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- A REVIEW

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ABSTRAKT

Web breaks are a rare phenomenon. It is generally difficult to perform typical cause-effect investigations and to find the principal factors controlling web breaks. Accordingly, discussions of pressroom runnbaility often abound in anecdotes and observations, with little quantitative data and few analyses. This report reviews recent studies of web breaks in the literature with the main focus on *quantitative* discussions of the problem. Major conclusions drawn from this review are as follows:

- Macroscopic defects can cause breaks. These include wrinkles, holes, cuts, and bursts. However, the presence of such defects alone does not induce breaks, unless the size of the defects is exceedingly large or tension surges coincide with defect occurrences. Therefore, statistically, defect-induced breaks constitute only a small portion of web breaks in pressrooms.

- The majority of web breaks are caused by tension variations (in space and time) in the press system, combined with strength variations of paper web. Recent studies on tension variations, web/nip mechanics, and paper strength statistics have started to provide very realistic predictions of web breaks.

- The paper strength properties controlling pressroom runnability are machine direction tensile strength, strain-to-failure, and the uniformity of tensile strength. Field data support this conclusion. The data also demonstrate that tensile strength is the most consistent predictor of web breaks among the routinely measured strength properties of paper. Tear strength did not consistently predict the runnability.

- The most effective way to reduce break rates by an order of magnitude is to reduce tension variations. Tension variations are caused by both pressroom operation and the paper itself. Paper-related factors that have been identified so far are paper splices, out-of roundness, and web tension non-uniformity. The impacts of these factors depend highly on pressroom operation and press configuration. In the literature, these factors have been shown, in at least one study, to make statistically significant contributions to web breaks.

KEYWORDS: Runnability, Press Rooms, Web Breaks, Statistical Analysis, Tesile Strength, TEAR, Stretch, TEA, Strength Uniformity, Kraft Content, fracture toughness, tension, tension nonuniformity, defects

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INTRODUCTION

Web breaks are a major runnability issue in many pressrooms. Accordingly, this is also a major driver for papermakers to continue to improve strength properties and to reduce occurrences of defects in the paper web.

Breaks are rare events. Some well-maintained pressrooms in North America run paper rolls at a 1 or 2% break rate, i.e., 1 or 2 breaks per 100 rolls [1]. It is also well known that some Japanese pressrooms run at a 0.1 % break rate or less. This implies that it is becoming extremely difficult to obtain statistically significant data simply by running paper rolls manufactured under different conditions to find a cause-effect relationship. This difficult situation has created a number of questions over the years in both pressrooms and paper mills. Some of the questions are as follows:

(1) How reliable are the break data? (Statistical confidence.)
(2) Do defects control breaks? In other words, are (macro-) defects the major cause of breaks?
(3) In the same sense, do shives control breaks?
(4) Which strength parameter do we need to monitor to predict runnability? Tear, TEA, burst, tensile, or fracture toughness?
(5) Does kraft pulp have a special "miracle" effect on runnability?
(6) To what extent do roll structures (roll density profile and roll shape) affect the runnability?
(7) To what extent does the web tension non-uniformity in the roll width direction affect the runnability?
(8) Why does the same paper run at a few percent break rate in one pressroom and at more than 10% in another?
(9) Why does paper break in the pressroom?

There have been many "theories" proposed to answer these questions. Unfortunately, these theories often lack *quantitative data or analyses* to support their claims so that papermakers have difficulties in deciding concrete actions to improve their runnability. This review is an attempt to answer these questions on a quantitative basis by examining some of the recent studies on web breaks in the literature, as well as information collected from the field.

BREAK STATISTICS

Break frequency is often reported as a percent break rate, such as the number of rolls broken divided by the number of rolls run. A basic question is how reliable such data are.

If printing of paper rolls is considered as a process of consuming a number of rolls, breaks may be regarded as a process of marking some rolls, *randomly*, among the whole rolls consumed. Suppose one takes n rolls from the total population. The probability that one finds n_b marked rolls (breaks) among the n rolls follows the binomial distribution. It is also known that as the total number of rolls increases with a constant rate of marking, the binomial distribution approaches the Poisson distribution. Page and Seth [2] examined the distributions of the break rate (n_b/n) demonstrating that the distribution is indeed approximated by the Poisson distribution.

If the break rate follows the binomial or Poisson distribution, a 95% confidence interval can be estimated by using the single proportion inferences calculation method [3]. Since the distribution is not a normal distribution, the upper and lower bounds of the interval are not symmetrically located. The upper and the lower bounds of the 95% confidence interval are given by the following equations:

$$BR_{Lower} = \frac{\left(2np + 1.96^2 - 1\right) - 1.96\sqrt{1.96^2 - \left(2 + \frac{1}{n}\right) + 4p\left(nq + 1\right)}}{2\left(n + 1.96^2\right)}$$
$$BR_{Upper} = \frac{\left(2np + 1.96^2 + 1\right) + 1.96\sqrt{1.96^2 + \left(2 - \frac{1}{n}\right) + 4p\left(nq - 1\right)}}{2\left(n + 1.96^2\right)} \qquad (1)$$

where

$$p = \frac{n_b}{n}, q = 1 - p \qquad (2)$$

Figure 1 shows the upper and lower bounds of the 95% confidence interval for the case of a 2% break rate (p=0.02). As seen in Fig. 1, the observation of 500 rolls, gives a confidence interval between 1% and 3.8%. In other words, suppose that paper is made under two different trial conditions and 500 rolls are produced and printed at each condition. If the break rates for these two conditions happen to fall between 1% and 3.8 %, we can not effectively distinguish the difference in the effect of the trial conditions. We could obtain a reasonably tighter bound, say 2% ± 0.2%, only after running more than 10,000 rolls. This makes a typical runnability trial extremely difficult, presenting a need for different approaches to investigate break causes. At the same time the result also suggests that all break data should include this statistical confidence estimate.

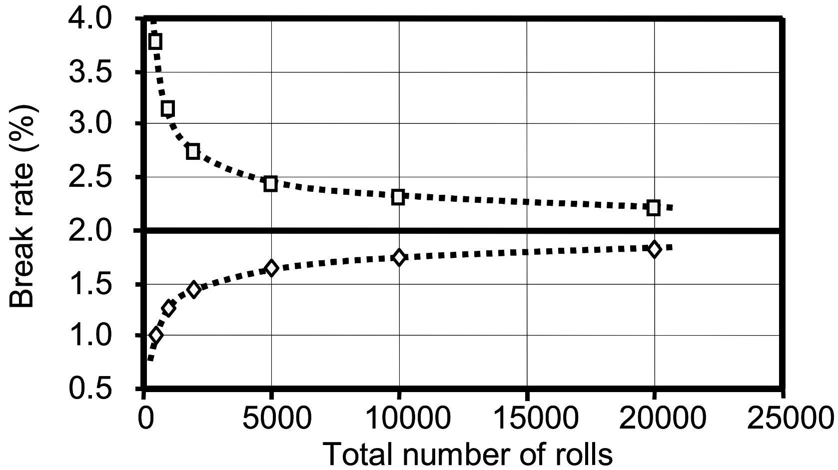

Figure 1. Upper and lower bounds of 95% confidence interval as a function of the number of rolls obeserved for the average break rate 2%.

EFFECTS OF "DEFECTS"

Defects are often considered as the major cause for web breaks. The basic idea is that the defects act as "weak" spots in the paper web or the sources of stress concentration, triggering breaks. Although the idea is plausible, it is not clear *to what extent* the defects contribute to the total number of breaks. In other words, suppose one eliminates all defects, how much improvement one can achieve in the runnability.

Defects may be classified into two categories: One category is macroscopically visible defects, such as holes, cuts, thin/thick spots, burst, and wrinkles. Shives may be included in this category, since in many cases they are visible. The other is "natural disorder" of paper, such as formation (mass density distributions), and local fibre orientations, which originate from the stochastic nature of paper structure, caused by its unique manufacturing process. We will here restrict the discussions to those macroscopically visible "defects". The second category of "defects" will be discussed later.

