Preferred citation: Ø.W. Gregersen. Review: Runnability, Fracture and Pressroom Breaks. In **Advances in Paper Science and Technology**, *Trans. of the XIIIth Fund. Res. Symp. Cambridge, 2005*, (S.J. I'Anson, ed.), pp 797–825, FRC, Manchester, 2018. DOI: 10.15376/frc.2005.2.797.

RUNNABILITY, FRACTURE AND PRESSROOM BREAKS

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INTRODUCTION

Runnability of the paper web during production and converting is a topic which has always concerned the pulp and paper industry. Good runnability at the lowest possible production cost is of primary importance to paper producers, converters and printers. This paper will review the literature on runnability and fracture of dry printing paper webs.

Several review articles have been written on this and related subjects. Niskanen [1] gave a thorough review of strength and fracture of paper. Niskanen reviewed the relationship between fibres, bonds and strength. He also discussed the relationship between web tension and fracture frequency before thoroughly describing the development of fracture mechanics methods. Kortshot [2] and Mäkelä [3] have also given excellent reviews of paper fracture and fracture mechanics. Roisum [4,5,6] has written reviews of the runnability of paper.

It is important to remember that many causes for paper web breaks are quite trivial. Paper rolls are damaged by transport and handling. Direct contact with water or condensation due to rapid temperature changes may give damage. Poor tape gluing may give web breaks during the flying splice. For many such problems the best procedure for improving runnability is to keep the paper mill tidy, the floors clean and even. Further to follow and quality check the paper transport. Avoid gravel on the floor of transport containers, adjust the clamping pressure on the trucks used to handle paper rolls and so on. Yet even if the best precautions are taken, there will always be some damaged and weaker zones in the paper web. Thus, it is meaningful to use fracture mechanics as a tool to investigate if such defects will develop to a web fracture at the web tension conditions used.

Much work on improving runnability of paper has been done based on the assumption that if the paper's tensile strength, tear strength or fracture toughness is increased, then even the runnability will be improved. I will discuss this assumption and argue that the best way to improve runnability is to perform an engineering analysis of the converting or printing application where the fractures occur. The important factors in such an analysis are web stress, defect size distribution and mechanical properties of the paper.

PRESSROOM BREAKS AND PAPER PROPERTIES

Most practical runnability development work in paper mills is focused on improving one or several strength properties of the paper like tear strength, tensile strength or fracture toughness. Researchers have also tried to link the paper strength properties to pressroom web break statistics. Page and Seth [7] did an extensive investigation of runnability in a Canadian pressroom. As web breaks are rare events (~2 breaks/100 rolls) subjected to random statistics, a very large number of rolls must be run to observe any significant differences. Page and Seth concluded that in the short term, break records are difficult to interpret because of the large random variation in the data, while in the long term other factors cause drift in the break levels, again prohibiting easy interpretation. The long term factor referred to in their study was an annual variation in the indoor humidity in the pressroom causing drier and more brittle paper during winter and consequently also significantly more web breaks (Figure 1).

Page and Seth [7] found no difference in strength properties for rolls with a web break compared to other rolls from the same producer. However, when paper from different producers were studied in the pressroom during a 15 month period, it was found that paper with higher fracture resistance had better runnability (Figure 2). Moilainen and Lindquist [8] have also reported that rolls where failures occurred tended to have lower fracture toughness when paper rolls from different producers were investigated.

Uesaka *et al.* [9] made a large statistical evaluation of runnability data during three years in three different pressrooms. The break rate was correlated with different paper properties. Higher tensile strength and MD stretch reduced the break rate, whereas CD tear and kraft pulp content did not have any significant effect.

In conclusion, it may be said that there exist few studies linking web break statistics directly to paper properties. The reason for this is the extremely large number of rolls that must be run to gain reasonable significance levels. It

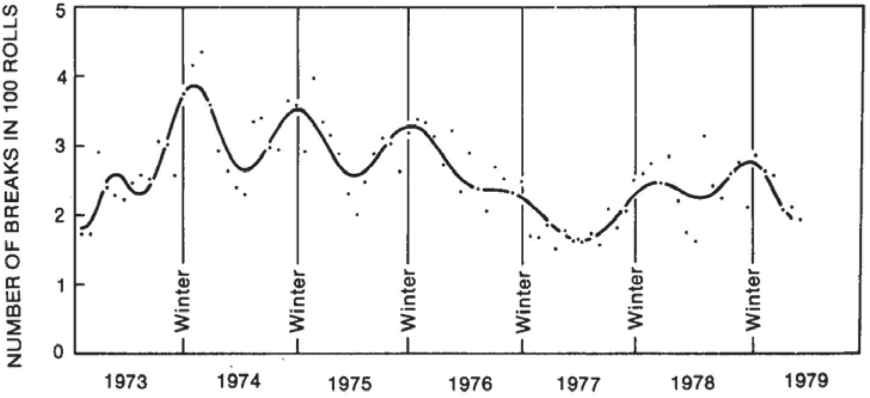

Figure 1 Plot of break frequency with time, showing that the number of breaks in the pressroom peaked during winter when the indoor humidity was low [7].

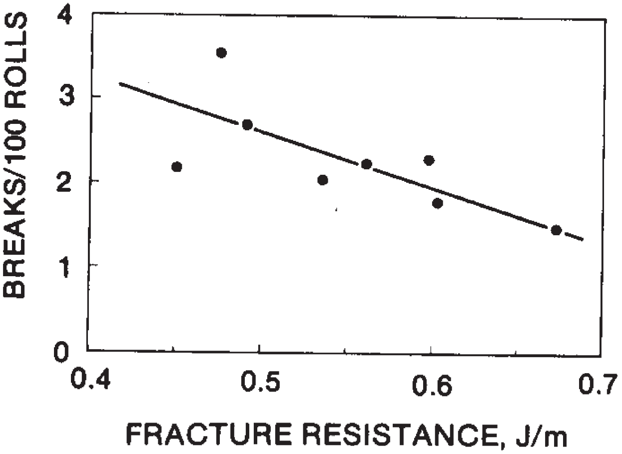

Figure 2 Plot showing the relationship between the mean fracture resistance of paper from different suppliers and the number of paper-related breaks in the pressroom [7].

seems as if fracture toughness, tensile strength and elongation at break correlate negatively with break rate. However, only very small improvements in runnability may be achieved for a mill by improving these measures as their level is pretty much decided by the process design and raw material. There is no evidence supporting the view that improving tear strength will improve runnability.

TENSILE STRENGTH VARIATION OF PAPER AND WEB BREAKS

Another way of investigating web breaks is through weak link statistics. Weibull [10] developed a statistical tool which could explain the well known fact that larger structures generally have a lower ultimate tensile strength compared to smaller ones. This is frequently also referred to as “the weak link effect”. Simply stated a structure will fail in its weakest point and the larger the structure, the greater the probability of finding an even weaker point.

The argument from Weibull’s original publication went like this: The strength of a material has a distribution. This means that the test pieces will have different strength due to the variations in material properties.

