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FACTORS CONTROLLING PRESSROOM RUNNABILITY OF PAPER

T. Uesaka, M. Ferahi, D. Hristopulos, N. Deng, and C. Moss

Pulp and Paper Research Institute of Canada

ABSTRACT

Web breaks in pressrooms have been modelled in terms of web strength variations and tension variations to identify principal factors controlling the pressroom performance. The web strength variations and their scaling law (the size dependence) have been formulated based on an extreme statistics approach, and the distribution parameters have been determined for a number of mechanical printing grades. By using the tension variation statistics data obtained from a pressroom trial, a parametric study has been conducted to examine the relative magnitude of the effects of key paper properties. The predictions have been compared with field study data. Among the conventional paper properties, tensile strength and elastic stretch consistently predicted the break frequency. The strength uniformity parameter (Weibull exponent) was shown to have the highest impact on the break frequency based on the parametric study.

INTRODUCTION

Web breaks are one of the most persisting runnability issues in pressrooms. The issue has been studied for a number of years in terms of pressroom tension variation [1], basic strength properties and fracture toughness [2–6], effects of shives and other defects [7–10], effects of winding, reeling and roll structure [11–14], and web tension uniformity [15–17]. In spite of the overwhelming amount of information generated from these studies, there is, surprisingly, very little quantitative data showing a clear relationship between pressroom breaks and the above variables.

For example, in pilot-scale runnability studies [7,8], shives were convincingly shown to be the dominant cause of web breaks. However, to the authors' knowledge, there is no quantitative data from pressrooms indicating such a strong effect of shives. Holes, cuts and other macroscopic defects are also considered as major culprits for breaks. This notion prompted many researchers to tackle the break problem from the point of fracture mechanics for the last 20 years.

However, the recent study conducted in the authors' laboratory [18] showed that, unless the size of the defect reaches a significant length (e.g., more than 40 mm), the breaks rarely occur due to such defects under normal operating tension conditions in pressrooms. This was further confirmed in our field study, which examined 50 broken samples randomly taken from a US pressroom. The result showed that there was only one break associated with a clear defect (crepe wrinkle), and other breaks had no sign of the conventional macro defects or shives. In addition, Moilanen and Linqdvist [9] also examined the relationship between "defects", as detected by the web inspection system installed at a rotogravure press, and breaks. They found that among 76 breaks from 2372 rolls run, only three breaks *may* be due to holes. These results from analytical and field studies indicate that the typical defect-driven breaks certainly exist, but they are not the cause for the majority of the breaks. Then the natural question arises: what controls web breaks, and what should we focus on in papermaking to improve pressroom performance other than eliminating defects?

There have been a number of attempts to answer these questions, particularly from an empirical or phenomenological viewpoint. Multivariate analyses, including principal component analysis and multi-linear factor analyses, are most often used to identify underlying factors of web breaks, based on the data of pressroom performance, paper roll qualities, and pulp properties. Typically, a number of paper properties and operating variables, somewhat arbitrarily chosen, are input to the analysis system (black box) to relate them to the pressroom performance. However, these analyses involve some fundamental problems. The most prominent problem is that the analyses are based on the assumption that the variables involved are linearly related. Unfortunately, the problem of web breaks contains a number of variables whose relationships are strongly non-linear and interdependent.

In this paper, we take a mechanistic approach as an attempt to quantitatively or, at least, semi-quantitatively identify important factors controlling pressroom breaks. The phenomenological approach is taken only for the purpose of examining the validity of the predictions made from the mechanistic approach. The overall approach is described below.

OVERALL APPROACH

The pressroom break is considered here as "system performance" which is controlled by both paper-related and press-related parameters. First, stochastic modelling of pressroom breaks is done to relate both web strength distributions and tension variations to pressroom breaks. In order to determine web strength statistics, paper strength distributions are measured for different size samples, and the scaling law is examined. Secondly, tension variations in a press system are modelled, using a general continuum mechanics approach, to derive basic equations needed for experimental investigations and also to explore the potential sources of tension variations. Thirdly, web breaks are predicted based on the data recently obtained from a pressroom to evaluate the relative magnitude of the effects of key runnability parameters. Finally, using pressroom and paper data obtained over a three-year period from a North American mill, relationships between break frequency and conventional strength parameters are determined to compare the general trends with the predictions. In this paper, we will mainly discuss the paper-related aspects (the first, the third, and fourth aspects). The details of the second aspect (the formulation of tension variation and web dynamics) will be discussed elsewhere.