MACRO DEFECTS

Moilanen and Linqdvist [4] installed a web inspection system at the in-feed section of a rotogravure press to observe any detectable defects from paper rolls going into the printing press. The total number of rolls run in this trial was 2372, and 76 breaks occurred during the trial. Investigating the break incidents and the defects detected by the inspection system, they stated that only three breaks (among 76 breaks) were probably due to holes, and other breaks had no correspondence with the presence of holes and cuts in the in-feed section. Although current web inspection systems may not perfectly detect all defects, this result, at least, posed a fundamental question of whether web breaks in pressrooms are really dominated by macro-defects.

Ferahi and Uesaka [5] took 50 broken samples *randomly* from a US pressroom, and inspected the samples with special optics to visualize macroscopic defects and shives. They found that almost all of the samples had no indication of typical macro defects, except one which was clearly associated with a crepe wrinkle.

Uesaka and Ferahi [6] predicted web breaks for typical newsprint rolls containing macro defects, using a stochastic, fracture mechanics model. The macro-defects were represented as cracks, and it was assumed that each roll contains a single crack perpendicular to the machine direction either in the centre or at the edge of the roll. This modelling is considered as an upper estimate of the effect of a single macro-defect on breaks, since a crack creates the highest stress concentration among different shapes of defects *at a given size*. Local paper web strength was assumed to fluctuate, so that at a given crack length failure tension still varied. Figure 2 shows the predicted total number of breaks plotted against the crack length.

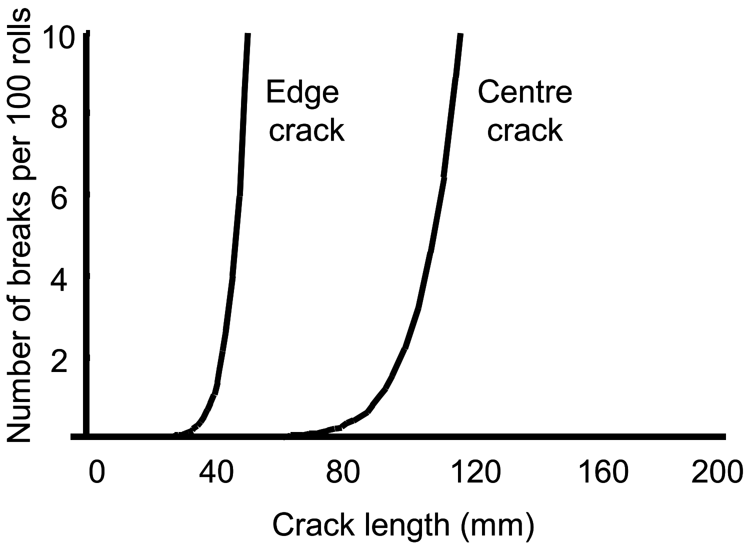

Figure 2. Number of breaks per 100 rolls as a function of crack length. Tensile strength in the machine direction (per unit width) =2.45 kN/m, pressroom tension=0.196 kN/m, strength uniformity parameter m=19, where m is defined in the approximation of strength distribution by the Weibull distribution [6]. The higher the m, the more uniform the distribution.As seen in Fig. 2, there are certain crack lengths at which the number of breaks sharply increases: about 40 mm for the edge crack, and about 80 mm for the centre crack. The edge crack clearly has a more damaging effect on web breaks than the centre crack. This was also observed in many paper winders and in pressrooms. Such edge cracks are sometimes (not always) *snapped off* (or caught) at the roll edges, causing breaks. However, it should be noted that the critical length of such cracks is very large, i.e., 40 mm and 80 mm, in order to see a significant effect on the web breaks. The basic condition applied to this model calculation is that the press room tension is kept constant at a *nominal tension* value, which is specified by press manufacturers. That is, *as long as the press tension is controlled properly*, the model predicts that it is rare to see defect-driven breaks. Also note that the result is an upper estimate of the effects of macro defects, and the actual effects of defects of non-crack types will be smaller. In other words, if a significant number of breaks occur due to the macro defects, it is a good indication of the presence of exceedingly high average tension or tension non-uniformity both in the web transport system and in the printing nips. Again this analysis posed a question of whether most of the breaks are really caused by typical macro defects, such as holes and cuts.

The above trial and analysis results are actually consistent with the field data.

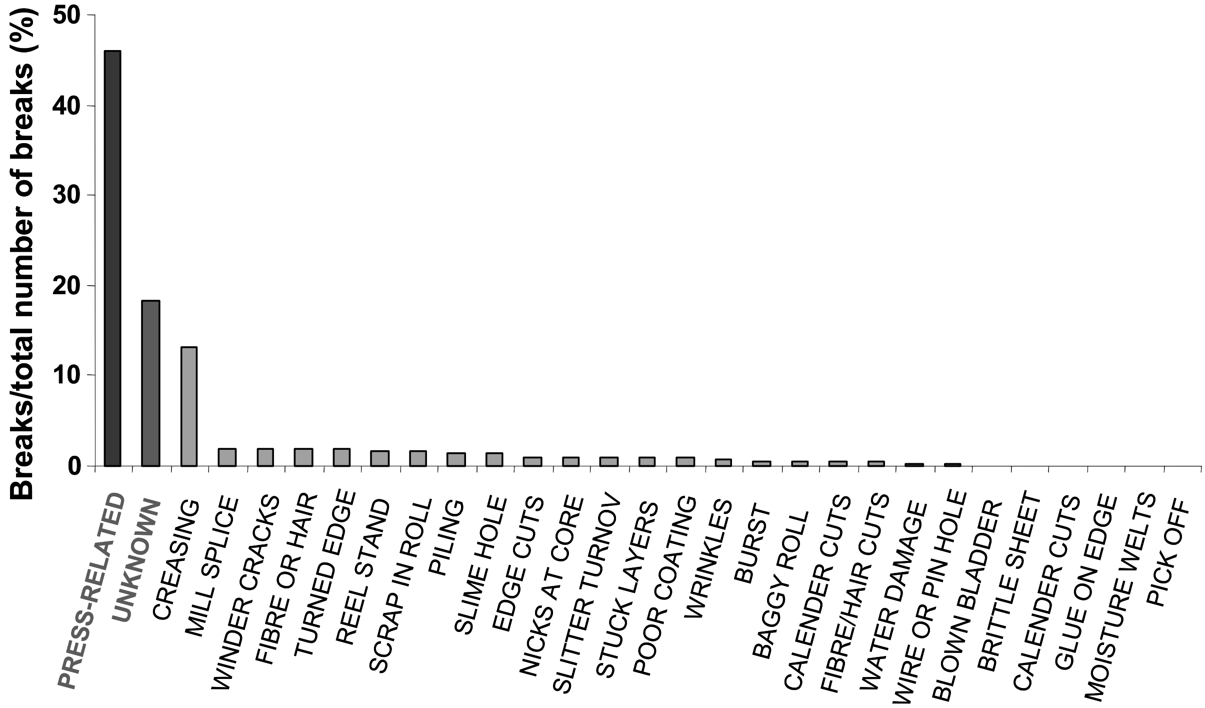

Figure. 3 Break cause statistics (Heatset offset press)

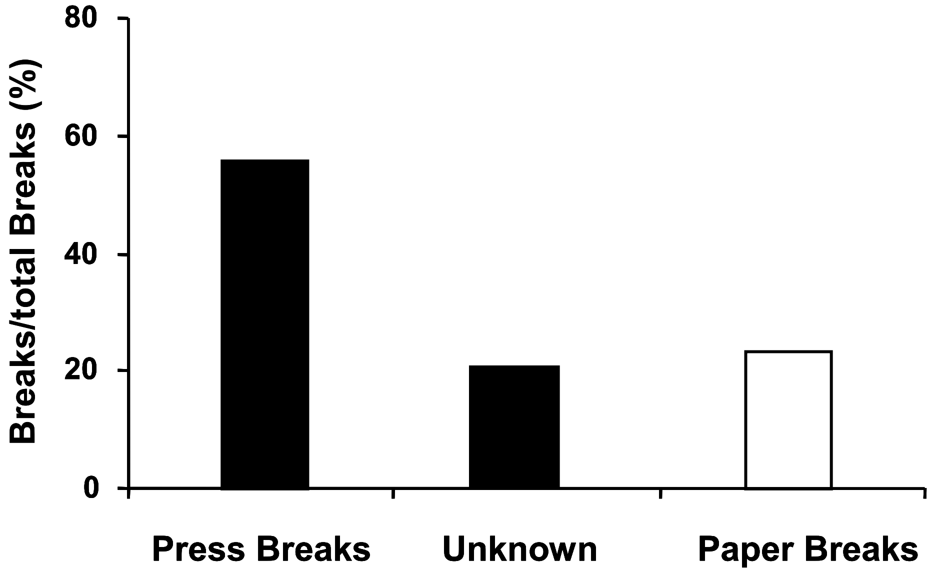

Figure. 4 Break cause statistics (Coldset press printing newsprint)

Figures 3 and 4 show break cause statistics taken by pressrooms using heatset (Fig. 3) and coldset (Fig. 4) offset presses [7]. Typically, so called "press-related" breaks and "unknown" breaks constitute the majority of breaks in many pressrooms. Among the paper breaks, the typical, weak-spot-like defects contributed very little to the total breaks (Fig. 3). The only significant, but not necessarily dominating, paper defect factor is creasing (or wrinkling). This was also documented in the early statistics [8].