Weibull then introduced the survival probability $P(V,\sigma)$ which is a function of the volume (V) and stress (σ) of the specimen. Consider now the survival probability of a specimen of double length: $P(2V,\sigma)$

$$P(2V,\sigma) = P(V,\sigma)*P(V,\sigma) = P(V,\sigma)^2 \tag{1}$$

Or generalized considering specimens of two arbitrary volumes V_o and V:

$$P(V,\sigma) = P(V_o,\sigma)^{V/V_o} \tag{2}$$

Here constant stress in the specimen is assumed. Because this (roughly) is the stress situation in tensile testing of paper, no other stress distributions are considered here.

Weibull proposed a two parameters[1] empirical strength distribution which fitted his data quite well:

$$P(V_o,\sigma) = \exp(-(\sigma/\sigma_o)^m) \tag{3}$$

Here, the Weibull modulus *m* and the reference stress, σ_o are material parameters which can be estimated from the survival probability distribution $(P(V_o,\sigma))$ of a single specimen size or fromstrength tests of several specimen sizes.

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[1] The Weibull distribution also has a three parameter form, however as the two parameter distribution fits the measurement data of paper well [11, 35], the three parameter distribution is neither used nor discussed.

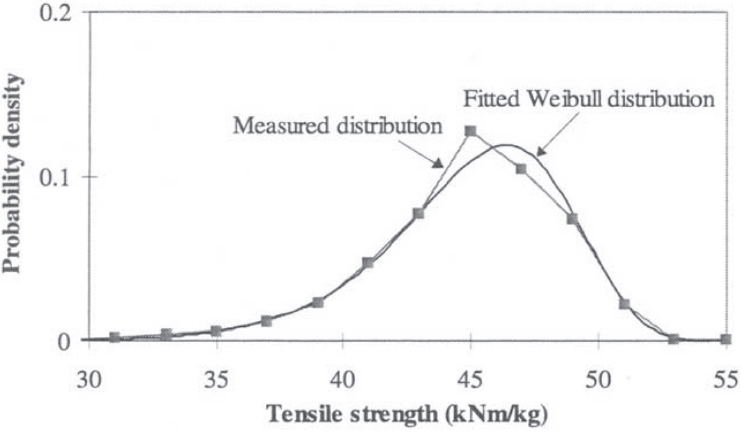

Figure 3 Strength distribution of a population of 1000 15 mm × 100 mm newsprint test pieces and a fitted Weibull distribution [35].

The Weibull modulus, m is a measure of the strength variation (lower m represents larger strength variation). A lower m also means that tensile strength will decrease more rapidly as the sample area increases. Figure 3 shows the strength distribution of 1000 15 × 100 mm newsprint test pieces and the corresponding fitted Weibull distribution.

It is not obvious which volume (V) that should be applied in the equations. If all fractures are initiated at the paper edge, then the volume should be the length of the edges of the specimen. However, if the fractures are initiated randomly over the entire surface, the area of the specimen should used as the volume in the equations. Unfortunately both literature [16] and fracture mechanics theory tell us that fracture is more likely to start in the edge. However, fractures may even start in the bulk area of the specimen. This means that two Weibull distributions may be needed, one for the edges and one for the bulk area. To estimate two such distributions one has to test at least two different specimen widths.

Calculation of average strength

When the Weibull distribution is known the average strength can be calculated from the integral:

$$\overline{\sigma} = \int_0^{\infty} P(V_o,\sigma)^*\sigma d\sigma \qquad (4)$$

However, this integration must be done numerically, so a simpler solution is desirable. What we are searching is the equation of a line in the Weibull space connecting the points defined by the average fracture stress for the different volumes. These fracture stresses are defining a corresponding constant survival probability P(V,σ).

$$P(V_1,\bar{\sigma}_1) = P(V_2,\bar{\sigma}_2)$$

$$\Updownarrow$$

$$\exp(-\bar{\sigma}_1/\sigma_o)^m = (\exp(-\bar{\sigma}_2/\sigma_o)^m)^{v_2/v_1}$$

$$\Updownarrow$$

$$(\bar{\sigma}_1/\sigma_0)^m = \frac{V_2}{V_1}(\bar{\sigma}_2/\sigma_0)^m \tag{5}$$

$$\Updownarrow$$

$$m*\ln(\bar{\sigma}_1/\sigma_o) = \ln(V_2/V_1) + m*\ln(\bar{\sigma}_2/\sigma_o)$$

$$\Updownarrow$$

$$\bar{\sigma}_1/\bar{\sigma}_2 = (V_2/V_1)^{1/m}$$

This is used to derive the equation of the line:

$$\ln(\sigma) = -\frac{1}{m}*\ln(V) + K \tag{6}$$

Equation (6) provides us with a tool to calculate the average fracture stress of any volume. The equation may also be applied to calculate the strength corresponding to any wanted survival probability. Say that we for instance want to calculate the web tension corresponding to 95% survival probability for an entire roll of paper. This can be done simply by substituting the average stress in Equation (6) with the stress corresponding to 95% survival probability.

Weibull statistics has been used to a limited extent to describe paper failure phenomena. Bergström [12] used a three parameter Weibull equation to describe the strength distribution of newsprint strips. This distribution was compared to the experimentally determined web tension distribution in a printing press. The overlapping area indicated the total rupture probability. Westerlind [13] used Weibull statistics to compare and explain the difference in compression strength obtained for different specimen sizes of corrugated board. In a study of coater web breaks Swinehart [24] combined linear fracture mechanics and a Weibull shaped flaw size distribution. He developed a model where both measured fracture toughness and on line hole count on the paper machine was utilized to predict runnability. Gregersen [35] investigated if the strength decrease with area of small test pieces could be used to predict the fracture strength of large sheets of 1.8 m^2. The Weibull analysis slightly overestimated the strength of the larger sheets. It was also concluded that to obtain reliable Weibull data the width of the test samples should be at least larger than 30 mm to avoidsignificant geometry effects of small edge defects like shives. Uesaka [9] and Hristopolous [11] used a Weibull distribution fitted to the low strength part of the strength distribution curve to predict runnability of paper. In a parametric study they found that the Weibull modulus (m) was the parameter that had the highest impact on web break frequency.

The major criticism against weak link statistics based on strength measurements on relatively small paper test pieces is that if the defects causing web breaks are holes or cuts in the paper, there is noway the number or size of such defects can be predicted based on strength variation caused byshives and formation.

ENGINEERING ANALYSIS OF PRESSROOM BREAKS

To get a more complete understanding of runnability in printing presses, it is necessary to look into the three factors that are known to determine whether a material will break. That is the stress situation, the defect size and the fracture toughness. The full use of engineering analysis of paper web breaks by fracture mechanics has been limited by problems in measuring the fracture toughness for paper, problems in measuring the stress state in the paper and problems in measuring the defect size distribution. However, in all these fields huge progress has been made during the last 20 years. This review article will describe this progress and discuss how fracture mechanics can be used in runnability research in the future.

Defects

Different origins for weak spots in paper have been identified in paper web breaks. Adams [14] reported the distribution of web break causes in newsprint listed in Figure 4.

