Tests for Z-Direction fiber orientation

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ABSTRACT

Fibers that acquire a Z-direction tilt in the forming process help bond adjacent strata of the paper sheet, increasing Z-direction shear and other properties. For certain tests, this manifests itself as a test difference upon 180° in-plane rotation of the sheet. Seven of eight different paper grades ranging in grammage from 73 to 268 g/m^2 were found to show this difference for Scott internal bond tests, directional brightness tests, or both. Directional effects were compared using an extensional and a shear metric. One-third of comparisons showed significant directional effects at the 75–100% confidence level, including roughly equal numbers of Scott bond and brightness comparisons. However, the two tests did not reinforce each other strongly; agreement regarding directional effects occurred in only 60% of comparisons. The number of significant effects in the cross-machine direction matched those in the machine direction (MD), suggesting a more complex model may he needed. The best support for the fiber-tilt model was in the case of MD Scott-internal-bond testing.

KEYWORDS

Fiber tilt, grain, Z-direction, test directionality, running direction, extensional, shear, Scott internal bond, brightness, tape pull, fiber pull, Student's *t*-test, confidence, significance, toward headbox, toward reel, Fourdrinier, rush, drag

INTRODUCTION

At the 2006 Progress in Paper Physics Seminar (Miami University, Ohio, USA), the subject of paper property differences in the two machine directions arose. either in presentations or in questions after presentations. MacGregor has studied the issue extensively, primarily using a tape pull test [1], and was interested to know if Scott-internal-bond testing showed any differences when directionality was changed by 180°. I'Anson and Sampson discussed the interaction of pencil with paper [2] and noted that some artists claim to be able to differentiate the two machine directions by the feel of the pencil on the paper.

The common model suggesting differences in paper properties in the two machine directions is that of fiber tilt [1]. Although paper is a highly stratified material, hydrodynamic forces in the forming process of a Fourdrinier machine are likely to cause one end of a generally machine-direction (MD) fiber to migrate a greater distance toward the wire side. Paper made under drag conditions is likely to have fibers with the ends closest to the reel lying closer to the wire side [1]. The tilt is reversed for papers made under rush conditions. Fibers tilted in either direction, even if only a few degrees, can intersect multiple fiber layers. By forming bonds within adjacent layers, they tie the layers together, increasing Z-direction properties [3]. If a convenient fiber tilt measurement could be developed, it would provide papermakers with a useful tool to help tune Z-direction mechanical properties.

The goal of this work is to quantify MD and anti-MD sensitivity for tests that probe the volume of a sheet of paper. It is not obvious how a test that fractures or optically probes paper internally reacts to different fiber-tilt directions. Demonstration of volume sensitivity would help to characterize fiber tilt more completely than can be done with surface tape pulls. Samples that show significant directional effects can be studied in detail to understand the forming mechanisms at work. Samples that do not show directional effects are interesting for the same reason.

EXPERIMENTAL

Tests

The tests that have been performed to date include Scott internal bond strength [4] and directional brightness [5] (henceforth, “Scott bond” and “brightness”). Both tests have a directional component. For Scott bond, the motion of a pendulum that impacts an L-shaped platen taped to the specimen defines direction. For brightness, direction is defined by the projection of an incident light beam on the plane of the sample. Since Scott bond is a destructive test, it is not possible to test an area of paper and retest the same area in the opposite MD direction. Brightness is a non-destructive test, and it is possible to do multiple tests on the same area of the sheet. This helps to eliminate noise associated with local variations, and may lead to more confident determination of directional effects.

Table 1. Samples for directional testing of Scott bond and brightness.