WEB STRENGTH DISTRIBUTION AND STOCHASTIC MODELLING

Web Strength Distribution

First we will consider the strength distribution of a web of length L and width W, consisting of $p \times q$ characteristic elements, subjected to a nominal tension T (per unit width) (Figure 1). We will define the characteristic elements later in this section. We define the cumulative distribution functions (CDF), i.e., the probability that the strength is less than the nominal tension T, for the web and for the characteristic element as $F(T;A)$ and $F_0(T)$, respectively. The probability that the web survives without failure when the nominal tension T is applied, is given by $1 - F(T;A)$, which, in turn, is expressed as

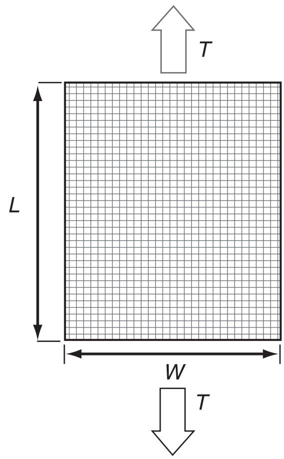

Figure 1 Web under tension with a number of characteristic elements.

$$1 - F(T;A) = \prod_{i=1}^{pq} \{1 - F_0(T)\}. \tag{1}$$

Taking the logarithm of the above equation gives

$$\ln\{1 - F(T;A)\} = \sum_{i=1}^{pq} \ln\{1 - F_0(T)\}. \tag{2}$$

Since $F_0(T) \ll 1$, i.e., the strength of a web is controlled by the tail of the local strength distribution, equation (2) is approximated by taking the first term of the Taylor series of the right-hand side as

$$\ln\{1 - F(T;A)\} \approx -\sum_{i=1}^{pq} F_0(T) = -pq \cdot F_0(T). \tag{3}$$

Therefore, the CDF of the web is expressed as

$$F(T;A) = 1 - \exp\{-pq \cdot F_0(T)\}. \tag{4}$$

The above derivation is a direct result of the application of the weakest link formulation, that is, when the weakest spot in the web fails, the whole web also fails. In reality, unlike very brittle materials such as ceramics, the paper doesn't fail in such a fashion even if the weakest point fails. Instead, the actual failure process involves the failures of weak spots, the coalition of these failed areas forming clusters, the further growth of clusters, and finally the formation of a critical cluster leading to global failure.

Recently, there have been a number of stochastic modelling and simulation studies for various material systems to relate the interactions of failed clusters and the local load sharing to the overall strength distributions [19]. Especially, Ibnabdeljaslil and Curtin [20], showed that there exist specific-size elements, called "characteristic elements", which behave as though they are statistically independent and connected in series links. The size of the characteristic element depends on the microstructure and local mechanical properties [20]. This implies that if such elements exist and the paper size is large enough compared to the size of the characteristic elements, then the paper can behave, phenomenologically, in the way predicted by the weakest-link formulation (equation (4)). The basic questions are whether the paper behaviour follows the weakest-link predictions and, if so, what the size of the characteristic element in paper is.

The number of elements, p and q, can be expressed in terms of the size of the characteristic elements, δ_L and δ_W as

$$p = W / \delta_W, \quad q = L / \delta_L. \tag{5}$$

Rearranging equation (4) with equation (5) yields

$$\ln \ln \frac{1}{1 - F(T;A)} = \ln WL - \ln \delta_W \delta_L + \ln F_0(T). \tag{6}$$

Equation (6) indicates the scaling law of the strength distributions of finite size specimens: the plots of the left-hand side of equation (6) for different size specimens should form a single curve by vertical translations given by the first term of the right hand side of equation (6).

Figure 2 shows such plots for the specimen sizes of 1.5 × 10 cm, 3.0 × 20 cm, 6.0 × 40 cm, and 7.5 × 50 cm. Although there are inherent scatters in the lower tail of the plots, because of the limited number of measurements, the shifted curves generally follow the above prediction without systematic deviations. This implies that the standard size specimen (1.5 × 10 cm) is already large compared to the size of the characteristic element of the paper tested. In the previous study [18], the size of the characteristic elements was shown to be in the order of 1 mm, depending on the fibre length.