In the literature most attention has been given to shives [14–22]. A clear correlation between the number of shives and web breaks is found in the older studies. However, it may be questioned how important shives are for web breaks today, as improved screening technology has reduced the shive

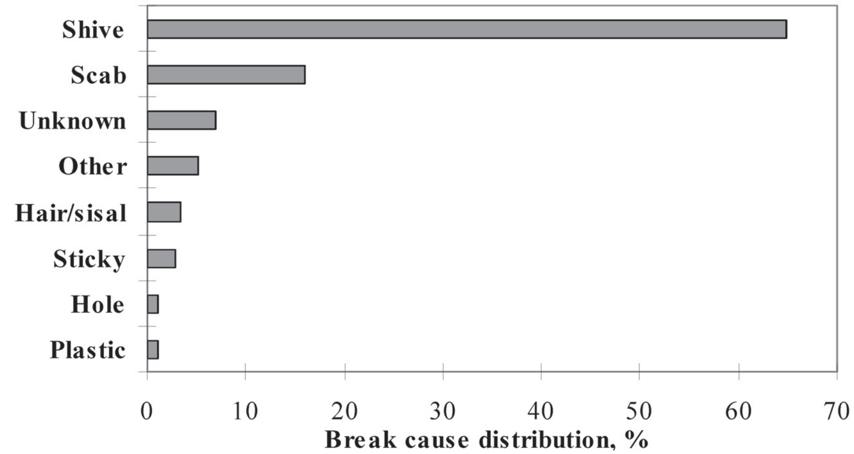

Figure 4 Break cause distribution of newsprint found in an offline rewinding trial using elevated web tension values [14].

amount drastically. Machine calendering generally reduces paper strength in the higher basis weightareas of a sheet [22]. Shives raise local basis weight in the sheet and thus tend to reduce the strength in this area after calendering. Boadway *et al* [23] noted that shives in calendered paper act similar to slits. Gregersen *et al.* [15] found that it is the summerwood shives that act as small slits in the paper after calendering due to their high contribution to the local basis weight and then also the local calender pressure.

Slits may also be caused by edge damage to the reel or accumulation of particles on the calender surface. Thus model experiments have been performed testing strength of paper webs containing slits [23] and modelling of strength properties and web breaks utilising slit length distributions and paper toughness measurements [24]. Eriksson *et al* [25] found that edge cuts in newsprint had to be at least 23 mm long to cause web breaks in a conventional printing press. This implies that shives and other small defects are of little importance at normal web tensions.

Holes in the paper web will also cause a stress concentration which reduces the effective strength of the paper web. To monitor and reduce this problem, on-line hole detection systems are installed in more and more paper mills [26]. On line cameras can also be installed in pressrooms and be linked to web break sensors. Thus it is possible to capture a video of the paper in the press at the time of a web break. This may be a very useful tool in the investigation of what kind of defect that triggered the fracture. Further, information of the defect size distribution is one of the three factors necessary to fully understand the cause of web breaks.

Web tension

Web tension measurements

Web tension has traditionally been measured by a load cell fitted to a guiding roller. This is a robust measurement which gives the average web tension in N/m if calibrated correctly. However, no information of the web tension distribution in CD or rapid tension variation can be obtained with this equipment. As both the CD distribution and the dynamics of the web tension may be very important to web break frequency, it is highly desirable to have online measurement systems that can monitor this. Linna and Moilainen [27] tested four measurement systems in 1988, but concluded that there was no universally suitable technique for measuring web tension. Two of the instruments were based on measurement of the speed of sound, one of air pressure measurement and one of contact pressure measurement. However, Linna and Moilainen also concluded that all the tested instruments could be used to solve specific runnability problems in paper machines or printing presses. Later the air pressure measurement system has been refined and is now commercialized by Metso as IQTension [28]. Measurements with this system have revealed that the web tension at the end of the paper machine frequently is lower at the edges (Figure 5). This profile is transferred to the paper rolls during reeling resulting in edge rolls with one tight and one slack edge. Streaks in caliper, basis weight or moisture content [29, 30] may also lead to an uneven CD web tension profile when the rolls are unwound in the press room. Flying splices and un-round rolls will give peaks in the web tension [29].

It is important to remember that static MD web tension is not the only force experienced by the paper web. Other important forces are tack forces acting in ZD of the paper when it exits the printing nip and frictional forces subjected to the web when it passes over stationary equipment. Such friction is particularly important if a defect like an edge cut causes a part of the web to protrude out of plane compared to the rest of the web (Figure 6). Edge flutter caused by a loose edge may cause rapid tension variation in the tense part of the web. Further, aerodynamic forces caused by the air layer following the web at ~10 m/s into nips may also contribute to the complex stress situation.

Measurement or calculation [31] of the web tension situation is still the most challenging part for fully understanding the runnability of paper. It is disturbing as it seems that most papermakers do not know which web tension

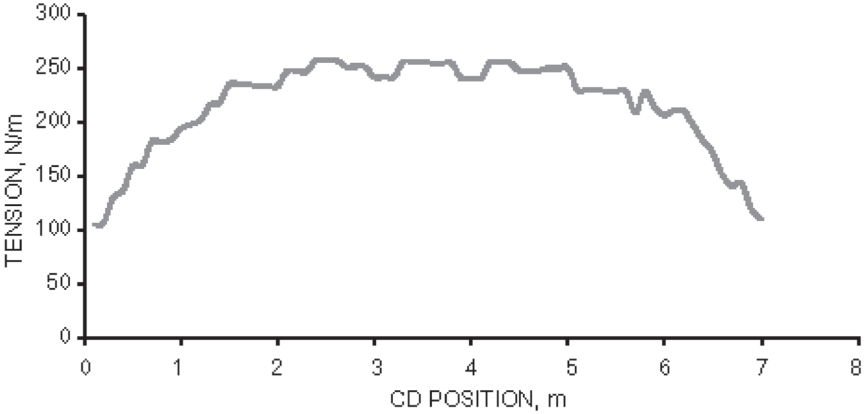

Figure 5 CD Web tension profile in the dry end of a paper machine. The edges are less tight [33].

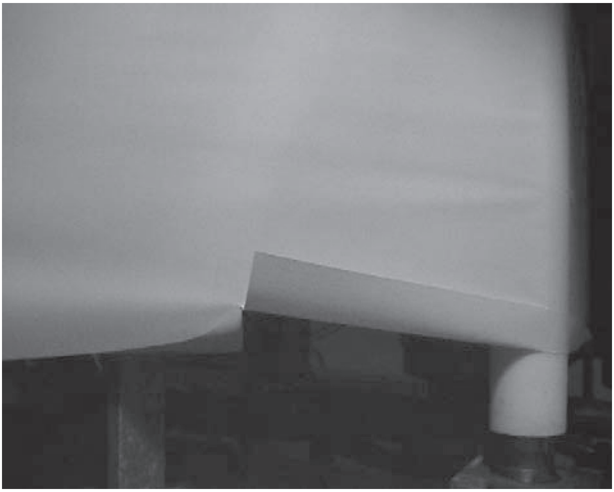

Figure 6 A protruding edge cut that will give local friction forces attacking at the tip of the cut when the cut passes stationary equipment and guiding rollers.

profile their rolls will produce when unwound. The web tension profile seen in Figure 5 is a probable explanation for the observed runnability problems with edge rolls [32].

