Prediction of Fold-Cracking Propensity through Physical Testing

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ABSTRACT

Fold cracking of linerboards is problematic in the converting process of box making. It is commonly exacerbated by the use of starch surface sizing, use of bleached kraft top liners or increased recycle content. It is desirable to have cracking preventable by selection of materials by testing prior to manufacture. This paper describes a series of tests that can predict fold cracking performance. The devised predictive tests are based on the principle that fold cracks are formed whenever surface fibers become strained beyond their yield points. Surface cracks, once formed, then propagate through the remainder of the cross section of the sheet. A modified tension test, and a modified Mullen burst test are configured to measure the yield strain in curved geometry thus preferentially straining the surface fibers. These new measurement techniques are shown to correlate with other more tedious fold crack testing such as the IPST crack angle test, MIT fold or AF&PA crack test and can be useful in linerboard production quality control.

INTRODUCTION

Cracking at folds causes pages to fall out of magazines or corners of boxes to split. The occurrence of fold cracking becomes more prevalent at low humidities and becomes worse when the ductility of surface fibers becomes diminished as may occur through application of starch coating or in the case of low freeness pulp being used in the top ply of multi-ply sheets. Increased use of recycled fibers also exacerbates the potential for cracking of sheets. An understanding of cracking mechanisms their measurement and control is desired for optimized production quality.

The basic mechanism for cracking is the higher stresses that occur on the surface fibers when a sheet is folded. These stresses more become greater for higher basis weights where the bending strains in the outer layers are directly proportional to the thickness *t* of the sheet for a given bending radius of curvature *R*. As depicted schematically in Figure 1, for a beam of modulus E_{MD} , length *L*, bent to a curvature *R*, the maximum stress σ_{MAX} and strain ε in the outermost layer can be shown [1] to be:

$$\sigma_{\max} = E_{MD}\frac{t}{2R}\left[1+k\frac{E_{MD}}{G_{MD-ZD}}\left(\frac{t}{L}\right)^2\right] \qquad (1)$$

$$\varepsilon = \frac{t}{2R}\left[1+k\frac{E_{MD}}{G_{MD-ZD}}\left(\frac{t}{L}\right)^2\right] \qquad (2)$$

where $G_{MD\text{-}ZD}$ is the shear modulus along he beam in the thickness direction and k is a constant related to the beam constraints. The terms contained in the square brackets in (1) and (2) account for shear of the beam in the direction of bending. The discussion is focused on MD which is more sensitive to cracking and surface stresses compared to the CD.

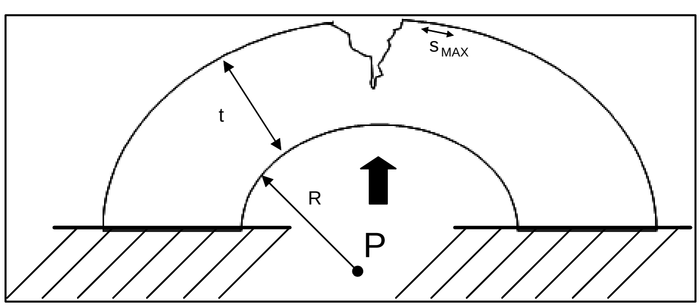

Figure 1. Schematic of fold cracking of a beam. Fissures start at the surface where strains are largest.

TESTING METHODS FOR CRACKING PREDICTION

It is highly desirable from economic considerations to know the likelihood of a product to crack before its is shipped to a customer for converting. This section describes several tests that have promise to predict cracking. Additionally, two new techniques are proposed based on the measurement of the stretch-to-break for a specimen tested in a curved configuration.

IPST Crack Angle Test

Previous work at IPST has established a correlation between the crack angle [2] and cracking propensity expressed as a percentage in a series of reports [3,4] which attempted to show relationships between various sheet properties and cracking. The developed cracking tester consists of two platens one of which remains fixed while the other is rotated. A sample strip is rigidly clamped across the platens with the intention to bend the sample until a visible fissure is observed across the CD. The edges of the anvils where the sample is bent are rounded to a radius of 0.010 inch.