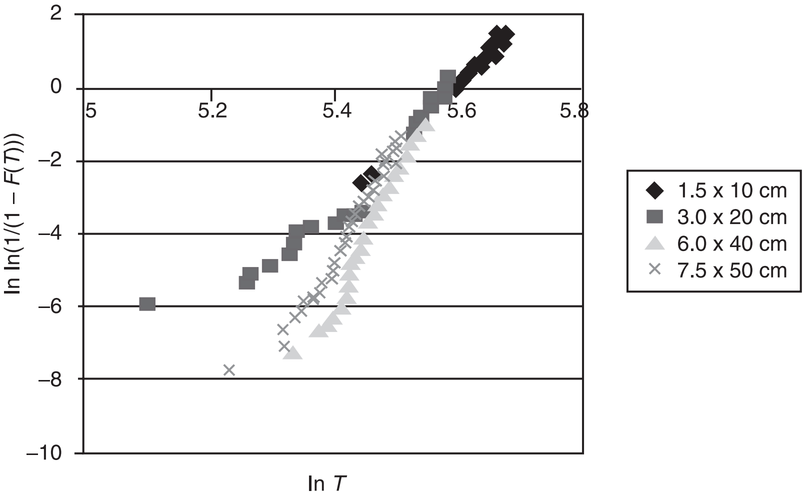

Figure 2 Weibull plots for different size specimens.

The local CDF, $F_0(T)$ is often assumed to be the Weibull form, that is

$$F_0(T) = \left(\frac{T}{T_s}\right)^m. \tag{7}$$

Smith and Phoenix [21] showed that an asymptotic approximation of $F_0(T)$ leads to a Gaussian distribution instead of the Weibull distribution, and the Weibull approximation gives a higher estimate of the failure probability. However, as m increases, both distributions yield a very similar distribution of overall strength. In this study we use the Weibull approximation to calculate the break frequency because of its conservative nature of the reliability prediction. Figure 3 shows a typical Weibull plot of tensile strength collected over a three month period from a newsprint mill. If the strength distribution follows equations (6) and (7), the Weibull plot gives a linear relationship. Figure 3 indicates the validity of this approximation.

Break Frequency

Here, we shall relate the distribution function $F_0(T)$ to break frequency. The probability that a differential web element, shown in Figure 4, breaks at a tension less than T, is

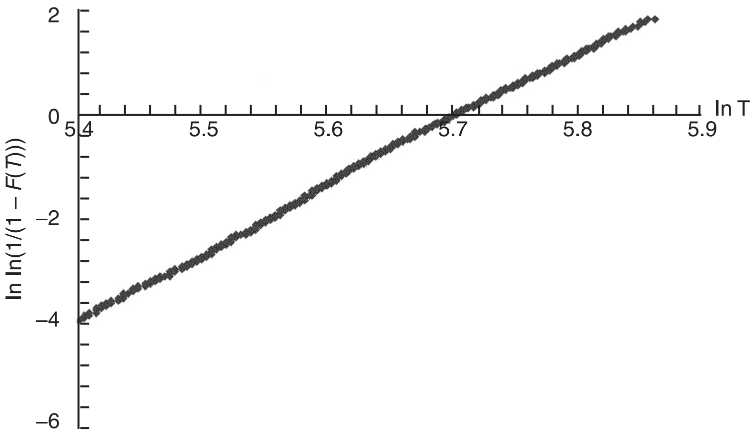

Figure 3 Weibull plot of tensile strength data.