Runnability testing in laboratory rewinders

As pointed out by Page and Seth [7] an extremely large number of rolls must be run in a printing press to get reliable statistics and during the time necessary to do this, other factors may change. To overcome this problem, runnability research has been done in special rewinders. Here the web tension and climatic conditions can be carefully controlled. Thus fewer rolls are needed to get useful statistics.

It has been experimentally established that there is a logarithmic relationship between break frequency and web tension [14, 16, 34]. If these curves are extrapolated to web tensions used in commercial plants, the runnability of different paper grades may be evaluated (Figure 7). Gregersen [35] pointed out that this logarithmic relationship may be explained if we assume that paper web fractures follow the Weibull theory.

Rewinding at higher web tension has two weaknesses as a runnability research method. It is necessary to extrapolate the measurement data several decades in web break frequency to reach the average tension levels used during printing. Further the amount and size of defects (typically shives (Figure 4)) that trigger the breaks at higher web tension are not necessarily a good indicator of the amount of larger defects that will trigger a web break at lower web tension.

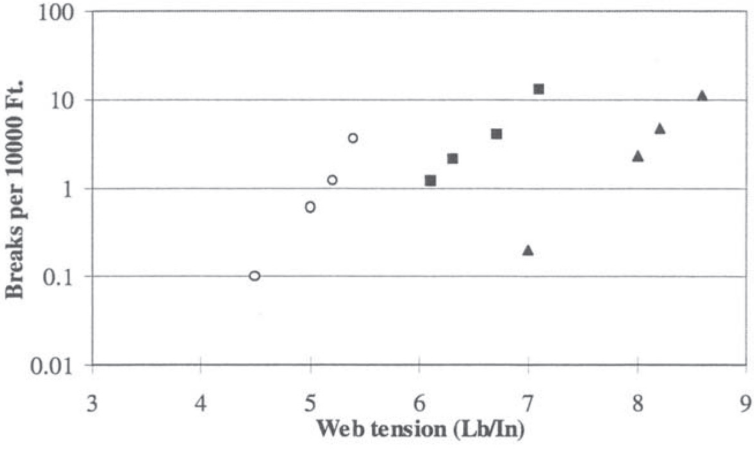

Figure 7 The logarithm of web break frequency plotted against web tension. There is a linear relationship for each paper grade [16].

Fracture toughness

In addition to defect size and stress situation, fracture toughness is the last factor necessary to predict web breaks. Fracture mechanics has been successfully utilised in general solid mechanics research since the pioneering works of Griffith [36]. The theories have been developed from being able to solely covering isotropic linear elastic materials to take care of plasticity, anisotropy and damage. However, the demand on numeric computation is increasing when the more complicated constitutive material models are used. Closed form solutions are generally not available and numeric methods like FEM must therefore be employed.

A broad presentation of the field of fracture mechanics is beyond the scope of this review article, however, I will look into the fracture mechanics basics and the efforts to characterize paper by fracture mechanics. First I will look into the theoretical foundations [37] of the different fracture mechanics measurement systems that have been used for paper.

Linear elastic fracture mechanics (LEFM)

When analysing a notched isotropic elastic structure subjected to loading, it is possible to show that there exists a stress intensity factor which completely characterises the stress and displacement state in the crack tip vicinity. The stress intensity factor, K_I for mode I fracture is defined by Equation (7). The x_1, x_2 coordinate system has its origin at the crack tip as shown in Figure 8.

$$K_1 = \lim_{x_1 \to +0} \sigma(x_1,0)\sqrt{2\pi x} \tag{7}$$

Analytic solutions for different geometries have been found and are compiled in several engineering textbooks. The general form of the solution is (Equation (8)):

$$K_1 = \sigma_{gen}\sqrt{\pi a} * f(\text{geometric parameters}) \tag{8}$$

The dimensionless function f contains the geometric information and is often of the order unity. The quantity σ_{gen} is a measure of the applied load with the units of stress. a is defined as the crack length for edge cracks and half the crack length for cracks in the body of geometrically symmetric structures subjected to symmetric loading. The purpose of this discussion of stress and strain fields in cracked elastic bodies is to obtain a criterion for when crack growth starts. As the state in the crack tip vicinity is completely determined by the stress intensity factor, it is natural to base the criterion for crack growth on this factor. Thus a viable criterion for the initiation of crack growth should be (Equation (9)):

$$K_1 \geq K_{cr} \tag{9}$$

The critical quantity K_{cr} is defined to be the material property fracture toughness.

Very few materials are in fact perfectly elastic. Most materials show non-linear and irreversible deformation in the high stress area in the crack tip vicinity. Fortunately LEFM can be extended to more general cases. Assume that non-linear deformation occurs in a region with size r_p. Assume further that outside this region there exists a boundary for instance along a circle with radius r_1 where the stress and displacement fields are reasonably well described by the linear elastic solution for a crack tip. Then the information about the conditions on the outer boundary can only reach the crack tip region through the singular field and the stress intensity factor can be used to characterize the state within this region. For this assumptions to be valid the plastic zone must be significantly smaller then any dimension of the body.

J-integral

When the non-linearly deforming zone around the crack tip becomes too large, LEFM gradually becomes inapplicable. Theories accounting for the particular non-linear behaviour of the material are needed. In the same way as for LEFM one seeks to find a parameter that uniquely characterizes the state in the crack tip vicinity. The criterion for initiation of crack growth can then be formulated in the same way as in Equation (9). The J-integral is the line integral defined in Equation (10) integrated along a path around the crack tip (Figure 8). In equation (10), W_t is the deformation work per unit volume, σ_{ij} and ε_{ij} are stress and strain tensor components, u_i is the displacement vector components and n_j the normal vector components of the contour S enclosing the crack tip.

$$J = \int_s {}_s(W_t dx_2 - \sigma_{ij} n_j \frac{\delta u_i}{\delta x_1} ds)$$

$$W_t = \int \sigma_{ij} d\varepsilon_{ij} \tag{10}$$

Provided that the stress can be expressed as the derivative of the strain energy W with respect to strain as in Equation (11), the J integral is path independent.

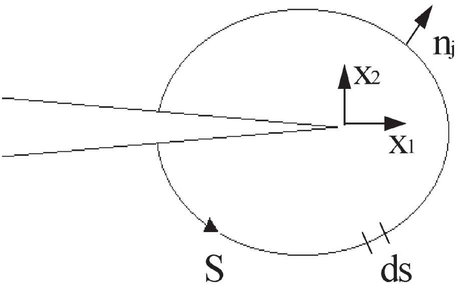

Figure 8 The integration path around a crack tip to evaluate the J-integral.

$$\sigma_{ij} = \frac{\delta W}{\delta \varepsilon_{ij}} \tag{11}$$

Equation (11) is not satisfied for plastic materials in general, however, it has been found in numeric studies that approximate path independence prevails even for incremental plasticity, provided the external loading is monotonously increasing. In such cases J can be applied as a crack-tip characterizing parameter. There are different methods for experimental determination of J. Some of them have been applied to paper as described below. It seems that direct calculation of the J-integral from Equation (10) and a FEM model of the cracked structure is the best evaluation method for materials showing complex stress strain behaviour. Exact measurement of the stress strain behaviour and modelling of this in constitutive equations which describe the material well, is essential for correct calculation of the J-integral.