Sample	Grammage (g/m²)	Caliper (mm)	Density (kg/m³)
Linerboard 268	268	0.41	660
Cylinder board	265	0.37	726
Linerboard 214	214	0.33	645
Linerboard 209	209	0.30	688
Tagboard	126	0.18	705
Envelope	92	0.14	677
COPY	76	0.11	721
Z-fold printing	73	0.10	703

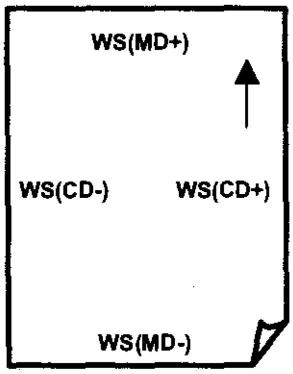

Figure 1. Directional notation for testing.

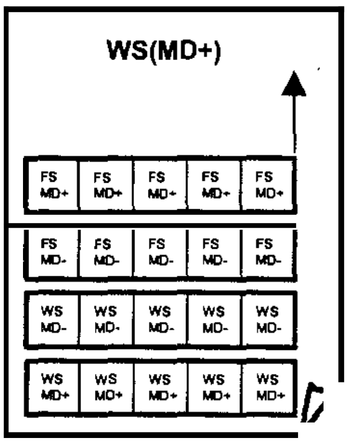

Figure 2. Specimens for MD Scott-bond testing, showing 1 of 11 such sheets in a sample.

Samples

Eight samples were selected to represent a wide range of grammage and commercial applications (Table 1). The samples were all taken from a roll, a package, or a stack of papers that had previously been slabbed from a roll. In each case all specimens were labeled with an arrow that pointed in the MD or anti-MD. It was not possible, nor was it necessary for present purposes, to know if the identifying arrow for our samples pointed to the headbox or the reel of the paper machine.

Figure 1 shows the labeling conventions used. An arrow pointed to the edge of sheet labeled MD+ and away from the edge labeled MD-. In an ideally known specimen, MD+ would be selected as the edge closest to the reel. The wire side was designated WS. We duplicated all MD testing with cross-machine direction (CD) testing. Note that when the paper was rotated about the MD axis to observe the felt side (FS), CD+ was on the left side of the sheet. All specimens within a sample were labeled consistently. Samples were pre-conditioned and subsequently conditioned and tested at TAPPI standard temperature and relative humidity[6].

Testing

The typical sample contained 50 consecutive sheets, spaced by 27.9 cm (11 in.) in the MD. Considering a sample as 10 units of 5 sheets each, one sheet in each unit was dedicated to MD Scott-bond testing, an adjacent sheet to CD Scott-bond testing, a third to brightness testing, and two were spares. Figure 2 shows how specimens were prepared for the MD Scott-bond test. Four strips were cut parallel to the CD. These allowed for all four combinations of felt side, wire side, MD+, and MD- testing. Five specimens of a given geometry were cut from each strip and tested sequentially. The testing was sensitive to short-term variation on a scale of 1–10 cm (spacing within a single sheet) and intermediate variation on a scale of 1–10 m (spacing within multiple sheets). To account for Scott-bond test failures, such as cohesive tape failure, an eleventh sheet was selected from among the spares and tested. The number of successful tests was at least 50.

Because brightness testing was non-destructive, it was possible to test all eight combinations of felt and wire side, MD+ and -, and CD+ and - on the same sheet and in similar proximity. Five locations were selected: the four comers and the center of the sheet. Because no brightness readings were

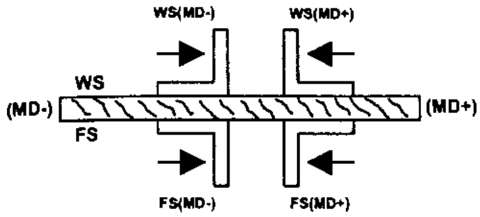

Figure 3. Scott-bond platen locations and pendulum directions for four tests used to characterize MD directionality of paper.

rejected as bad tests, $n = 50$ for all brightness tests of any given side, orientation, and direction. Because there were 16 (i.e., 2^4) combinations of test, side, orientation, and direction, approximately 800 measurements were needed to characterize each of the eight samples of Table 1.