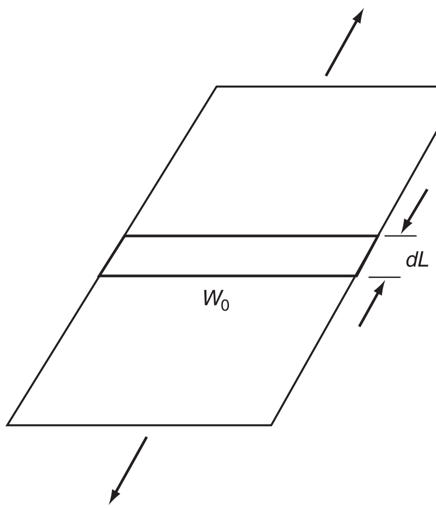

Figure 4 A differential element in a running web.

$$dF = g(T, W_0)dL. \tag{8}$$

Using equations (4) and (5), we have

$$g(T, W_0) = \left.\frac{dF}{dL}\right|_{L=0} = F_0(T) \cdot \frac{dpq}{dL} = F_0(T) \cdot \frac{W_0}{\delta_W \delta_L}. \tag{9}$$

The probability that this differential element breaks while it runs from the reel stand to the folder is

$$dF = g(T_{\max}, W_0)dL, \tag{10}$$

where $T_{\max}$ is the maximum nominal tension that this element experiences between the reel stand and the folder. Depending on the web path in the printing system and the type of operation (start up, reel change, emergency stop, etc.), $T_{\max}$ will vary as a function of space and time. The average number of breaks for this roll is given by

$$\begin{aligned} n_1 &= \int_0^{L_0} g(T_{\max}(L), W_0)dL = \frac{W_0}{\delta_W \delta_L} \int_0^{L_0} F_0(T_{\max}(L), W_0)dL \\ &= p(W_0)q(L_0) \cdot \frac{1}{L_0} \int_0^{L_0} F_0(T_{\max}(L))dL = p(W_0)q(L_0) \cdot \langle F_0(T_{\max}(L))\rangle L_0, \end{aligned} \tag{11}$$

where L_0 is the total length of one roll. The number of breaks per 100 rolls is simply

$$n_{100} = 100 \cdot n_1. \tag{12}$$

Expressing $T_{\max}$ as the sum of the average tension (tension value reported by the press-room) and tension surge due to the fluctuations of strain ($\Delta f_{\max}$):

$$T_{\max} = T_0 + \Delta f_{\max} \cdot E_{\mathrm{MD}}, \tag{13}$$

assuming that E_{MD}, the Young's modulus in the machine direction, is constant, and employing the Weibull approximation, we have an approximate expression for the break frequency:

$$n_{100} \approx 100 \cdot \ln 2 \cdot \frac{A_0}{A_r} \cdot \left\langle \left(\frac{T_0}{T_{\mathrm{MD}}} + \frac{\Delta f_{\max}(L)}{e_{\mathrm{MD}}} \right)^m \right\rangle_{L_0}, \tag{14}$$

where $A_0 = L_0 W_0$, and A_r is the area of the test specimens used for the strength distribution determination. As seen in the above equation, the break frequency depends on both pressroom parameters and paper parameters. As the strain variation ($\Delta f_{\max}$) increases (in a poorly controlled press system), the elastic stretch e_{MD} (= $T_{\mathrm{MD}}/E_{\mathrm{MD}}$) becomes important.

The expression given in equation (14) is considered to give an upper bound of the break frequency because of the conservative nature of the Weibull distribution, as discussed earlier. It should also be noted that the Weibull approximation (equation (7)) loses its accuracy when unusually high tension, approaching T_s, is applied, although the probability of such an event is extremely small. In this extreme case, we can "cap" the expression by the exponential function to calculate the expectation in equation (14) [18].

TENSION VARIATIONS AND WEB DYNAMICS

Information on tension variations in pressrooms is crucial to predict the break frequency. A model has been developed to investigate tension variations and also to guide experimental investigations. The model is based on the physical principles that govern the transport of mass and momentum along the web. Since the variations have both temporal and spatial components, an approach based on continuum mechanics is appropriate. Based on these considerations, we have derived a general system of equations that govern the web dynamics. From this general non-linear system, a simplified model of web dynamics that admits explicit solutions has been derived to predict tension behaviour in the steady state with and without small tension fluctuations, and tension surges observed in pressrooms during start-up. Tension variations were measured in a major US pressroom using a speed sensor, based on the laser Doppler method, in the "dynamic" (0–60Hz) range. The details of this web dynamic analyses will be reported elsewhere, but the results are used for the parametric study discussed in the following.