Essential work of fracture

Another way to deal with large non-linearly deforming zones around the crack tip is to divide the irreversible work (W_f) done on the specimen into an essential part (W_e) and an nonessential part (W_p) as shown by Cotterel [38]. The essential work of fracture is done in the inner fracture process zone, while the nonessential work is dissipated in the outer plastic region. The two work components can be separated by using deep double-edge notched tension specimens containing varying ligament (L) lengths. Before fracture the total yielding area will be circular with the ligament as diameter. The essential work of fracture will be proportional to the ligament, while the nonessential work will be proportional to the square of the ligament (Equation (12)).

$$W_f = W_e + W_p = Ltw_e + \beta L^2 tw_p \tag{12}$$

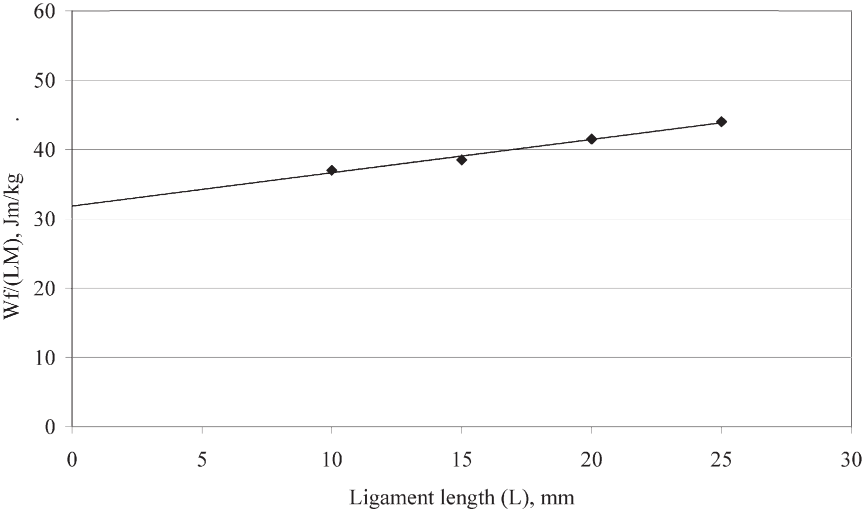

Figure 9 Plot of total work of fracture against ligament length [45].

w_e is the work consumed per unit crack area in the inner fracture process zone. This is the specific work of fracture. By dividing Equation (12) by ligament length and specimen thickness (t) the specific work of fracture can be found at L = 0 when plotting $W_f/(tL)$ against L. In Figure 9 the method is applied to paper, however, basis weight (M) is used in stead of thickness.

Paper and fracture mechanics

Linear elastic fracture mechanics (LEFM) as initially proposed by Griffith [36] was found not to be applicable to paper by Balodis [39] and Andersson [40]. This is not surprising as paper generally exhibits some plastic deformation before the catastrophic failure. The paper may yield just in the crack tip area if the paper specimen is large, the crack is long and the paper is reasonably brittle, like newsprint. However, if the crack is short, the specimen small or the paper ductile, there will be plastic yielding in large regions of the specimen before the catastrophic failure occurs. To deal with the non linearity of the material in the crack tip vicinity it has been tried to introduce an additional virtual crack length. Donner [41] calculated a virtual additional crack length to compensate for paper non linearity and the paper material's fibrous structure. He found virtual crack lengths between 0.25 mm and 0.88 mm. The area influenced by the crack has been measured. In the case of a bond long grained paper Choi [42] found the plastic zone shown to be 1.7 mm for a 5 mm centre notch at fracture. Andersson [40] found increased opacity indicating plastic deformation in a c a 1mm zone at the crack tip for sulphate paper.

Seth [43–45] developed a fracture mechanics test method for paper based on linear elastic fracture mechanics. Specimen and crack sizes were chosen to avoid plastic yielding anywhere but in the crack tip area. Recommended specimen length and width and recommended notch length were given for brittle papers and it was claimed that it was possible to determine such even for very strong papers. However, even for newsprint specimen widths over 10 cm were needed to avoid plastic yielding [43].

Swinehart [46] argues that LEFM based on the stress intensity factor K_c is superior to non linear fracture mechanics based on the J-integral. However, Mäkelä [3] proved that using the stress intensity factor to predict fracture with the material data provided by Swinehart [46] strongly overestimates the critical load. Mäkelä also pointed out that today the calculation of the J-integral for any geometry can be done on a PC, thus it is no more a problem that the method is calculation intensive and that closed form solutions do not exist. Mäkelä and Swinehart agree on one point:

- Materials can not be ranked based on knowledge of J_c alone, knowledge of the stress strain curve of the paper is also necessary.

Based on linear elastic fracture mechanics and an assumption that flaw lengths in paper follow the Weibull distribution, Swinehart [24] introduces a runnability model which predicts the average paper web length between breaks. The model seems to predict runnability reasonably well for the blade coated paper grade studied. Ferahi [47] applied LEFM to commercial paper and pointed out that in a highly anisotropic material like paper, the fracture direction will not necessarily be perpendicular to the applied load.

To solve the difficulties with plastic yielding in the bulk areas of the specimen during fracture mechanical testing of tough, ductile papers, Seth [49, 50] adapted the method of “essential work of fracture” to tough paper materials. The method eliminates irreversible work done in areas which are not close to the crack tips, thus the essential work of fracture can be an estimate of the fracture toughness of the material. Seth [51–52] then used this method to evaluate reinforcement pulps and strongly argued that the fracture toughness as evaluated by the essential work of fracture is superior to tear strength for pulp evaluation purposes. The essential work of fracture method has been made more efficient by Batchelor and Wanigaratne [53]. The use of cyclic loading of one notched paper specimen reduces the time and material consumption of this method substantially. The main weakness of the method nevertheless remains, it can not be used to calculate the critical load or critical elongation for any other geometry than the one used in the test.

