sample size pieces, 40x40 mm. The protecting film was removed from the tape and the paper sample was attached to a grip as shown in Fig. 1a. To align the second grip perfectly with the first, a positioning fixture was used (Fig. 1b). The grips were made of steel and had a radius of 17.5 mm and were equipped with radial slots with a length equal to the radius of a grip. These slots are visible in Fig. 1. The sensors were mounted at the centre point of each grip and the thickness of the steel layer was about 2 mm in that position.

The next step ensured to achieve a good bonding between both the grips and the adhesive tape and between the adhesive tape and the paper. A sheet press (Lorentzen and Wettre) was used with pressure levels between 3 and 7 MPa (Fig. 2a). A good bonding is necessary to get a fracture, which is confined to the paper structure only. An extensometer (MTS model 632, 110-210) was attached to the grips using rubber bands as shown in Fig. 2b.
Figure 3a shows an AE sensor used (VallenPROTO 410), which can be attached to the steel grips magnetically. Two sensors were used, one each grip. The loading setup with moment-free hinges is shown in Fig. 3b. A displacement rate of one mm/min was chosen.

The paper qualities considered were: light-weight coated (LWC) paper with surface weight (sw) of 60 g/m² and paperboard with sw of 281 g/m².

During some tests, delamination occurred not only in the paper structure but also in the tape/steel interface. When this happened, the results from the test were discarded. In the experimental study, at least 8 samples from each paper quality (two qualities) were tested.

**Cohesive Zone Model**

During the tests, it was observed that a crack in the paper initiated in a point on the circular boundary and propagated over the cross section of the paper sample. For simplicity the crack front is assumed to be straight and the stress state in the sample is assumed to be uniaxial and described by a simple cohesive relation according to Fig. 5. In Fig. 5a, $\sigma$ denotes stress and $u$ displacement in the thickness direction of the sample. On the compression side the material can be assumed to behave according to the vertical line since the grips are very stiff. For simplicity, the stiffness is assumed to be infinite as soon as $u$ becomes negative. When $\sigma$ becomes equal to $\sigma_c$, the cohesive zone starts to develop and transfers load up to the point where $u = u_c$. At this point, note that in small region around the (weak) point where the cohesive zone starts to
develop initially, the cohesive relation will most likely be different from the relation for the rest of the material in that for example $\sigma_c$ will be lower. In Fig. 5b are shown the degrees of freedom ($u_0, \phi$) used to describe the deformations.

The loading of the paper sample can be divided into three cases. Depending on the load level, the material can be entirely elastic, a cohesive zone starts to develop or the cohesive zone is fully developed and a crack is formed. The variables used to define a general situation are shown in Fig. 6 where a real crack has formed above the cohesive zone (the dotted area).

The elastic case (Case I) is obtained when $\theta_a = \theta_c = \pi/2$. Case II is defined by $\theta_a = \pi/2$ and $\theta_c < \pi/2$. Case III finally is given by $\theta_c < \theta_a \leq \pi/2$. $R$ denotes the radius of the grips. Letting $\sigma$ denote the stress in the thickness direction of the paper sample, the following two relations must be satisfied for reasons of equilibrium (see Fig. 5b):

$$\int_A \sigma dA = P; \int_A \sigma \xi dA = -Ps\phi$$

where $\xi$ is defined in Fig. 6 and it has been assumed that $\phi$ is a small angle. The above equations are given only to point out that due to the product $P\phi$, the problem will be non-linear. The results presented in this paper will be relevant for case III. In order to relate the results from the analytical model to the AE output, it is reasonable to assume that to create one unit of stress-free area, on average $N_0$ fiber bonds have to be broken. This means that for a given value of $\theta_a$, one contribution to the number of broken bonds is:

$$N_0 \int_{\theta_a}^{\pi/2} dA(\theta) = 2N_0 R^2 \int_{\theta_a}^{\pi/2} \cos^2 \theta d\theta.$$ 