Some pressrooms have conducted systematic studies to investigate the causes of breaks, although much of this work has not been published. Figure 5 presents the result of the investigation by a US pressroom, showing potential areas of runnability improvement [9].

Assuming that the average break rate is 2.0 %, we can estimate how much of the break rate can be reduced by specific actions.

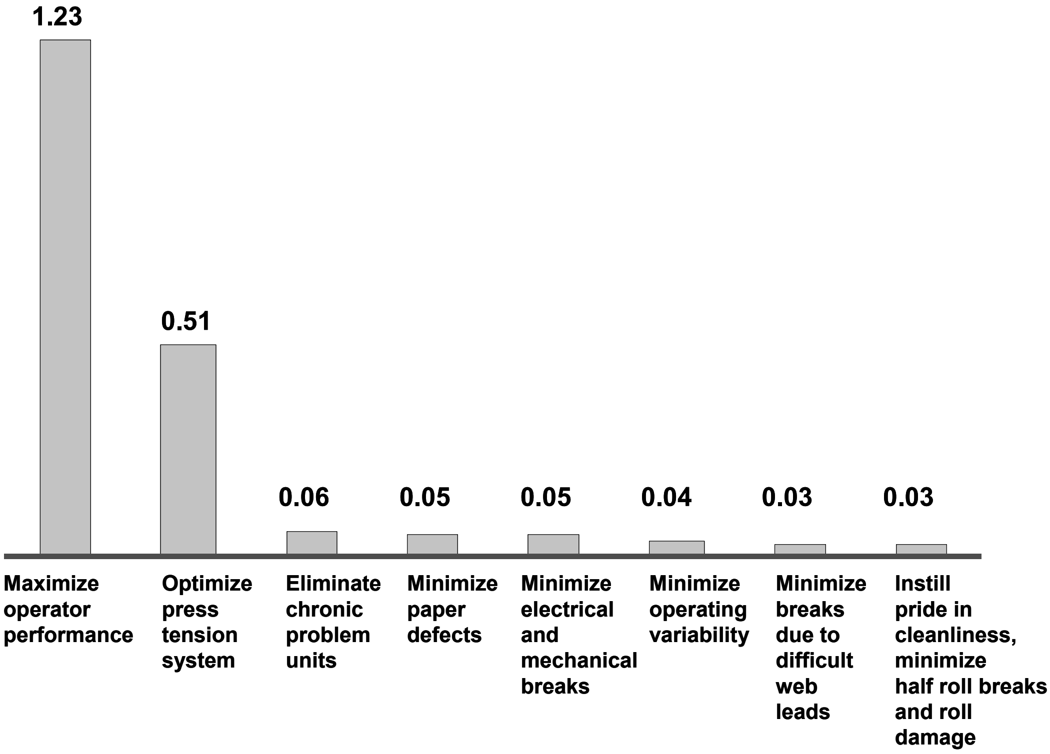

Figure 5 Potential areas of web break reduction (Average break rate: 2.0%)This study suggested that the largest effect on runnability improvement could be achieved by maximizing operator performance, and secondly by optimizing press tension system. Surprisingly, minimizing paper defects could reduce the break rate by only 0.05% (of 2.0%). This result also agrees well with the previous two pressroom results, as well as with the trial and analysis results discussed earlier. It is clear that many breaks, even at a 2-3% level, are caused by obvious human errors and/or tension system problems.

Therefore, the first step toward achieving the "below 1%" break rate, such as already achieved in Japanese pressrooms, will be to optimize the tension control system and the press room operation.

This doesn't, of course, disregard the importance of a defect reduction program in paper mills. Among the macro-defects, core bursts and crepe wrinkles have been well known defects causing breaks [8]. These defects tend to occur in specific locations of jumbo reels and wound rolls, so that by knowing the roll numbers and locations of breaks within a wound roll we can diagnose the presence of these specific defects [8]. The relative contribution of these defects to the total number of breaks is, however, limited in today's pressrooms (e.g., see Fig. 3).

SHIVES

Among visible defects, shives may require special attention. From the early days of newsprint production, shives have been considered as the culprit for web breaks both in pressrooms and on paper machines [10-14]. Accordingly a body of information has been accumulated. The readers can find the earlier literature in reference [15].

Sears, Tyler and Dentzer [15] gave one of the most convincing pieces of evidence that shive-induced failures indeed dominate web breaks, although in an *experimental* setting. Paper webs were continuously unwound using an experimental web strainer, subjected to 0.3 to 0.4% strain. They found that a 98.5 % of the more than 3200 breaks were due to shives. Shives longer than 3 or 4 mm and having a thickness equal to a considerable fraction of the web thickness were the principal weak spots and contributed to web breaks. This work was followed up by Adams and Westlund using a pilot-scale winder and applying a similar range of web tension [16]. The results showed that the predominant cause was, again, shives which caused "70%" of the total breaks.

Shives are known to cause strength reduction, particularly after calendering where thick, hard shives, such as the shives from latewood fibres, are crushed under calender pressure creating cracks and cuts in the web [11, 17-19].

Although pilot-scale results [15, 16] convincingly showed shives as the main culprit for web breaks, there have been *no pressrooms records* that have shown such dramatic effect of shives on breaks. Even in the case of runnability in the winder and papermachine, a close re-examination of the old literature revealed that the shives effect can be statistically discernable, but the effect is very *weak* and normally buried in the effects of other factors, as the authors also noted [13, 14]. In addition, over the last 40 years, the shive content in mechanical printing grades have been dramatically reduced. The break frequency, however, didn't decrease by 98.5 % or 70% in North America, unlike the predictions from the pilot scale test results [15, 16]. Furthermore, the observation of shive-induced breaks is rather rare in pressrooms.

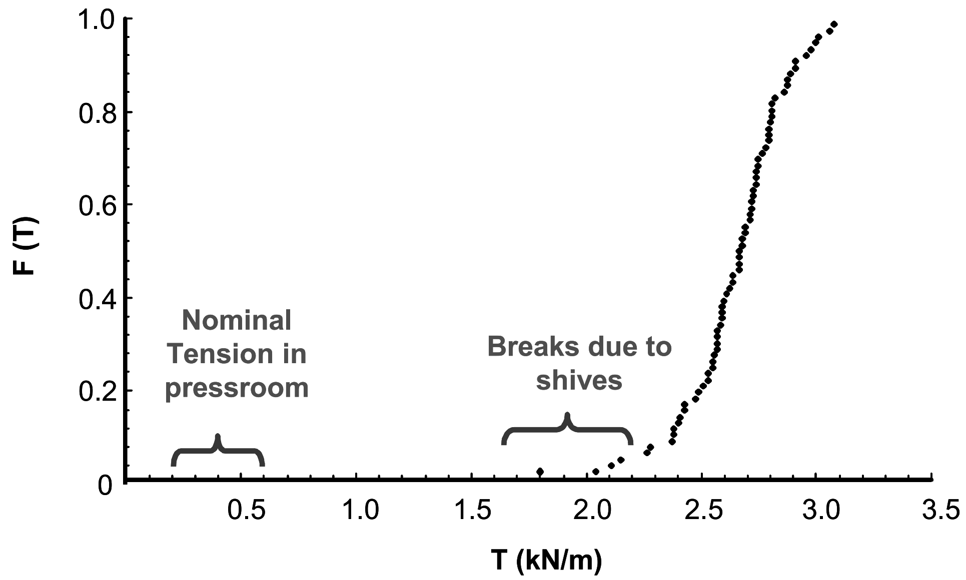

Figure. 6 Strength Distribution of Newsprint. F(T): Cumulative probability density function (the probability that paper breaks less than tension T), T: Tension per unit width