Another way of handling fracture toughness measurements of materials which are not linear elastic is to apply the J-integral. Several methods for measuring the critical value of the J-integral have been proposed and tried on paper materials [54–59]. Fellers [60] in cooperation with Lorentzen and Wettre developed a commercial apparatus for J_c measurement according to the Liebowitz method. Later the testing machine estimation method was changed. A large number of numerical solutions (FEM) for different geometrical configurations, using an orthotropic elastic-plastic constitutive model, were utilized to develop a semi-analytical expression for the J-integral. This expression was implemented in a software program for the evaluation of the fracture toughness of paper materials as well as for prediction of fracture in full-scale paper webs [61–62]. This kind of numeric calculations seems to have made older estimation methods for J_c obsolete. Wellmar [63] later proved that J-integral based fracture mechanics can be used to predict the critical load and elongation of a large paper web based on measurements on small samples (Figure 10). This is called transferability and worked fine both for newsprint and sack paper representing two extreme points in brittleness and ductility. Fellers [64] has used the J-integral fracture mechanics method to optimise beating strategy and amount of reinforcement pulp in TMP. He recommends using critical load or elongation of a

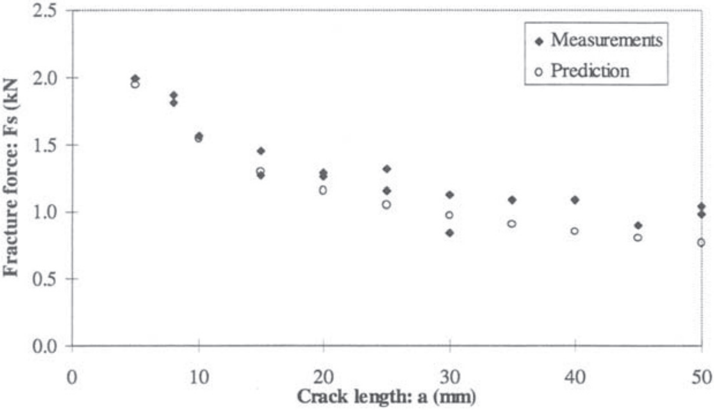

Figure 10 Fracture force (critical load) plotted against crack length for single edge notched sack paper strained in MD. Predictions based on the J-integral and measurements of the 0.5 m × 1.0 m sheets agree very well [63].

web with a defect as the evaluation criterion, not the fracture toughness directly.

Mäkelä [3] discussed several aspects of the different published fracture mechanics methods in his excellent review article. He argues that fracture toughness for non-linear paper materials can not be used directly as a ranking parameter for different paper grades. The reason for this is that paper with different fracture toughness in general also will have a different constitutive equation (stress-strain curve). A bit simplified we can say that the fracture toughness only can tell us where along the stress-strain curve a paper will fracture. Thus as the paper is changed, e.g. by increased beating, the fracture toughness will change (increase) and the stress-strain curve will be steeper. This will yield a higher critical load for a paper with a crack and a reduced elongation at failure. These two last parameters (critical load and elongation at failure for paper containing a crack) are the meaningful ranking parameters for paper.

APPLICATION OF FRACTURE MECHANICS

Many fracture mechanics studies in our field have been done to develop and test the merits of new fracture toughness measurement methods. It is important to make sure that the measured fracture toughness is not depending on the sample dimensions and to find out if it is valid for all paper grades. The current status seems to be that linear elastic fracture mechanics requires large test pieces and is only applicable to very brittle paper grades like newsprint in MD. Non linear fracture mechanics (J-integral) works fine with all paper grades. The essential work of fracture method was developed for rather tough paper qualities, however, this method lacks the solid theoretical fundament of the two other techniques and is not suited to make predictions of critical load and critical elongation for any other paper geometry than the one applied in the test.

The next logical step when a fracture mechanics test method is established would be to test transferability using fracture mechanics for predictions of load and elongation at failure in paper webs of various dimensions. Such predictions and control by experiments was done by Wellmar *et al* [63] for the J-integral method.

However, instead much attention has been focused on how different papermaking variables will influence the fracture toughness such as beating [54, 65], climate [57], fibre length and proportion of failing fibres [66], proportion of reinforcement pulp [66, 67] and geographical differences in pulp [67]. This is unfortunate because both the fracture toughness and the constitutive behaviour (stress-strain curve) of paper will change when papermaking variables are changed. What should be investigated is the load at failure and elongation at failure of a paper web or structure of a relevant size to the natural end use of the product. This method has been applied by Fellers *et al* [64] in an investigation on the influence of beating, fibre shape and amount of reinforcement pulp on the strength properties of wood containing printing papers.

Optimizing paper quality by fracture mechanics

Several studies have attempted to optimize the runnability of paper by optimizing the fracture toughness of the paper. Researchers have investigated both the effect of different treatments and mixtures on the fracture toughness directly or done as recommended by Mäkelä [3]; optimized the critical load and critical elongation of a paper web with a crack. Both types of studies are referred here, however, the optimization of runnability by optimizing critical load and critical elongation is recommended.

Beating

Most attention has been given to beating of the chemical reinforcement pulp. Seth [54] found that fracture toughness increased with beating of reinforcement pulp and consequently recommends beating to a high tensile strength while maintaining acceptable drainage characteristics. Fellers *et al* [64] also found a slight increase in fracture toughness of TMP and kraft mixture sheets upon beating of the kraft pulp. However, the shape of the kraft fibres (curly or straight) was much more important. Koskinen *et al* [68] conducted a runnability study in a pilot coater and in laboratory scale where the influence of chemical pulp beating and addition level were investigated. They used TMP and GW raw papers for coating and investigated both the influence of holes and cuts in the paper web. It was found that the more beaten kraft pulp increased the critical load (tensile strength of damaged sample) more than a less beaten chemical pulp. Seth and Page [44] found that the fracture toughness for chemical pulps increases with beating until a maximum at quite high beating levels for bleached and unbleached softwood kraft pulp and for bleached softwood sulphite pulp. For bleached hardwood kraft pulp the fracture toughness increased monotonously with beating. Åström *et al* [69] found that increased beating of the kraft pulp in a kraft SGW furnish slightly increased the fracture toughness (Figure 11). However, Hiltunen [70] found that beating did not increase critical load or critical elongation for TMP-kraft mixture sheets. It seems as the beating of the kraft

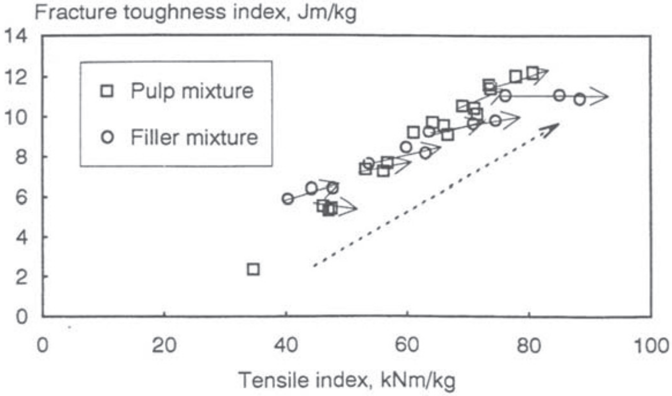

Figure 11 Fracture toughness vs. tensile strength for different mixtures of TMP, $CaCO_3$ and softwood kraft pulp. The dotted arrow signifies increasing amounts of chemical pulp and short arrows signify increasing beating[69].

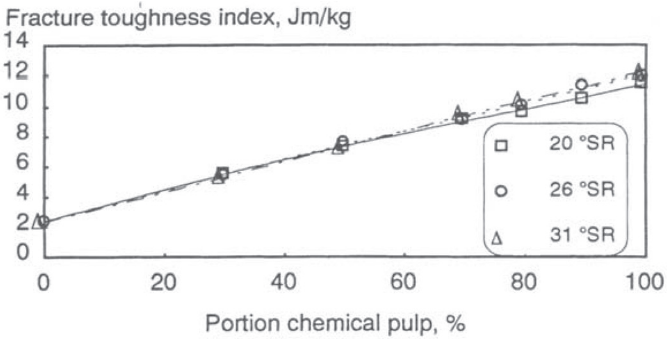

Figure 12 Increase in fracture toughness of TMP and softwood kraft sheets by addition leve lof softwood kraft pulp [69].

pulp in sheets of TMP and kraft has little influence on the fracture toughness.