In the cohesive zone the material has failed completely at $\theta = \theta_a$ while at $\theta = \theta_c$, the material is intact. If it is assumed that the number of broken bonds per unit area varies linearly over the cohesive zone, this will give another contribution to the total number of broken bonds by:

$$2N_0 R^2 \int_{\theta_a}^{\theta_c} ((\sin \theta - \sin \theta_c)\cos^2 \theta / (\sin \theta_a - \sin \theta_c))d\theta$$

such that the total number of broken bonds will be proportional to $\Psi$. This is given by:

$$\psi = \int_{\theta_a}^{\pi/2} \cos^2 \theta d\theta + \int_{\theta_a}^{\theta_c} ((\sin \theta - \sin \theta_c)\cos^2 \theta / (\sin \theta_a - \sin \theta_c))d\theta$$

If there is a direct proportionality between the total number of broken bonds and total number of AE events $\Sigma ev$, one will have the form of the AE curve of $\Sigma ev = \alpha \Psi$, where $\alpha$ is a constant.

**Numerical Example**

To solve the non-linear equations resulting from the analysis, MATLAB [6] was utilized. The following input data were used:

- $R = 17.5$ mm, $s = 50$ mm, $t = 0.042$ mm, $\sigma_c = 50$ MPa, $E = 500$ MPa,
- $G_c = \sigma_c u_0/2 = 0.14$ N/mm

In Fig. 7a is shown the applied load $P$ vs. the load-point displacement $u_0$. Figure 7b shows $\Psi$ vs. the load-point displacement $u_0$. Note that the results given in Figs 7a and 7b are at best qualita-
tive. However, the experimental $P$ vs. $u_0$ curves show the same behavior as predicted in Fig. 7a. In addition, the experimental AE curves exhibit a steep slope just after reaching the load maximum and leveling off of the AE curves as the load-point displacement $u_0$ is increased. One limitation of the model is that it does not account for the initiation of damage, i.e., for case II, but only for the propagation of a real crack across the cross section of the grips, i.e., for case III.

![Graphs showing load $P$ vs. load-point displacement $u_0$ and $\Psi$ vs. $u_0$.](image)

**Fig. 7:** (a) The load $P$ vs. $u_0$. (b) $\Psi$ vs. $u_0$.

![Graph showing curves for load and accumulated hits of two paper grades, paperboard and LWC.](image)

**Fig. 8:** Curves for load and accumulated hits of two paper grades, paperboard and LWC.
Experimental Results

The load-displacement curves and corresponding AE curves are shown in Fig. 8 for the two paper qualities, LWC paper and paperboard. The curves represent average values for at least 8 specimens. The parameter on the horizontal axis in Fig. 8 is time. With a fixed deformation rate, this can easily be converted to displacement.

As can be seen in Fig. 8, a big difference existed between the behavior of LWC and paperboard. The most obvious difference is the peak load level. The load curve for paperboard peaked at about 320N while the load curve for LWC peaked at about 700N. The shapes of the curves are also different. LWC seems to be quite brittle since the load decreases rapidly after the load peak and there are also few AE events before the peak load was reached. As the load decreases after the load peak, the AE events increased dramatically (in agreement with the results from the analytical model). The paperboard, on the other hand, had a more non-brittle behavior in that damage (AE) started well before the peak load was reached. The drop in load after the peak load was not as dramatic as for LWC.

Discussion

An experimental device for studying the damage evolution in paper when loaded in the thickness (Z) direction has been presented. The method, when applied to two different paper qualities, shows promising results. It is possible to get some information regarding the toughness of the paper material. It is also possible to determine the load or deformation when damage initiates. Together with the finite element method, this can give information about stress and strain fields at the onset of damage. An analytical model is also developed, which in spite of its simplicity seems to be able to predict, at least in a qualitative manner, both the load-displacement curves and AE-displacement relations. With a more refined model it might be possible to perform parameter estimation, i.e., to estimate from experimental data, the cohesive strength and fracture energy.

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