PARAMETRIC STUDY OF EFFECTS OF KEY PAPER PROPERTIES ON BREAK FREQUENCY

A parametric study has been done based on the preliminary measurements of draw and strain in the pressroom, as described in the previous section. The strain variation was reasonably approximated by the Gaussian distribution. The values of paper properties, including tensile strength in the machine direction, T_{MD}, elastic stretch e_{MD} (= T_{MD}/E_{MD}), and the Weibull parameter m, were obtained from the data accumulated in the previous study [18]. The average tension T_0 was obtained from the pressroom trial.

Figure 5 shows the effect of strain variations on the break frequency (the number of breaks per 100 rolls). The values of other parameters used in this calculation are shown in the figure. As the standard deviation of strain reaches 0.08–0.1%, the break frequency sharply increases. In our measurements of strain variations in the draw-controlled section (after the first printing nip) in the pressroom, the standard deviation was about in the range of 0.03 to 0.05%. Therefore, we don't expect any significant number of breaks in this section. In fact, breaks never occurred in this specific section during the trial. However, in the first section between the reel stand and the first press nip, we can easily expect much higher variations, particularly in the transient stage (start up, reel change, emergency stop). In the subsequent calculation, the standard deviation was set as 0.11% to examine the relative effects of

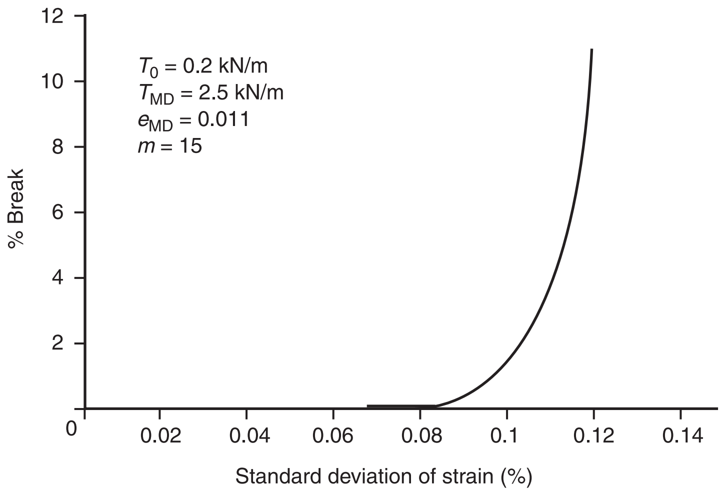

Figure 5 Effect of strain variation.

different paper properties. It is, therefore, understood that the results of this parametric study are still of semi-quantitative nature.

Figure 6 shows the effect of tensile strength in the machine direction. The break frequency decreases with tensile strength with slight non-linearity. The range of tensile strength variations was chosen from our survey of different newsprints [18]. In spite of the large variation of tensile strength, the change in break frequency is, unexpectedly, small. Elastic stretch showed a much greater effect on the break frequency than tensile strength (Figure 7). According to equation (14), the elastic stretch term becomes more important as the web strain fluctuation increases.

The Weibull parameter *m*, representing the uniformity of tensile strength, showed the greatest effect on break frequency, as shown in Figure 8. Since the Weibull approximation is a conservative estimate of the system reliability, particularly in the lower tail of the distribution, the actual break frequency is expected to be smaller than the ones observed in Figures 5 through 8. Although this parameter is rarely measured, in our survey of different paper machines producing newsprint and directory grades, the *m* parameter varied from 12 to 25. In addition, anecdotal evidence from a few mills also showed that two papers with the same average tensile strength, made from the same furnish and from two paper machines of the same configuration, still exhibit 100% difference in the pressroom break performance. This supports, qualitatively, the strong influence of the strength uniformity on web breaks shown in this figure.