Samples are spray painted flat black with solvent based paint for examination of crack angle. Test samples are conditioned at 20% RH for 48 hours prior to testing at 20% RH. The clamped samples are progressively folded the manual rotation of movable platen to the point were fibers underneath the blackened surface show through all along the fold line as may be seen in Figure 2 below. Bright illumination and low magnification assist with the determination of the onset of fissuring.

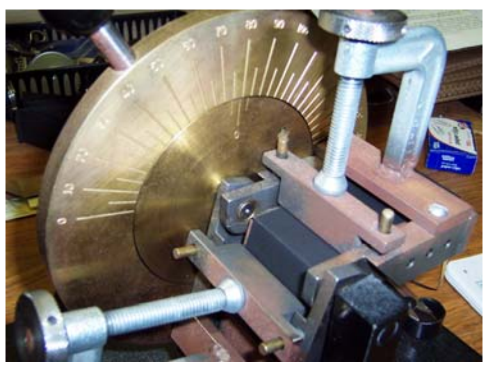

Figure 2. Photograph of the IPST crack angle tester, the sample is progressively folded to larger angles until the fibers underneath show through the blackened top surface.

The angle at which a crack is observed across the width of the sample is recorded, larger angles approaching 90 or greater indicate a larger resistance to cracking.

AF&PA Fold crack tester

Since paper is a viscoelastic material, the rate of deformation in testing is important since paper becomes stiffer at smaller time scales. The general rule is that paper strength properties decrease 7.5% for every decade increase in time scale. Accordingly, the AF&PA tester consists of a pair of motor driven rotating shafts which can be fitted with a pair of flat anvil metal scoring wheels with the gap set equal to the linerboard thickness shown in Figure 3. Linerboard samples are first folded loosely along the CD, then sent through the nip rotating at 400 fpm. Samples are visually examined under low magnification and the length of cracks divided by the length of fold examines is reported as the % cracking. The method is time consuming and detection of cracking is rather subjective. Painting the sample with solvent based flat black paint as in the IPST Crack Angle Test procedure can increase the contrast to detect the cracking more easily.

Figure 3. Use of the AF&PA (Honshu) fold crack tester. Loosely folded over samples are sent through a pre-set nip of rotating anvils and the resulting sample is sighted along the fold to calculate the % length of cracked sample.

Folded tensile stretch to break measurement

A new method in attempt to predict cracking is based on previous findings [5,6] that measurement of the strain to failure of specimens in a curved configuration is correlated with cracking. A nine inch strip of liner length along the MD is wrapped around the metal dowel, 5mm in diameter of a standard 1.5 inch wide Finch cup tissue wet strength (Tappi method T 456) test fixture secured in the movable crosshead clamp of a tensile tester. Finch or equivalent test fixtures are available from Thwing-Albert or Zwick suppliers. Strips are 15 mm wide and the distance from edge of the top clamp to the dowel pin is 4 inches as per standard T 494 tensile testing. The loop ends are secured by the top stationary clamp connected to the measuring load cell. This geometry of the sample around the dowel is similar to the scenario depicted in Figure 4. Samples are observed to usually break at the dowel where there is the greatest amount of surface strain. An Instron Model 1122 testing machine with Series IX software is used to measure the stretch to break along with TEA, tensile stiffness and tensile strength.

Figure 4. Strip sample looped around the Finch cup dowel to measure the stretch to break with the sample in curved geometry.

The dowel diameter and robustness of the support frame of the Finch cup fixture are not optimized for the measurement of heavier linerboards where the dowel supporting frame will flex somewhat which will add an offset to the measure of stretch strain. Nonetheless, the Finch device as is, is used here to demonstrate the proof-of-concept.

Stretch to break measurement using Mullen burst and TSO

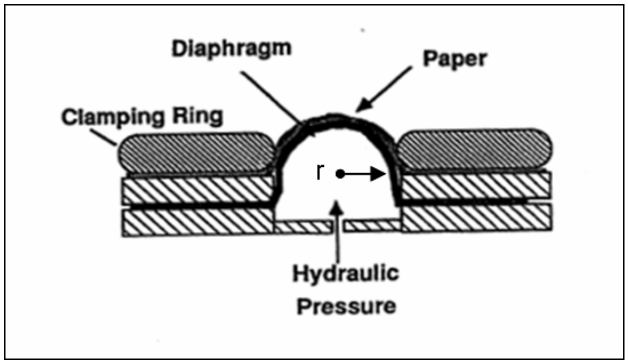

Figure 5. Mullen burst test also has the test specimen subjected to high strain in curved geometry.