Data Handling

Two metrics, the extensional metric and the shear metric, were developed to accurately characterize the data with regard to directionality but without regard to two-sided variation in directionality. Each metric does this by averaging data from the felt and wire sides of the sheet. This choice was in keeping with our focus on volume effects. It also helps to simplify the analysis and interpretation. Later, two-sided effects on directionality can be incorporated.

Extensional Metric. Figure 3 shows a schematic model of a sheet of paper, viewed edge-on, with four icons representing four MD Scott-bond tests that were performed. (In practice, the Scott-bond instrument is stationary and the paper must be rotated between tests to accommodate the four measurements shown.) The diagonal lines running through the paper thickness represent tilted fibers. As an example of the notation, the quantity WS_{MD+} represents the MD+ test result from the wire side. For MD testing, a comparison metric called the MD extensional metric, is given by

$$\Lambda_{MD} = \frac{[WS_{MD+} + FS_{MD+}]}{2} - \frac{[WS_{MD-} + FS_{MD-}]}{2} \quad (1)$$

Similarly, for the CD,

$$\Lambda_{CD} = \frac{[WS_{CD+} + FS_{CD+}]}{2} + \frac{[WS_{CD-} + FS_{CD-}]}{2} \quad (2)$$

When these metrics are statistically different from zero, there is an "extensional" effect, the term used by analogy with extensional tensile testing, where both sides of a paper strip move in unison under tension. If MD+ and MD- were displacements at each end of a tensile specimen, the extension would be written as Equation (1). We have Scott-bond or brightness values instead of displacements, but the notation is the same.

Each of the two bracketed [ ] terms on the right-hand sides of Equations (1) and (2) were represented by approximately 50 values. We calculated the average and the standard error of the values. If the absolute difference in the averages was greater than the sum of the standard errors, there was a strong likelihood that the difference represented a statistically significant effect. This was determined by the Student's t-test. The Student’s *t*-test provided a percentage confidence level that the difference represented by the metric was significantly different from zero; that is, 100% confidence means there definitely was a directional effect.

Shear Metric. With reference to Figure 3, other combinations of the four test values are possible. Direct comparison of the WS_{MD+} test result with the FS_{MD-} test result would probably be dominated by two-sidedness effects. In the absence of sidedness effects, WS_{MD+} and FS_{MD-} test results should, by reason of symmetry of the simple model, be identical. Similarly WS_{MD-} and FS_{MD+} test results should also be identical, but different from WS_{MD+} and FS_{MD-} owing to the opposite sense of the fiber tilt. This difference is the basis for the shear metric. The equations are

$$\Gamma_{MD} = \frac{[WS_{MD+} + FS_{MD-}]}{2} - \frac{[WS_{MD-} + FS_{MD+}]}{2} \quad (3)$$

$$\Gamma_{CD} = \frac{[WS_{CD+} + FS_{CD-}]}{2} - \frac{[WS_{MD-} + FS_{MD+}]}{2} \quad (4)$$

As with the extensional metric, two-sidedness effects are averaged within each of the bracketed terms on the right-hand sides of the equations.

Note that the extensional and shear metrics are made up of the same four MD or CD measurements. In that sense they contain no different information from each other. However, the way the measurements are combined is analogous to an extensional effect in the case of Equations (1) and (2) and to a shear effect in the case of Equations (3) and (4). This facilitates interpretation of the results.

Statistical Analysis

At this point, statistical analysis is preliminary. Application of the Student's t-test assumes that data are normal and that variability within a sheet of paper is the same as between sheets of paper. These assumptions are likely violated for some portion of the data. The t-test produces a significance value a that expresses the probability that the measured value of a metric could be due to random effects. We use $100(1-\alpha)\%$ to express the confidence that the value of the metric is truly different from zero. Outliers could result in an expression of high confidence that is not justified. Similarly, a small sample space could result in a low confidence that is not justified. These possibilities remain to be quantified.