This large difference between the pilot-scale results and pressroom experience may be explained by considering the strength distribution of paper. Figure 6 shows a typical tensile strength distribution of newsprint, as expressed as a cumulative probability density function [6]. Tensile tests were conducted according to TAPPI Standards. In this specific example, the strength varied from about 1.7 kN/m to over 3.0 kN/m with its mean of about 2.6 kN/m. Shives-driven breaks were clearly observed for the specimens in the lower tail of the strength distribution curve. Therefore, if the tensile load is applied to newsprint in this specific tension range, it is expected that most of the breaks would be shive-driven. This is actually the tension range that was used in the pilot scale tests in the literature. However, as indicated in Fig. 6, the nominal tension applied in pressrooms is typically much lower than the tensions applied in the pilot scale web straining tests. Therefore, the probability that tension hits the range where the shive-driven breaks dominate is still small in the actual pressroom situation. In other words, in order to see the shives-driven failure constantly occur in pressrooms, the average tension needs to be raised to the level of the pilot scale tests.

Again this result doesn't undervalue shive-reduction efforts in the mills. A small amount of shives, of course, has long been known to have a serious impact on surface quality and printability.

WHY PAPER BREAKS

Tension variations have long been suspected as a potential cause of breaks in pressrooms. Experiences reported from paper mills and pressrooms suggest the presence of press-related tension issues. For example, paper rolls produced from the same paper machine performed, in one pressroom, at a level of a few percent break rate, and in the other pressroom, at more than 10%. In another case, the pressroom could reduce a break rate by more than 50% within a few months with the *same* paper supply. These observations point toward tension variations or some stress concentrations in the press systems as the main cause of web breaks.

One of the pioneering studies by Larsson [20] indicated that there are indeed large variations of tension in the printing press. Web tension varied from 200 N/m to 600 N/m at different sections of a press unit. The tension also varied as a function of time, particularly at roll changes (the paste period), and at emergency stops. Paper splices were another cause of tension variations. Subsequent work, with improved measurement technologies, also demonstrated the presence of tension variations in the press and in the cross-machine direction [21-25]. It was also shown that the magnitude of tension variations highly depends on individual presses and how they are operated.

Hristopulos and Uesaka [26] analysed a general web transport system, showing that the strain increment developed in each printing unit is not equal to the draw applied in the section, but is a complex function of the draw applied at each section, span length, and web speed. They found that at a *given draw variation*, the higher the speed and the shorter the span, the greater the tension variation. This explains why the tension variations are highly dependent on the press configuration and its operation. Web strain remains approximately constant in the free span, but changes abruptly at a point where the momentum is transferred, such as a printing nip, as shown in Figure 7. This implies that phenomena taking place in the printing nip are also important for understanding web breaks.

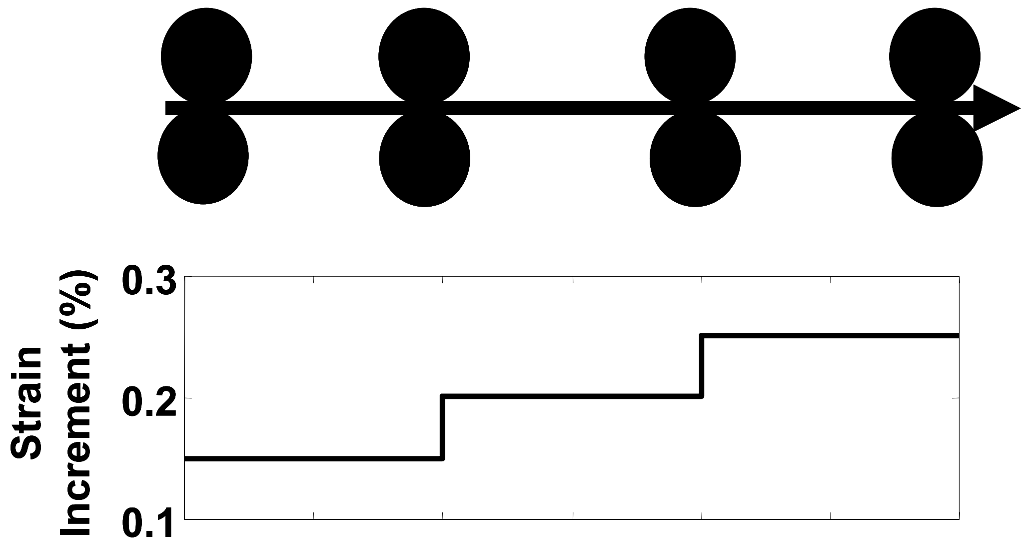

Figure 7 Web strain changes at printing nips.

The mechanics of rolling contact in the offset printing nips has been investigated by Wiberg [27] using a nonlinear finite element method. A deformable blanket under compression in the nip stretches the paper web both in the machine (MD) and cross machine directions (CD), and these strains vary in the nip region, depending on the boundary conditions and the material configurations of the roll cover. Figure 8 shows one of the predictions of the MD strain in the nip. The MD strain at the nip centre is plotted as a function of the position in the roll axis direction (CD) from the edge toward the centre. The strain in the centre was in the order of 0.1%, increasing toward the edge to 0.4%. This nip-induced strain is *added* to the strains already applied in the web transport system. The latter strains are also in the order of 0.1% or 0.2 %.

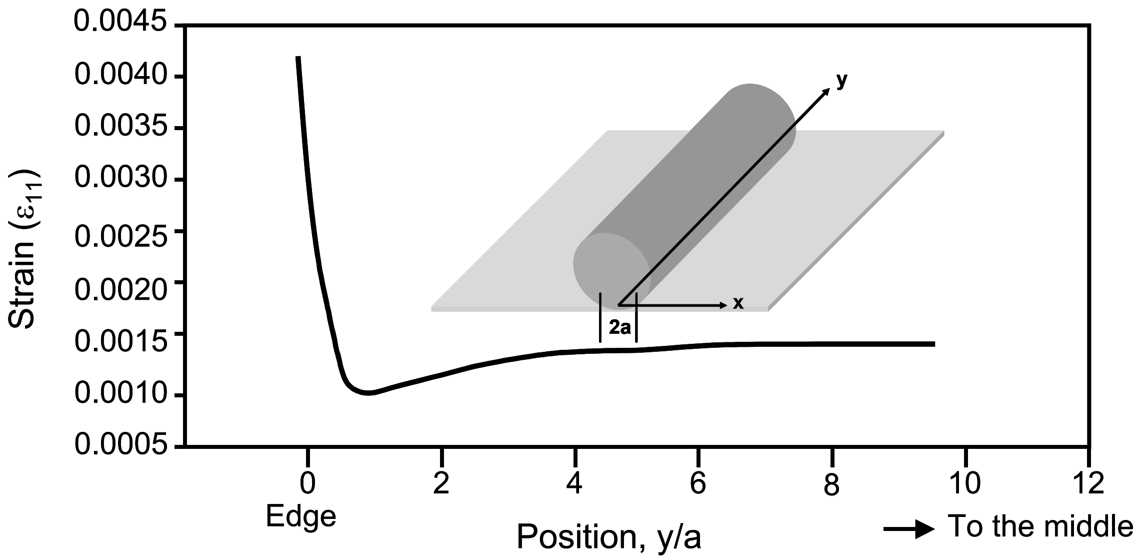

Figure 8 The distribution of the machine direction normal strain of paper along the roll axis direction. The strain is taken at the middle of the nip. y: Distance from the roll edge, a: A half nip width

Therefore, the paper web is subjected to a very significant strain in the printing nip, due to roll compression, together with the strain created by the web transport system (draw). Figure 9 illustrates the strain variation in the printing nip.