Mechanical analysis with approximations of the pressure in the Mullen burst test relates the strain of the surface ε to the pressure P required to burst the specimen in the form:

$$\varepsilon \approx \left(\frac{rP}{T_{CD} + T_{MD}} \right)^2 \qquad (3)$$

where T_{MD} and T_{CD} are the MD and CD tensile strengths which are related to the tensile stiffnesses, r is the radius of rubber diaphragm orifice. Whitsitt [7] states that this result (3), originally derived by van den Akker in unpublished work, is generally accepted as a reasonable approximation for paper and predictions of paper bursting strength have been in good agreement with experiment. It is convenient to realize that the tensile stiffness can be easily measured using the L&W TSI instrument where its index outputs TSI-MD and TSI_CD, multiplied by the basis weight β, are the tensile stiffnesses thus:

$$T_{CD} \approx TSI\_CD \times \beta$$
$$T_{MD} \approx TSI\_MD \times \beta \qquad (4)$$

The correlation between $TSI\_CD \; x \; \beta$ or $TSI\_MD \; x \; \beta$ with tensile stiffness measured by mechanical testing S_b has been established by testing at IPST and found to be:

$$S_b = TSI \times \beta (0.571) + 41.8 \qquad (5)$$

where S_b is the tensile stiffness in units of N/mm measured by standard tensile testing and the *TSI* are in $(km/s)^2$. The above equations (3,4,5) suggest that the combinations of the measurements of Mullen burst pressure *P*, basis weight β, and ultrasonically measured specific stiffnesses *TSI* to measure the stretch-to-break for a test specimen in curved geometry. This stretch-to-break in turn, is expected to be an indication of cracking likelihood.

Folding endurance

This is a conventional Tappi method T 511 where a sample strip under tension is placed in a clamping folding head which oscillates folding the strip through 135º until the strip beaks at the fold. Similarly to the IPST Crack Angle Test, the bends are made over edges that have a radius of 0.015 inches. A larger number of folding cycles should indicate a greater resistance to cracking, however the method scope states that if the outer layers of papers greater than 0.25 mm thickness rupture during the first few folds, the test loses its significance. Certainly, if the surface cracks in a multi-layer sheet due to lack of surface fiber ductility when it is bent through 135 degrees, then the MIT fold test must progressively crack underlying layers till the specimen breaks under its moderate tension. The expectation on the current study here is that the number folds are directly related to the ductility of the surface fibers

EXPERIMENTAL

A sample set consisting of white top linerboard along with clay coated and virgin kraft linerboard was investigated using the above-described methods. The clay coated linerboard was part of a waterproofing study previously described [8], the white-top linerboards consist of beached kraft top layers which are prone to cracking, and the softwood unbleached kraft linerboard sample is expected to be least susceptible to cracking and so was included in the investigation for comparison. The data set is expected to be augmented by more samples of interest as they become available.

Table 1. Summary of relevant properties of the investigated sample set

	caliper	basis weight	TSI MD	TSI CD	crack angle	Burst	MIT folds
Sample ID	**microns**	**gm^2**	**(km/s)^2**	**(km/s)^2**	**degrees**	**kPa**	
A	250.6	178.4	9.59	4.5	89	582.9	47
B	250	178.4	9.9	5.8	73	470	62
C	279.4	202.9	10.8	4.34	83	710.3	54
D	248.9	178.3	10.1	4.84	85	581.8	51
E	282.7	204.8	10.91	4.38	79	770.3	64
clay coated 42#	318.5	230	8.61	4.16	74	793.4	121
virgin kraft 42#	295.9	203.6	10.78	5.83	63	801.4	134