RESULTS

Table 2 shows the t-test confidence that the metrics of Equations (1)-(4) are non-zero. Values above 75% confidence are shown in bold-underline. Twenty of 60 applications of the metrics showed significance at this level. The average of all confidence levels was 52%. Brightness testing was more optimistic about the significance of the MD results than was Scott-bond testing. The reverse was true in the CD. The results supported anecdotal evidence that test directionality matters; however, they raised a number of questions:

1. Why did the extensional (Λ) and shear (Γ) metrics show such a disparity in the case of MD Scott-bond testing and in no other cases?
2. Why did the CD metrics show significance at all, since it is difficult to justify a model in which tilted fibers lie 90° from the MD?
3. Why did brightness testing support the results of Scott-bond testing only about half the time? Should they not have correlated better?

Table 3 contains the average values of the terms used to calculate the metrics, for all the tests and all the samples. These averages and associated variances (not tabulated) are used by the t-test to determine the confidence levels shown in Table 2. Averages are of interest because they suggest possible relationships between tests and orientations. For example, CD brightness was higher than MD brightness in all samples. In the four heaviest and most opaque papers, the difference was significantly greater than in the four lightest, brightest samples (17% vs. 2%). This may reflect the tendency of the brightness signal to originate from near the surface of opaque papers. CD Scott bond was also higher in the heavier samples, by 4%, but the situation was reversed in the lighter grades.

The first and second terms making up the shear metric Γ and the extensional metric Λ were different in an absolute sense by an average 1.2% and 0.2% for Scott bond and brightness, respectively. Brightness showed as much or more significance than Scott bond testing because the standard deviations were much lower. The values of the metrics themselves were obtained as the

Table 2. Confidence that the value of the given metric was non-zero.

	Machine direction				Cross-machine direction			
	Scott bond		Brightness		Scott bond		Brightness	
Sample	Γ_{MD} (%)	Λ_{MD} (%)	Γ_{MD} (%)	Λ_{MD} (%)	Γ_{XD} (%)	Λ_{XD} (%)	Γ_{CD} (%)	Λ_{CD} (%)
Linerboard 268	**82**	28	33	67	67	**99**	**90**	21
Cylinder board	**95**	23			**85**	**80**		
Linerboard 214	**97**	4	**99**	**97**	1	17	71	50
Linerboard 209	6	19	**89**	**77**	18	32	41	58
Tagboard	15	2	**100**	**84**	**98**	**100**	**84**	**79**
Envelope	**88**	5	33	45	**99**	48	14	25
COPY	15	6	66	72	34	35	6	18
Z-fold printing	52	13	49	72	**96**	57	30	25
Averages	**56.2**	**12.5**	**66.9**	**73.5**	**62.3**	**58.3**	**48.0**	**39.4**

Table 3. Averages of Scott-bond and brightness test values used in the metric calculations.

Sample	Scott bond Γ_{MD} (J/m²) 1st term	2nd term	Λ_{MD} (J/m²) 1st term	2nd term	Brightness Γ_{MD} (%) 1st term	2nd term	Λ_{MD} (%) 1st term	2nd term
Linerboard 268	169.5	167.1	168.6	167.9	12.15	12.12	12.17	12.10
Cylinder board	213.5	220.9	216.9	218.1				
Linerboard 214	165.0	170.2	167.4	167.5	15.57	15.45	15.57	15.46
Linerboard 209	196.6	196.4	196.3	196.9	16.05	15.97	16.04	15.98
Tagboard	586.8	588.0	589.2	589.0	53.16	53.04	53.09	53.12
Envelope	447.8	434.5	441.4	440.9	75.25	75.31	75.25	75.32
COPY	203.6	203.0	202.9	202.6	83.43	83.35	83.36	83.44
Z-fold printing	372.0	368.4	369.9	370.6	71.45	71.53	71.55	71.43
	Γ_{CD} (J/m²)		Λ_{CD} (J/m²)		Γ_{CD} (%)		Λ_{CD} (%)	
Linerboard 268	175.1	173.3	177.2	172.1	14.08	14.19	14.13	14.14
Cylinder board	230.2	235.9	236.0	241.5				
Linerboard 214	168.7	168.7	168.6	169.0	18.17	18.23	18.18	18.22
Linerboard 209	199.2	199.9	198.7	199.9	18.73	18.77	18.72	18.78
Tagboard	548.6	563.4	550.0	565.5	54.29	54.32	54.29	54.32
Envelope	420.4	437.4	430.9	426.8	77.01	76.99	77.02	76.98
COPY	194.9	193.3	195.1	193.9	84.80	84.81	84.81	84.80
Z-fold printing	378.1	368.6	374.7	372.0	72.56	72.52	72.52	72.55