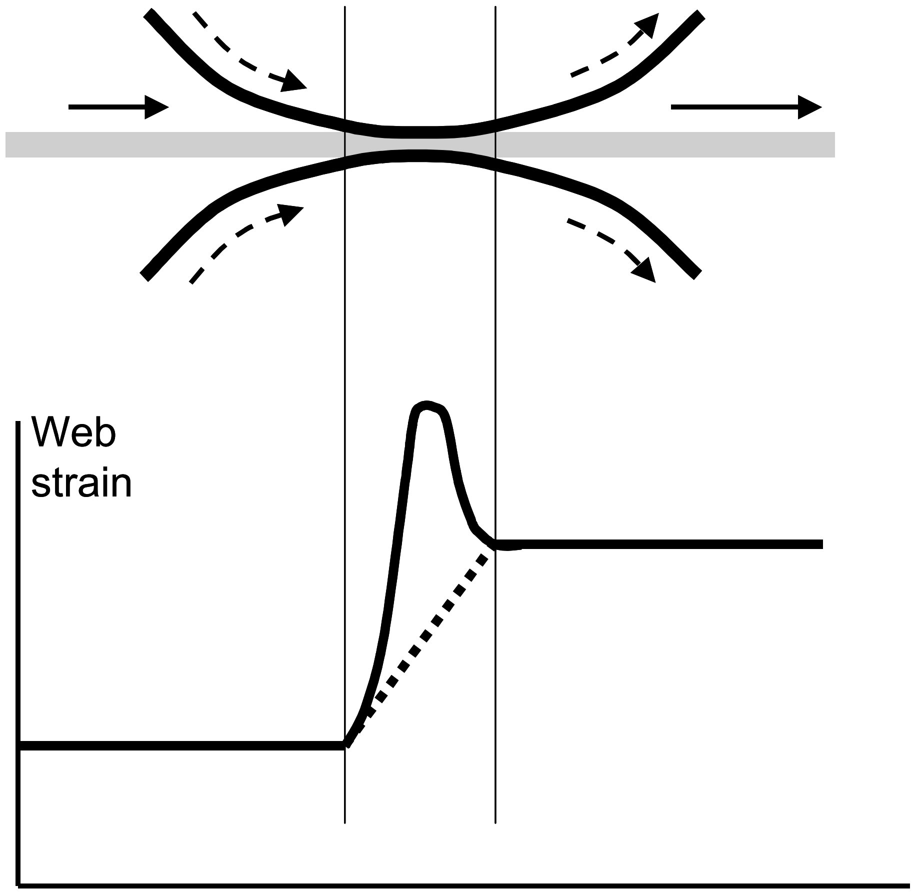

Figure 9 Change in web strain in the printing nip. When there is a difference in web speed before and after the nip, the web undergoes a strain change (dotted line). In addition the nip impression causes expansional strain in the paper. The total effect is represented by the solid line.

The next question is whether these tension variations *quantitatively* explain the break frequency observed in the pressroom. Uesaka and Ferahi derived an approximate expression for the break rate based on the weak-link scaling model when no macroscopic defects are present [6]. In the press, paper web undergoes tension variations as it moves from the unwind station to the folder through various printing nips. The probability that a certain portion of the web breaks is determined by the maximum tension or strain that the portion would experience while running in the entire press system. This maximum tension T_{max} can be expressed as

$$T_{\max} = T_0 + \Delta T_{\max} = T_0 + E_{MD} \cdot \Delta\varepsilon_{\max} \tag{3}$$

where T_0 is the set tension in the pressroom, and ΔT_{max} is the maximum of the deviation of tension from the set value, E_{MD} is the elastic modulus in the machine direction, and $\Delta\varepsilon_{max}$ is the maximum of the strain deviation. ΔT_{max} or $\Delta\varepsilon_{max}$ varies depending on when it is measured, such as the beginning of the roll (pasting), in the middle of the roll, and at the time of emergency stop. The break rate, as expressed in percentage, is then given by [6]

$$n_{100} = 100 \cdot \ln 2 \cdot \frac{A_{roll}}{A_{ref}} \cdot \left\langle \left(\frac{T_0}{T_{MD}} + \frac{\Delta\varepsilon_{\max}(L)}{\varepsilon_{MD}} \right)^m \right\rangle_L \qquad (4)$$

where A_{roll} is the total area of a paper roll, A_{ref} is the area of the specimen that is used for determining average strength T_{MD} and strength uniformity m, ε_{MD} is strain to failure (or elastic stretch, T_{MD}/E_{MD} [6]), and m is the Weibull modulus, representing the uniformity of the tensile strength distribution of the test specimen: the higher the m value, the more uniform the tensile strength. The operator $< >_L$ denotes averaging over the length of the roll L for the random variable $\Delta\varepsilon_{max}$.

Inspecting Equation (4), we find two sets of variables controlling pressroom breaks: One set is mainly for the pressroom variables, i.e., the set tension and the strain variations; the other is for the paper mechanical properties, i.e., tensile strength, strain to failure, and strength uniformity. (As will be discussed later, the strain variations $\Delta\varepsilon_{max}$ are also caused by paper.) Assuming that $\Delta\varepsilon_{max}$ follows a normal distribution with mean value equal to zero, and using experimentally determined values of paper mechanical properties, Equation (4) can be plotted as follows:

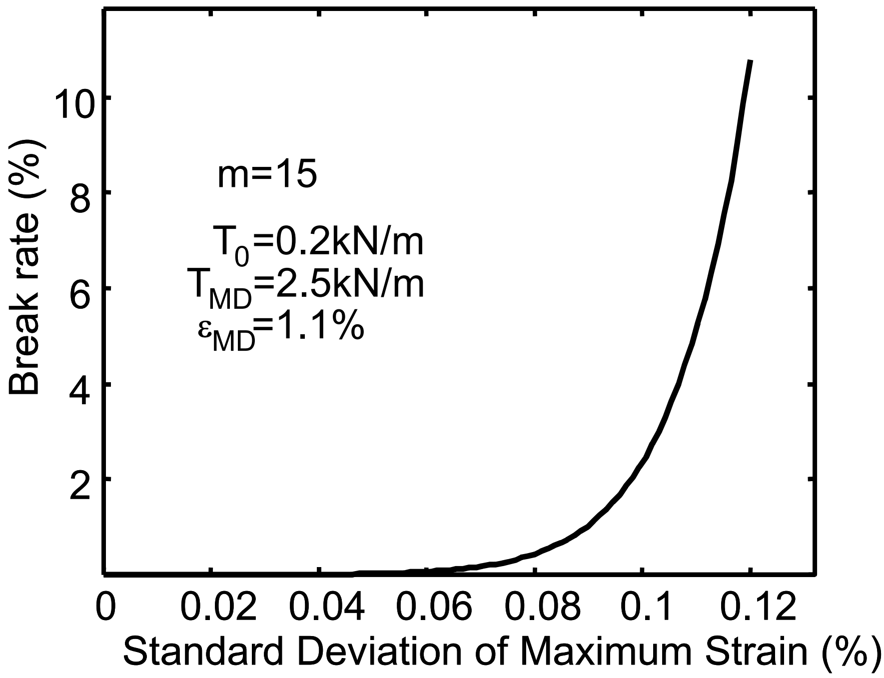

Figure 10 Break rate as a function of standard deviation of maximum strain deviation

As seen in Fig.10, when there is no deviation of tension from the set value, i.e., the standard deviation of $\Delta\varepsilon_{max}$ = 0, the break rate is virtually zero. However, as the strain variation increases, exceeding a standard deviation of 0.08%, breaks become visible and significant. It is interesting to note that the additional strain created in the nip, about 0.1%, as discussed earlier, already gives a very realistic level of break rate, even without considering the variations of tension due to draw variations.