Addition level of kraft pulp

Fellers *et al* [64] found a strong increase in fracture toughness, critical load and critical elongation by increasing amount of kraft pulp in kraft and TMP mixture sheets. The increase was most pronounced for the first 10% addition of kraft pulp. Shallhorn [71] found that the fracture resistance of a mixture of softwood kraft and groundwood increased most rapidly for the first 20% of kraft pulp addition. Kärenlampi *et al* [66] and Åström *et al* [69] found that the fracture energy increased linearly by increasing addition of reinforcement pulp both measured by the J-integral and EWF method (Figure 12). It is interesting to note that the addition level of reinforcement pulp gives a linear or slightly better than linear effect on the fracture toughness, whereas the effect on tensile strength at small addition levels is known to be almost zero.

Addition of fillers

Åström *et al* [69] found that the fracture toughness decreased approximately 1.5% pr percent of calcium carbonate added (Figure 13).

Kraft pulp characteristics

Eriksson *et al* [25] have investigated the effect of using ten different commercial kraft pulps as reinforcement in TMP. No significant differences in critical load or critical elongation were found between the pulps when the sheets were wet pressed to the same density. However, Seth [52] showed that fine fibres have higher fracture toughness than coarse reinforcement fibres when plotted against tensile strength (Figure 14). The coarse fibres had a coarseness of 241 µg/m whereas the fine fibres had a coarseness of 125 µg/m. Fellers *et al* [64] found that straight beaten fibres gave highest critical load

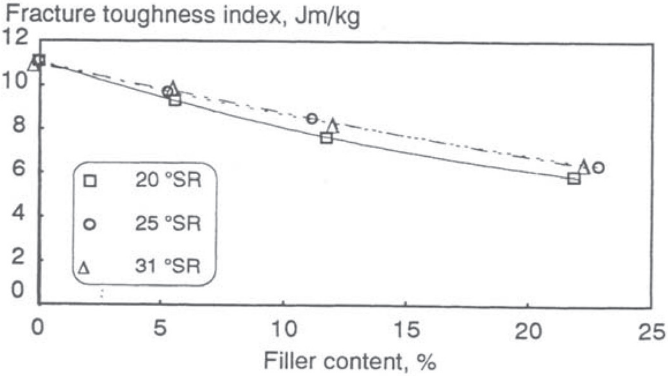

Figure 13 Effect of addition of $CaCO_3$ on the fracture toughness [69].

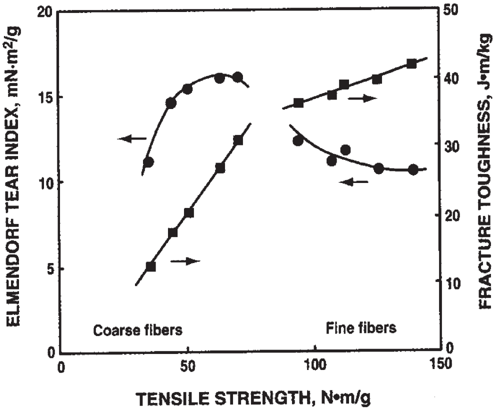

Figure 14 Finer fibres have a higher fracture toughness compared to coarser ones [52].

whereas beaten curly fibres gave the highest critical elongation. In mixture sheets Kärenlampi *et al* [66] found that coarse long reinforcement fibres gave slightly higher fracture toughness values than shorter less coarse fibres from young softwood in calendered mixture sheets.

Wet pressing

Shallhorn [71] found that higher loads in wet pressing increased the fracture toughness both for softwood and hardwood kraft pulps.

Calendering

Shallhorn [71] found that calendering dramatically reduced the fracture toughness of a softwood kraft sheet when the density passed 700 kg/m^3 (Figure 15).

Moisture content

Steadman and Fellers [56, 57] and Shallhorn [71] found that the fracture toughness increased with increasing moisture content when the moisture content of the sheets were changed by changing the relative humidity of the surrounding air (Figure 16).

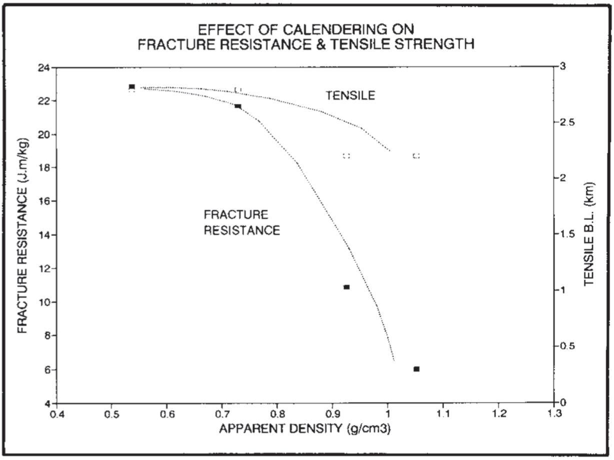

Figure 15 Calendering reduced the fracture toughness when the sheet density passed 700 kg/m^3 [71].

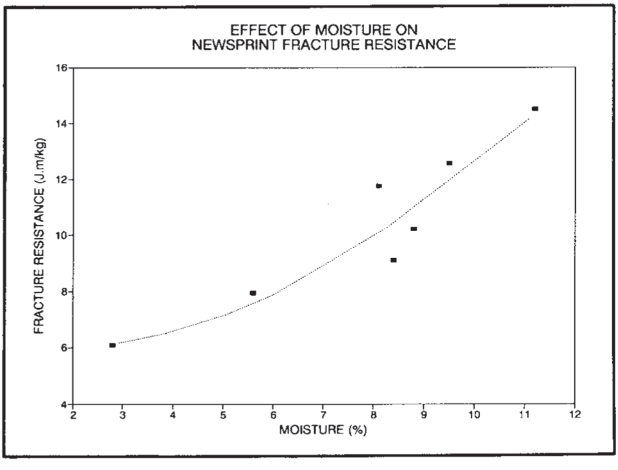

Figure 16 Fracture toughness of newsprint as a function of moisture content [71].

Predicting behavior in end use situations

When the fracture toughness is measured according to the J-integral method it is possible to calculate the critical load and critical elongation for any geometry containing a cut. This was done by Wellmar *et al* [63] for stationary webs of 0.5×1.0 m of newsprint and sack paper containing centre and edge cuts. The predictions based on fracture mechanics fitted well with the experiments for both geometries when the paper was prevented from buckling by anti buckling guides. If a centre cut is allowed to buckle the critical load will be reduced by some 10–15% depending on the cut length. Edge cuts will not buckle and are correctly predicted by the J-integral theory.