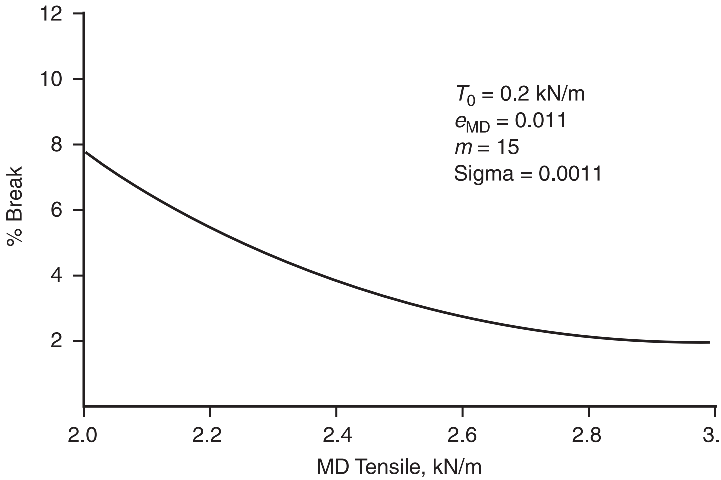

Figure 6 Effect of MD tensile.

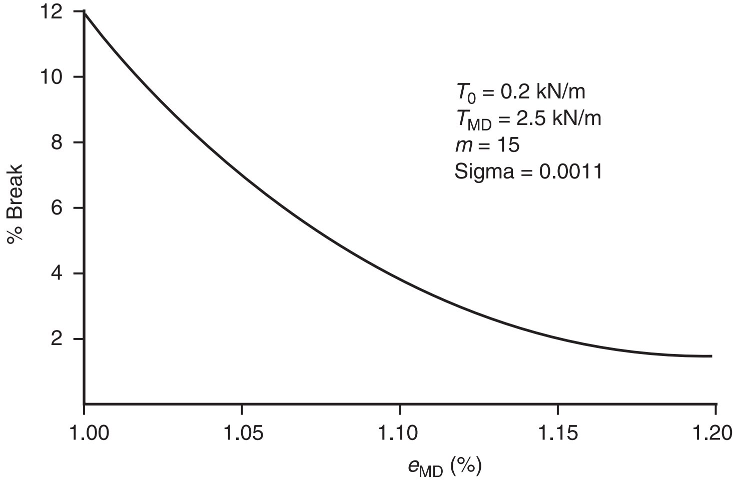

Figure 7 Effect of elastic stretch.

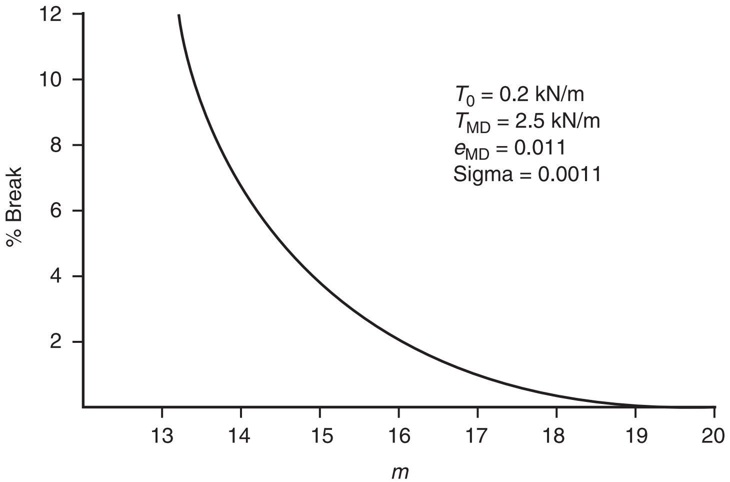

Figure 8 Effect of strength uniformity.

FIELD STUDY

Field studies have been conducted in three pressrooms in collaboration with Paprican's member companies.

First, three-year data of paper strength properties for each jumbo reel were collected and related to its pressroom performance. The number of rolls examined was between 30,000 to 50,000 depending on the pressrooms. Because of the expected non-linearity, we used χ^2 tests to determine the statistical significance of various relationships at a critical level. The tests involve the examination of (1) whether the break frequency "varies" (not necessarily linearly) with the variable in question, (2) if it "varies", whether it is statistically linear, and (3) if it is linear, whether the slope is statistically significant. This procedure allows us to determine, step by step, whether there is any single variable controlling pressroom breaks, and also to avoid accidental correlations, caused by non-linear interdependence among the variables examined, from the multivariate analysis.