Although more accurate information is still needed for tension variations (space and time), the quantitative predictions are already in the very realistic range of break frequency. This suggests that, as have long been suspected, the majority of breaks in pressrooms are "stochastic failure", caused by tension variations in the press systems and paper strength variations. This constitutes the "unknown" and "press-related" breaks in break cause statistics.

STRENGTH PROPERTIES THAT CONTROL BREAKS IN PRESSROOMS

In paper mills a number of strength properties are routinely measured, such as tensile, burst, tear, TEA, and sometimes fracture toughness. One of the important questions is what strength properties should be controlled to ensure the runnability. Surprisingly, very little data have been published showing the relationships between such strength properties and actual break frequencies in pressrooms.

According to Eq. (4), MD tensile strength, MD strain-to-failure, and the strength uniformity parameter (Weibull modulus) are the main paper factors controlling breaks in pressrooms. Figure 11 shows a sample calculation of the effect of MD tensile strength on break rate [28]. Increasing MD tensile strength certainly decreases break rate. It is, however, very difficult to confirm such relationship experimentally because of the large fluctuations of press conditions ($\Delta\varepsilon_{max}$), the high sensitivity of break rate to $\Delta\varepsilon_{max}$ (Figure 10), and the limited number of rolls available for trials (Fig. 1).

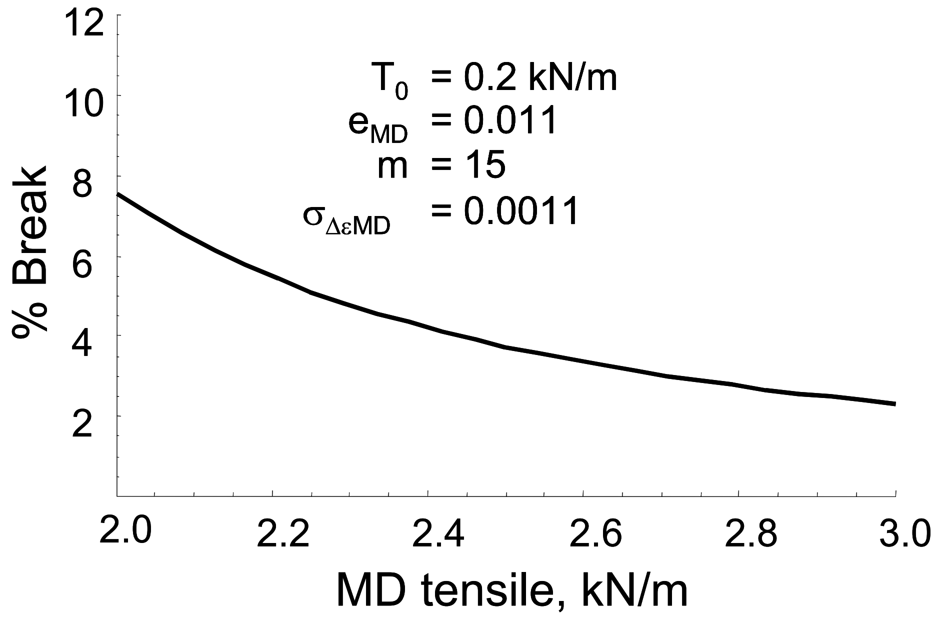

Figure 11 Prediction of the relationship between break rate and the machine direction tensile strength.Ferahi and Uesaka, and Deng and Uesaka [7, 28] collected break and strength property data from both pressrooms and paper mills to examine whether there is any relation between strength properties and break frequency. The total number of rolls examined for *each* pressroom was in the order of 20,000 to 50,000, and seven pressrooms were investigated. Because of the expected nonlinear relationships, a statistical "association" was

tested using χ^2 analyses [3], instead of the *correlation* analyses. That is, we tested whether the break rate *varies*, not necessarily linearly, with the variable in question.

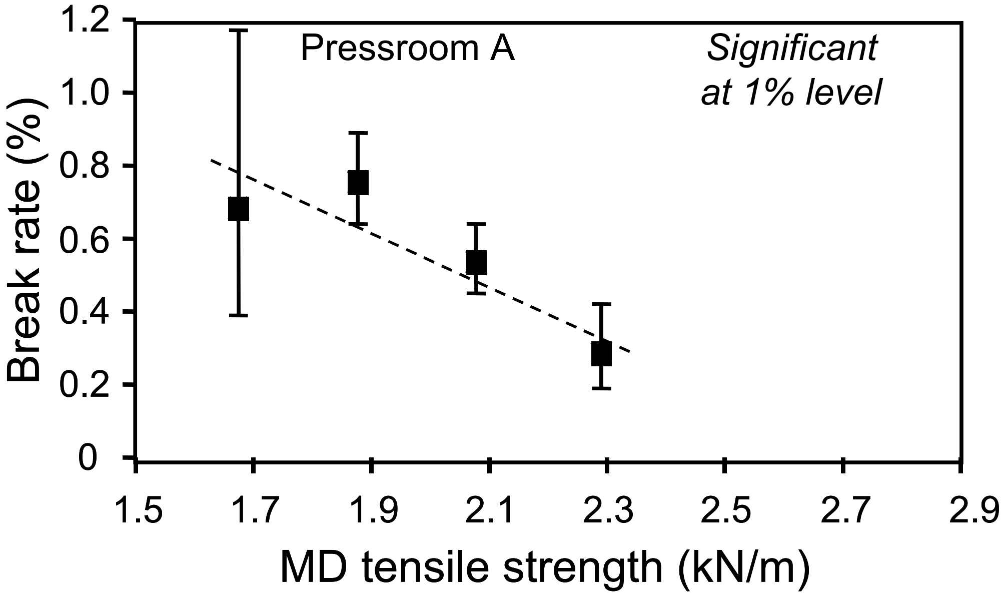

Figure 12 Break rate plotted against the machine direction tensile strength.

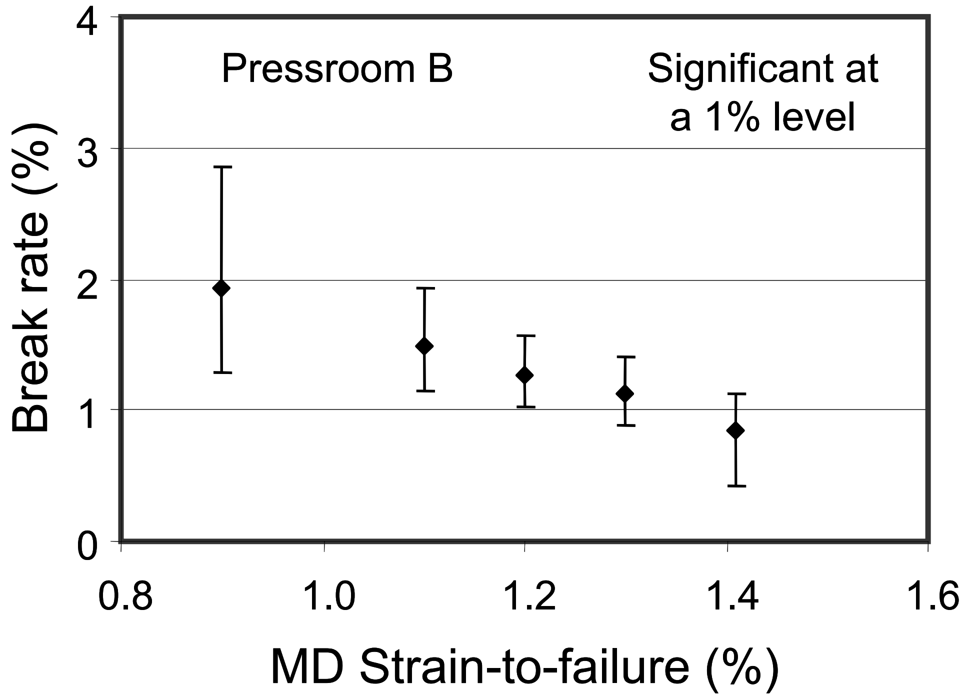

Figure 13 Break rate plotted against the machine direction strain-to-failure.

Figures 12 and 13 show the relations of MD tensile strength and MD strain-to-failure with break rate. With increasing tensile and strain-to-failure, the break rates indeed decreased. The statistical "associations" for these two cases were significant. Among the typical strength properties examined, including tensile, strain-to-failure, TEA, tear and burst, tensile strength predicted the break rate most consistently.