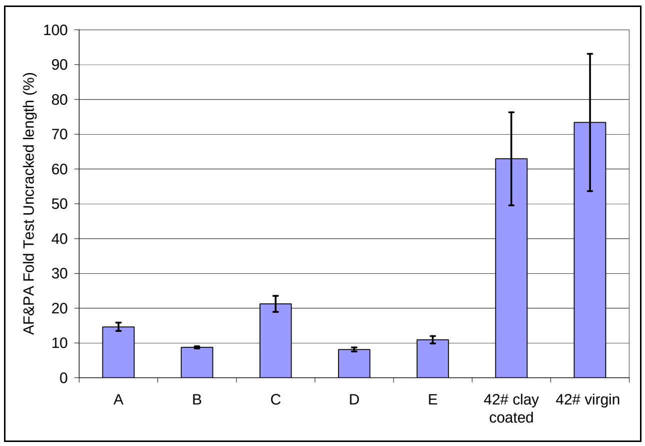

Figure 6. Intact fold length (%) measured using the AF&PA nip technique.

The AF&PA rotating nip cracking test method is taken to be as the most likely indicator of end-use cracking likelihood due to its high speed. Measurement of the uncracked length of the sample set required spray painting of the top sides to enhance contrast to measure the length of cracks. The results shown in Figure 6 show that the bleached white top samples are prone to cracking having uncracked intact lengths less than 20% of the entire fold length of 23 cm, the clay coated and virgin kraft samples are much less so. Although this method of cracking measurement is closest to end use, it is time consuming, somewhat subjective and not practical for regular quality control testing. Accordingly, other measurements were undertaken for comparison to determine whether a consistent picture of cracking likelihood arises.

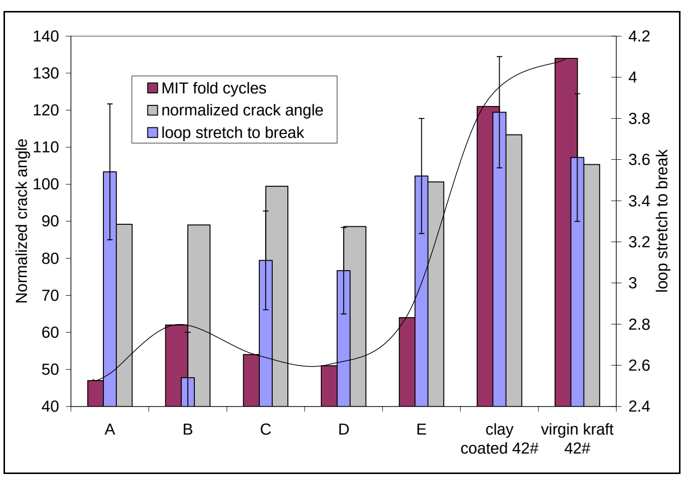

Figure 7. Fold cycles, crack angle and loop stretch

Figure 7 plots the fold cycles to break, normalized crack angle and loop stretch to break. The IPST Crack Angle is normalized with respect to caliper to have a better qualitative agreement with other measurements. Comparison of Figure 7 with 6 shows qualitative agreement in the general trend of cracking.

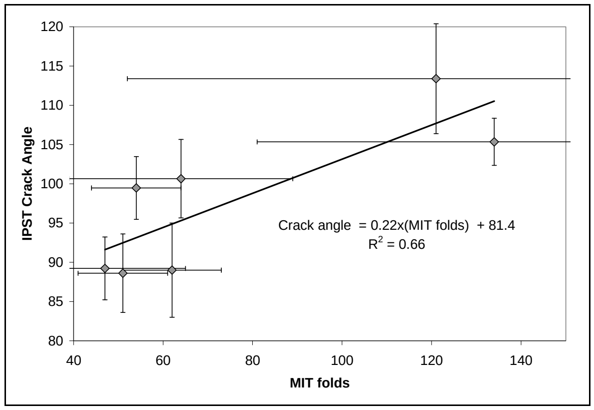

Figure 8. IPST crack angle versus MIT folds for the sample set.