For coldset printing of newsprint it has been difficult to get meaningful results directly from fracture mechanics based calculations. Full scale experiments in printing presses at reasonable web tensions (150–250 N/m) show that web breaks start to occur for edge cuts above 23 mm[25]. However, cuts of 23 mm in newsprint should be able to withstand a web tension of approx. 700–800 N/m [64]. This discrepancy should be more closely studied, however, it is this author's opinion that all relevant forces are not taken into account when only average web tension is considered. There are tack forces in the printing nip, skew web tension due to length differences between zones in the web (bagginess) and web flutter due to aerodynamic forces. The contribution from such forces may be large compared to the effect of the average web tension.

FUTURE USE OF FRACTURE MECHANICS IN RUNNABILITY RESEARCH

One interesting use of fracture mechanics that has not been much exploited for paper runnability is sensitivity analysis. That is calculations to see the relative effect of changes in the defect size, web tension or fracture toughness of the paper. Such analyses can be combined with the cost of changing fracture toughness, defect size and web tension. The benefit of such analyses is that the mill will understand whether it will get the greatest reduction in web breaks pr capital invested on increasing the critical elongation or critical load of the paper, reducing the number or size of defects or evening out the web tension profile of the rolls.

One other aspect which has received little attention is whether the web tension during printing is a state of prescribed web tension or web elongation. The truth often is a mixture of the two states, the brakes on the unwinding section will define a certain web tension, however, once the first printing nip is passed, the situation changes more to one of defined elongation. This is important, because it will tell us if it is the critical elongation or critical load which is the most meaningful paper parameter to optimize.

Of the three factors governing fracture, fracture toughness has received by far most attention, defects much attention and the web tension quite limited attention. There are several reasons for this. The web tension has largely been out of the papermakers control as the level is set by the printers, further anything but average web tension has been very difficult to measure. It is, however, not true that the papermakers have no influence on the web tension in the printing houses. A skew web tension profile inherent in the roll will influence the web tension distribution in the printing press. Further hygroexpansion in MD may cause tension loss between printing units. Both the web tension skewness and the hygroexpansion rate are influenced by the papermaking process. Even web tension distribution in CD and low hygroexpansion will allow the printers to apply low average web tensions during printing.

It is now possible to use digital camera systems that monitor web defects. There exist online systems that can measure web tension distribution. When such systems are combined with roll identity and measurements of the fracture toughness properties of the paper, the paper mills will have an excellent tool for reduction of web breaks in the most economical manner.

ACKNOWLEDGEMENTS

Torbjørn Helle, Christer Fellers, Petri Mäkelä, Knut Roar Braaten and the FRS-committee are gratefully acknowledged for reading the draft manuscript and giving very valuable comments. The Norwegian University of Science and Technology are acknowledged for letting me do the research work I want to do.

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Transcription of Discussion

RUNNABILITY, FRACTURE AND PRESSROOM BREAKS

Øyvind Weiby Gregersen

NTNU

Tetsu Uesaka Mid Sweden University

Obviously, your argument is based on the old idea of defect-driven breaks in the pressroom. The question is that, although the defects certainly drive some breaks, how many percent of the breaks in pressrooms are caused by so-called macroscopic defects? In the past, as you might have already seen in the literature, I am aware of at least 3 or 4 sets of data. This body of data shows that defect-driven breaks do exist; however they are not in the majority. Did you have any specific data set showing that the defect-driven breaks dominate most of the breaks?

Øyvind Gregersen

This will obviously vary between different printing methods because there are different web tensions and we have different paper qualities with different quantities of defects in them. But in newsprint printing, which I have been working mostly with, we can explain approximately 50% of the web breaks using the digital cameras, as I showed in the presentation. Those cameras only detect defects which are quite large. So if you have a hair cut or a shive it will not be seen by the camera and also if you have a crepe wrinkle inside a paper roll which may lead to web fracture, then you will not see that either. You need a hole or a cut or something if you are to see it with our camera system. 50% of breaks (and I would guess that there are even more where we do not see the defect) were caused by defects. However, in other printing applications, the situation may be different.

Discussion

Tetsu Uesaka

Normally, using the digital camera technique, it is very difficult to determine whether a break is caused by pre-existing defects, or whether we are just looking at the actual failure processes. There have been many, many applications of this technique. The conclusion is that it is difficult to detect which one is which. These techniques cannot effectively distinguish between pre-existing defects and the ones from actual failure process in the press.

Øyvind Gregersen

Camera monitoring of the web in printing presses can give information of the size and position of some of the defects that cause web breaks. The origin of these defects can only be found by searching the entire production chain from the PM wet end to the camera position in the press. The shape, position and frequency of defects are useful information when we try to find and eliminate their source.

Derek Page JPPS

Thank you for the literature references, which are substantially complete, I think, but I would like to draw your attention to two. One was by a man by the name of Beckett, who worked for the New York Times. He had the quaint name of Thomas A. Beckett. He wrote a paper entitled, *Strength Testing of Newsprint and Newsprint Breaks: The Road to Nowhere*. The conclusion of our 1982 paper was similar. We are never going to find out anything related to the strength of newsprint as measured by any kind of a test, there are just too many other variables that come in. There is another paper that we wrote in association with a gentleman by the name of Archie Bruce, who worked for Abitibi. He had collected break data from 3 million rolls. When we analysed the data, we found there were good pressrooms and bad pressrooms, that is pressrooms which had high rates of break and low rates of break on the same newsprint and then we found there were good newsprints and bad newsprints. But the good pressrooms and the bad pressrooms caused a much wider variation in the number of breaks than good newsprint or bad newsprint. So the answer to the problem of newsprint breaks lies in the pressrooms, to a substantial extent. I am not hopeful that you are going to get very far with the use of fracture mechanics for example, on this problem.

Øyvind Gregersen

Thank you for giving me the references. To the last comment, when you say it is more variation within pressrooms than it is within the papers. Yes, that is to be expected. They have, in general, different presses and they run them differently, particularly they run them with different web tensions. This can be analysed by fracture mechanics, so I disagree to your conclusion. I think that what you mean is that we should not be too optimistic in getting great results by improving the fracture toughness of a paper and I can agree with that. However we have the two other variables: web tension and defect size. Perhaps the most efficient way of reducing web breaks is to cooperate with the printing press producers, because they surely are able to make progress by keeping a lower and more even web tension through the printing press.

Patrice Mangin U.Q.T.R./CIPP

I have been working for the last two years in pressrooms, about one year with a French offset printer. We installed a camera for looking at the web breaks, as you did, and found about 50% of web breaks related to defects. Now, we also investigated the other 50%. There we found that web tension variations were very important. Better control of web tension by the equipment manufacturers is not sufficient on its own as, if you have any defects in the roll winding itself, then you get peaks in tension. We related that to the actual maximum tension. I think we should look more into dynamic effects and do that for very, very short times. For example, imagine you have a drop in tension, let us say for an average of about 400 Nm^{-1} you go down to 200 and then, in a fraction of a second, go up again to some thing like 400 or 500. That is the mechanistic effect we should look into to explain the actual breaks that we cannot relate to defect or fracture toughness.

Øyvind Gregersen

Thank you for your comments. I agree.