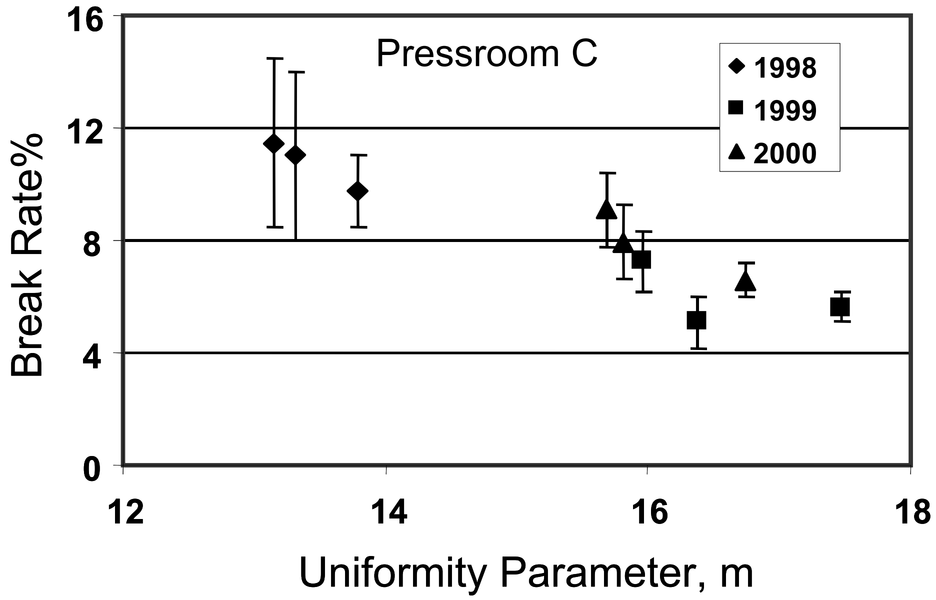

Figure 14 Break rate plotted against the strength uniformity parameter, m

Figure 14 shows a break rate vs. the strength uniformity parameter m (Weibull modulus). The uniformity parameter was determined at three positions (front, centre and back) of a North American newsprint machine, between 1998 and 2000. During the three years, average tensile strength remained constant. Break rate decreased as the strength uniformity is improved. These results in Figures 12 to 14 are consistent with the predictions from Eq. (4) [28].

Tear strength in the cross machine direction is often considered as a crucial parameter controlling runnability in pressrooms. Figure 15 shows a plot for the cross machine direction tear strength. As seen in the figure, there was no statistically significant "association" between the break rate and the tear strength. It was reported that although a significant association was sometimes found for some pressrooms, the predictability was not consistent compared to MD tensile strength: among the seven pressrooms examined, the association of tensile strength data was significant for all seven pressrooms, whereas the association of tear strength was significant for only four pressrooms [5, 7]. This result has an important implication to the use of kraft pulp, since the main motivation of adding kraft pulp to mechanical pulps is often for improving tear strength.

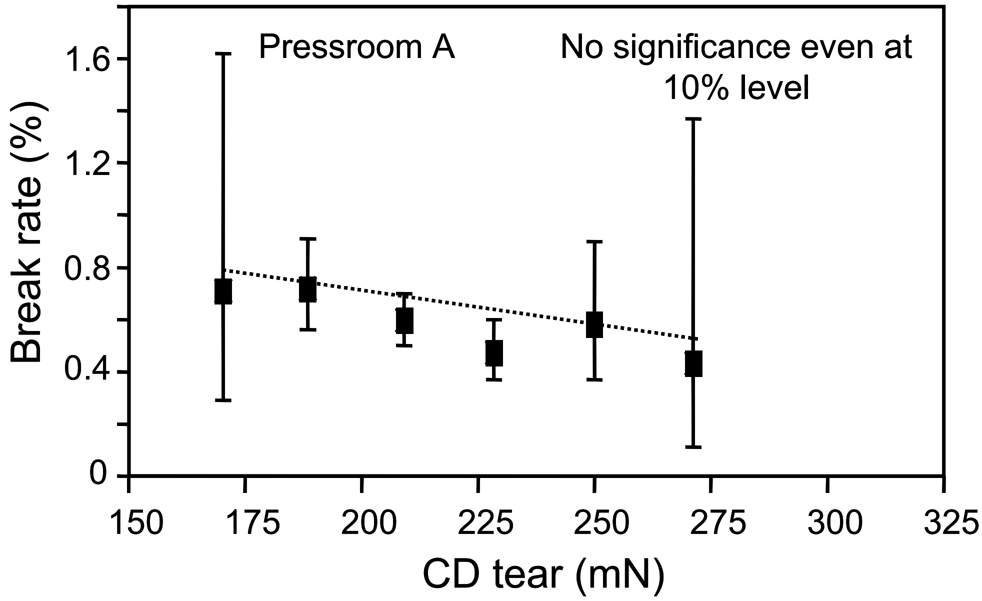

Figure 15 Break rate plotted against the cross machine direction tear strength.In earlier work by Page and Seth, fracture resistance, as one of the fracture toughness parameters, was shown to have a statistically significant correlation with break rate [2]: with increasing fracture resistance, break rate decreased. The data is based on the fifteen-month period records from one US pressroom. This observed correlation may be consistent with the previous results for tensile strength T_{MD} and strain-to-failure ε_{MD}, since fracture resistant was shown to be phenomenologically related to these two parameters through:

$$\text{Fracture resistance} = T_{MD}^{\alpha} \cdot \varepsilon_{MD}^{\beta} \quad (5)$$

where $\alpha = 0.6 - 0.7$ and $\beta = 0.5 - 0.6$ [29]. Figure 16 shows a plot between a combined parameter, $T_{MD} \cdot \varepsilon_{MD}^{0.5}$ and break rate. Again the break rate showed a statistically significant association with the combination of tensile strength and strain-to-failure, as expected.

Fracture toughness is a valid parameter when failure is driven by (“macro-“) cracks in paper web. (The “macro” scale refers to the length much larger than the typical disorder size in paper web, i.e., > 1-2 mm.) In the initial discussions of this review, it was shown that the majority of breaks in pressrooms are not necessarily driven by macro defects. Therefore, fracture toughness may not be the relevant parameter to pressroom breaks. However, the empirical relation Eq. (5) can make fracture toughness correlate with breaks in pressrooms as well.

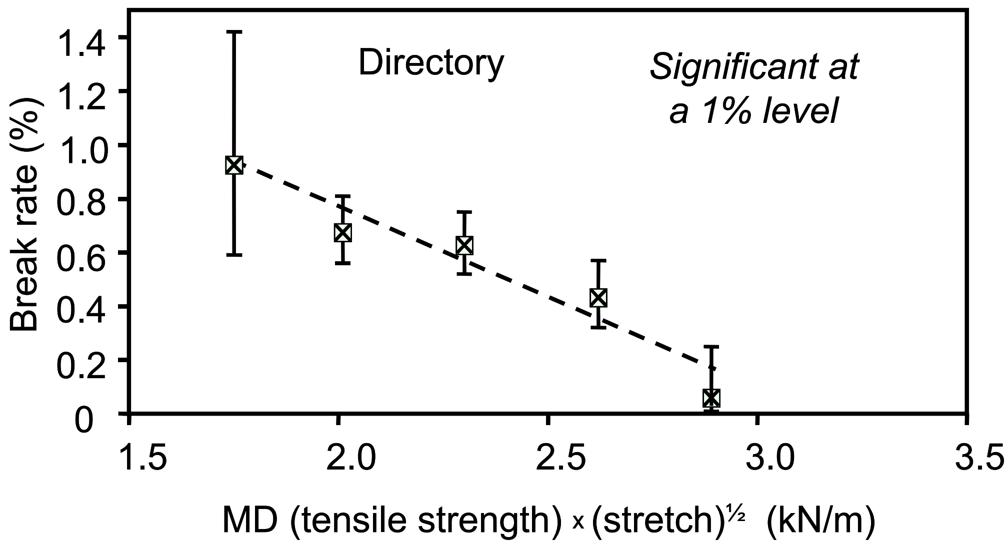

Figure 16 Break rate plotted against a combined parameter.TEA is often mentioned as a predictive parameter of web breaks since it is phenomenologically related to both tensile strength and strain to failure. The analyses of mill and pressroom data [5, 7] indeed showed that TEA has a good association with web breaks in pressrooms, although the consistency is not as high as the one for tensile strength.