However, crack angle measurements are not widely available since the equipment is not commercialized. However, MIT fold testers are commonly available as test instruments. A comparison of IPST Crack Angle with MIT folds in Figure 8 shows a fair correlation, note that the variation in MIT folds is 33% compared to about 6% for crack angle despite that crack angle relies on the visual subjective evaluation of the onset of cracking as the tester angle is progressively manually advanced.

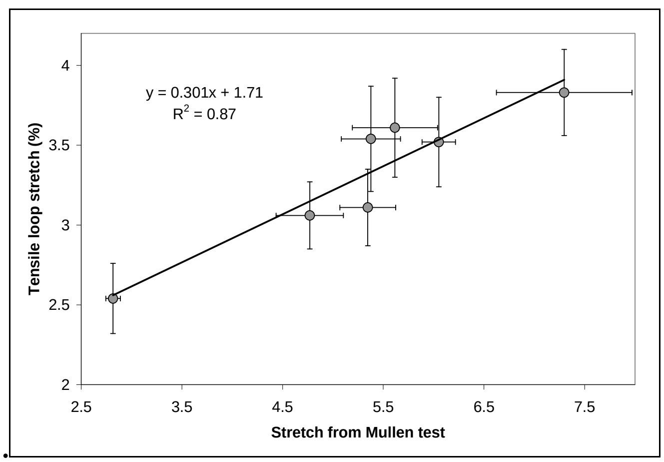

Figure 9. Comparison of tensile loop stretch and stretch form Mullen and TSO measurements

The tensile loop stretch-to-break correlated well (Figure 9) with stretch to break calculated from the combination of Mullen burst, basis weight and ultrasonic TSO. The stretch to break from Mullen burst pressure P is simply calculated as $\{P/(TSI\_CD + TSI\_MD) \times \beta\}^2$ x 100 which for simplicity ignores constants and unit conversions, using the units shown in Table 1 to produce relative values that are similar in magnitude as the stretch obtained from the tensile loop test. Both measurement techniques for curved sample configuration tensile stretch-to-break are comparatively convenient compared to IPST Crack Angle or the AF&PA test.

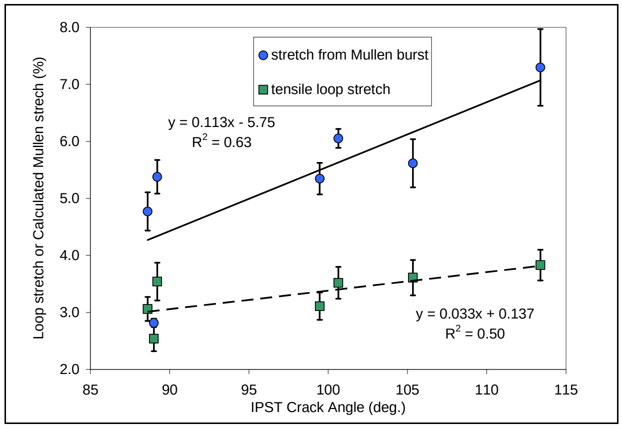

Figure 10. Comparison of curved geometry stretch to break measurements with IPST Crack angle.

The stretch measurements (tensile loop and Mullen) are compared to the IPST Crack angle and show a reasonable correlation in Figure 10. Thus, stretch in curved geometry may be considered to be an indicator of the likelihood of crackling if the level of variability in the measurements is acceptable.

CONCLUSIONS

The objective of this investigation is to devise a method of conveniently assessing samples for fold cracking propensity. The IPST Crack Angle method measures the bending angle at which cracking starts but the angle should be normalized with respect to caliper to have results that agree with other measurements and expectations. Since fold cracking arises from surface stresses that arise from sheet bending, measurement of the stretch to break is considered and shown to correlate with other measures of fold cracking. The preference for routine quality control is to devise a quick method using existing instruments to test samples for potential fold cracking problems. Specifically, the combined measurements of Mullen burst pressure, sample basis weight, and specific stiffness by the TSO instrument are shown to have good potential for automated in-line measurement implementation as the modules for theses test are commonly available. Alternatively, for lab measurements, the loop tensile test is an easy adaptation of the standard elongation testing machine test which simply requires recording the stretch to break of a sample looped around a dowel.

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