Figure 9 shows the relationship between break frequency and tensile strength. The grade is a directory paper of basis weight of 36.6 g/m^2. This relationship passed all three tests described above. In other words, tensile strength has a statistically significant and linear relationship with break frequency. Although the parametric study in the previous section predicted a weak non-linear relationship between the break frequency and tensile strength, such non-linearity may not be statistically resolved in the actual data. Tensile strength consistently showed better predictability, in the sense of

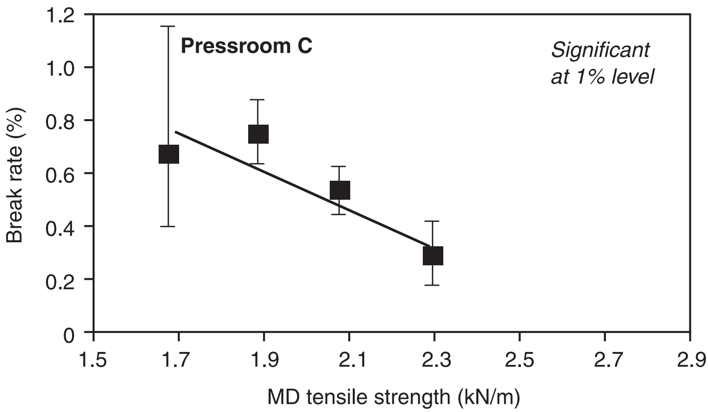

Figure 9 Effect of tensile strength.

the three tests, than other paper strength properties (including TEA, stretch, tear, and burst), in different pressrooms and different grades (newsprint and directory grades).

Stretch was also found to have a "statistically significant" relation to the break frequency, but the relationship was strongly non-linear, as seen in Figure 10. The elastic stretch value was not available in this field study data.

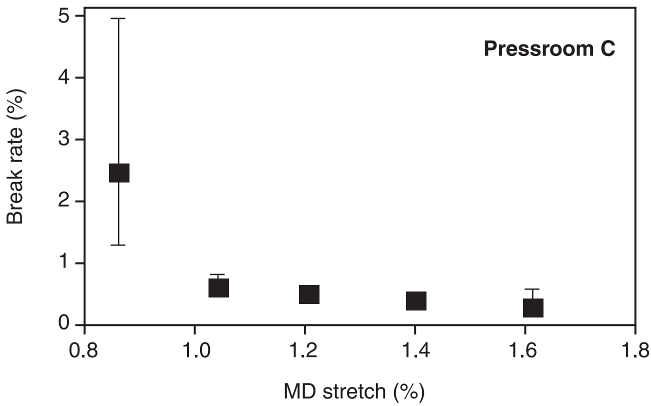

Figure 10 Effect of MD stretch.

However, as may be speculated from the parametric study results discussed earlier (Figure 7), the conventional stretch property is also expected to show a strong non-linearity. Figure 10 indeed showed such a trend. Figure 11 shows a plot of the break frequency against (tensile strength) × $(\text{stretch})^{1/2}$. This parameter is empirically defined, but has an indirect, close relationship with burst strength [22], TEA (tensile energy absorption), and essential work of fracture [23] under certain conditions. This parameter also passed, consistently, the three statistical tests.

Figure 12 shows the plot of break frequency against CD tear strength. The relationship was not statistically significant, even at 10% critical level. Similar inconsistency was observed for CD tear strength in other pressrooms. This implies that CD tear is not a controlling parameter of web breaks. It is well known that kraft pulp addition increases tear strength and therefore, sometimes, the improved performance is attributed to the increase in CD tear. Figure 13 shows a relationship between kraft content and break frequency. In spite of the very large change in kraft content from 0% to 15%, there is no

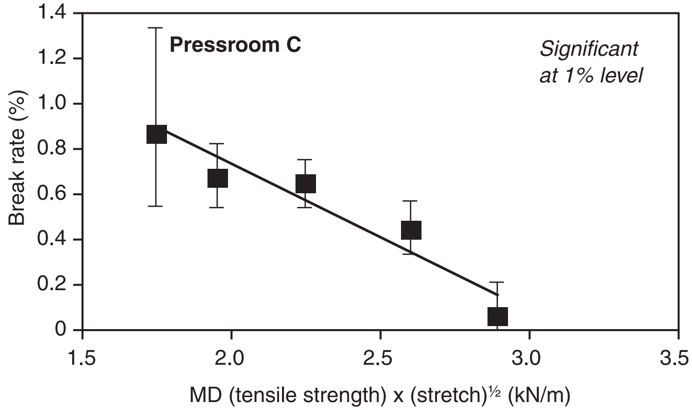

Figure 11 Plot of break frequency against (tensile strength) × $(\text{stretch})^{1/2}$.