In paper mills, multivariate analyses are often used to find, empirically, key paper factors controlling breaks in pressrooms. However, the analyses often yield contradictory results from one set of data to the other. There are several issues involved in the analyses. One is the highly non-linear nature of the relationships among the factors, as is clearly seen in Eq. (4). Therefore, a linear data structure, often assumed in the multivariate analyses, may not be valid in this type of problem, and can cause statistical artefacts. Secondly, because of the sensitivity to the press conditions and the *extreme statistics* (statistics of rare occasions) nature of break data, the analyses generally require an extremely large number of rolls (Figure 1), which are often an unrealistic number of rolls for most mill and press trials.

Dynamic properties are another important aspect of strength that needs to be considered in order to understand pressroom web breaks. As illustrated in Fig. 9, paper web is subjected to an almost step-change stretching at the printing nip. Assuming the strain increment at the nip is 0.2 % with 10m/s press speed and the nip zone is 1 cm, then we find the strain rate is about 200%/s, which is about 1,200 times higher than the strain rate for the standard tensile test. At this high rate of strain, paper will become more brittle and the strength statistics may be different from what we observe from the standard tests. To the author's knowledge there has been no information on the strength properties at this level of strain rate in the literature.

WEB TENSION NONUNIFORMITY

Web tension non-uniformity in the cross-machine direction has been discussed as one of the important causes of pressroom runnability, including wrinkling, misregistering, and web breaks. With the advent of equipment for measuring web tension non-uniformity, a considerable amount of knowledge has been accumulated over the last 20 years [22, 23, 30-37]. Recently, a direct comparison was made between the web tension profile measured on each roll and web breaks in a gravure press [38]. Figure 17 shows a relationship between break rate and a series of non-uniformity parameters of web tension. The 95% confidence intervals were added to the data by this reviewer based on the number of rolls reported.

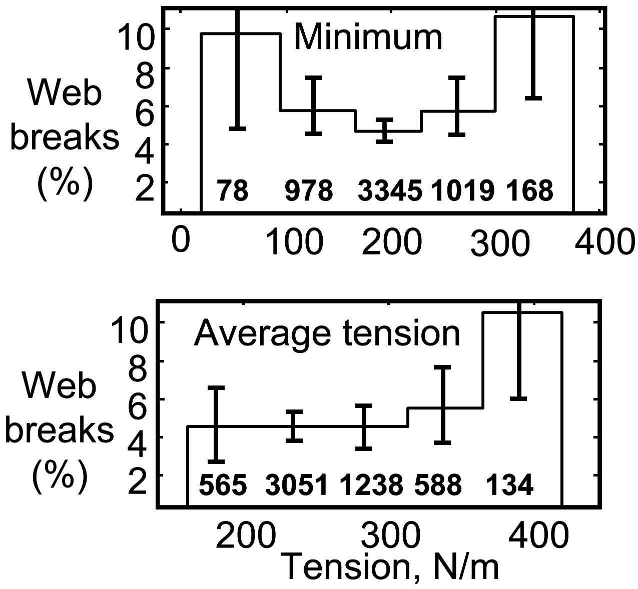

Figure 17 Effects of web tension nonuniformity on web breaks in pressroom.

The results showed that when the minimum level of tension, the maximum tension, or average tension are elevated to certain levels, breaks become visible in a statistically significant manner. Below certain limits, however, there was no statistically distinguishable difference in break rate. That is, an extreme level of web tension non-uniformity certainly increased the number of breaks. An additional effect of web tension non-uniformity is that press operators often raise average web tension to avoid wrinkling when they see the non-uniformity, causing a higher probability of breaks. There is also a large fluctuation of web tension at a roll change when rolls with different web tension profiles (often from different CD positions of paper machine) are unwound [38]. This will induce various web instability issues and motivate press operators to increase the average tension. Therefore, web tension non-uniformity is a combined issue of both pressroom and paper, causing a statistically significant effect on web break frequency.

EFFECTS OF ROLL QUALITY

Roll quality is a general term describing the absence of damage and wrinkles, as well as roll density uniformity inside the roll and the uniformity of the roll shape. Damage and wrinkles found in failed samples in pressrooms were extensively examined and classified by Frye [8], as noted earlier.

The roll density profile or wound-in-tension profile has often been speculated as a potential cause of tension variations in pressrooms. Papworth investigated the effects of roll density profile on tension variations in a pressroom by intentionally creating roll density changes by three methods [21]. One was by starting and stopping the operation of winder, causing a hump in the roll density profile in the radial direction. The second was by increasing calendaring pressure momentarily, creating a step change in roll density. The third was by making a step-wise change in winding tension. In all these three cases, no disturbances in the pressroom web tension were observed [21]. Although a bad roll density profile still has the potential to cause damage or degradation of paper, web tension was not affected by the profile. This is explained by considering the fact that the density profile reflects *internal stress* in paper, which is self-equilibrated within the roll, while web tension is an external boundary condition when the roll is unwound, which is completely controlled by the press system.

Out-of-roundness of paper rolls has been mentioned as a contributor to web breaks in pressrooms since early days [39]. Pressroom reports often note out-of-roundness as one cause of breaks. Out-of-roundness is known to create tension variations, and therefore it may contribute to web breaks in the mechanism discussed earlier. Hristopulos and Uesaka [26] analysed tension variations caused by out-of-roundness, and tried to quantify impacts on breaks. It was shown that the effects depend on web span length in the first section where the roll is unwound, and also on pre-existing strain variations in the press. The lower the span length and the higher the pre-existing strain variation, the higher the impact. Out-of-roundness of 6 mm or less, as defined as the difference in the maximum and minimum radius of the roll, was predicted not to create any immediate risk of breaks in most press situations. However, for a very short span (e.g., 1 m or less) and/or a large pre-existing strain variation (e.g., more than 0.1%) in the press, even such a modest out-of-roundness can cause significant breaks [26]. As for the cause of out-of-roundness, Papworth reported that, unlike the conventional view, roll hardness and out-of-roundness were poorly correlated, i.e., there is no strong indication that tightly-wound rolls have more resistance to deformation [40]. Clamp-truck handling had a significant impact on out-of-roundness; the first clamping action leaving a more permanent impression than the subsequent actions.

CONCLUSIONS

Web breaks are a rare phenomenon. It is difficult to perform cause-effect investigations in a traditional manner. Recent studies of web breaks, however, have started to shed light on the real nature of this problem with stochastic modeling, advanced measurement technologies, and massive data analyses. Major conclusions drawn from this review are as follows:

- Macroscopic defects can cause breaks. Those include wrinkles, holes, cuts, and bursts. However, the presence of such defects alone does not induce immediate breaks, unless the size of the defects is exceedingly large or the tension surges coincide with the occurrence of the defect. Therefore, *statistically*, defect-induced breaks constitute only a small portion of web breaks in today's pressrooms.

- The majority of web breaks are caused by variations of tension (in space and time) in the press system, combined with strength variations of paper web. Recent studies on tension variations, web/nip mechanics, and paper strength statistics have started to provide very realistic predictions of web breaks.

- Accordingly, the paper strength properties controlling the pressroom runnability are the machine direction tensile strength, strain-to-failure and the uniformity of tensile strength. Field data support this conclusion, and further demonstrate that tensile strength is the most consistent predictor of web breaks among the routinely measured strength properties of paper. Tear strength did not consistently predict web break frequency.

- The most effective way to reduce break rates by an order of magnitude is to reduce tension variations. Tension variations are caused by both pressroom operation and paper. Paper factors that have been identified as affecting tension variations are paper splices, out-of roundness, and web tension non-uniformity. Although the impacts of these factors vary with the pressroom operation and press configuration, there are statistically significant contributions to web breaks.

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