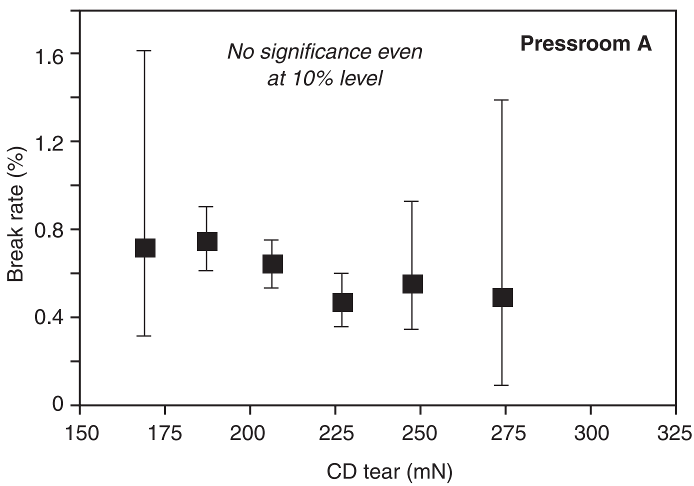

Figure 12 Effect of CD tear.

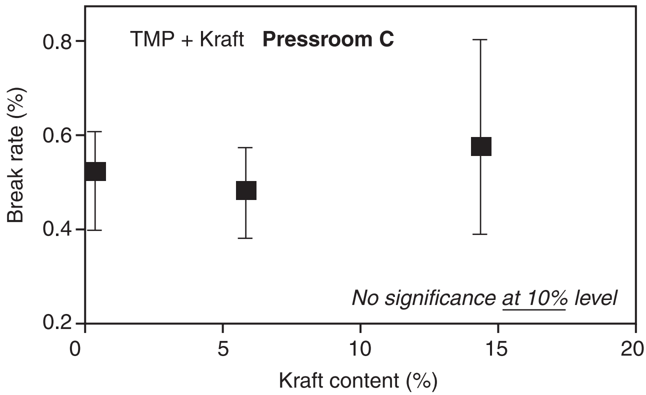

Figure 13 Effect of Kraft.

statistically significant change in the pressroom performance. In this specific case, (slightly beaten) kraft pulp is added to compensate for tensile strength property variations of TMP, and again CD tear increased with kraft content. However, the performance almost remained the same as tensile strength remained constant.

It should be noted that the relationships observed above may not be seen for a smaller number of rolls. Since the break frequency follows a binomial or Poisson distribution [24] instead of Gaussian (or normal) distribution, the confidence interval grows quickly as the number of rolls decreases, and becomes asymmetric between the positive and negative side. This often obscures the correlation data obtained from a smaller number of rolls.

CONCLUDING REMARKS

An attempt has been made to quantitatively relate the strength properties and uniformity of paper to the pressroom performance. Although there is still a need for obtaining precise statistics of tension variations in the transient state, the stochastic model proposed for estimating the upper-bound of break frequency describes reasonably well many anecdotal evidences of pressroom runnability. Among the key paper-related parameters, the strength uniformity, as represented by the Weibull exponent m, was shown to be the most influential property to the break frequency, followed by elastic stretch and tensile strength.

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Transcription of Discussion

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T. Uesaka, M. Ferahi, D. Hristopulos, N. Deng and C. Moss

Pulp and Paper Research Institute of Canada

Kari Ebeling UPM-Kymmene Corporation

I would like to congratulate you on a very good work, and the number of samples tested creates reliance on the results.

Brian Philips Consultant

I am not sure that if you did not get a relationship with 2000 rolls then you will get one with 20,000 rolls. I went to a pressroom where we had run several years worth of newsprint and presented an analysis of runnability showing correlations with paper properties. The pressroom manager said that the high breaks were due to running a particular product (i.e. newspaper) and nothing to do with the paper.