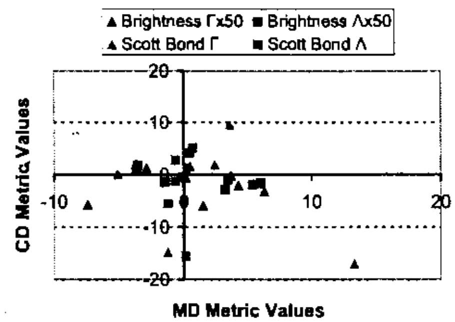

Figure 4, MD metrics vs. CD metrics for Scott-bond and brightness values (×50). each in the appropriate units.

difference between the first and second terms listed in Table 3 (plotted in Figure 4). The brightness metrics were multiplied by 50 to plot on the same scale as the Scott-bond metrics.

The high degree of scattering in Figure 4 shows the relative independence of MD and CD measurements. However, the MD and CD brightness values correlate with $r^2 = 0.40$. This suggests a common origin to some degree for the MD and CD results. MD and CD Scott-bond values correlate less well. Excluding an outlier contributed by envelope paper (the lowest right point in Figure 4), the correlation coefficient is 0.15. The best-fitting lines for brightness and Scott-bond data have oppositely signed slopes. CD metrics for Scott bond tend to increase as MD metrics increase, while the opposite is true for brightness. Most of the brightness data in Figure 4 are confined to quadrants 2 and 4. Most of the Scott-bond data are confined to quadrants 1 and 3.

ANALYSIS

MD vs. CD Effects

Our expectation of finding tilt effects restricted to the MD was not realized. As many significant extensional and shear effects were seen in the CD as in the MD. This prompted a more careful examination of tape-pull images of MacGregor [1]. These show that a dominant directional effect for tape-pull angles extends at least 45° to either side of the MD. This is well beyond the angles commonly associated with fiber-orientation misalignment. It suggests that cross-flows in the forming zone do not alone provide a mechanism for CD directionality. In the true CD, the tape pulls showed significant material removed in both + and - directions. The amount of material removed suggests the possibility of tilted fibers in both upward and downward tilt orientations.

The view of our results most consistent with the tape pulls is the following: Table 2 shows nearly equal numbers of MD and CD significances, hut the MD significances tend to favor the heavier grades tested. CD significances were more scattered and favored the lighter grades tested. Two of the linerboards showed MD significances bur no CD significances. The other linerboard and the cylinder board, also over 200 g/m^2, showed both MD and CD significances. It may be that the postulated MD fiber-tilt mechanism was always operative in the MD of heavier grades, but the CD tilt mechanism may or may not be operative, and was more likely to be operative in the lighter grades. Interestingly, the only grades that did not show any MD significances were the two lightest of those tested.

Could it be that an MD tilt mechanism favors heavy grades and a CD mechanism favors lighter grades? Supporting this idea was the observation from Figure 4 that the MD values of the metrics do not correlate well with the CD values. However, they did tend to have the same or opposite sign, depending on the test used. This indicated some commonality to the MD and CD mechanisms.

Scott Bond vs. Brightness

Sheets that showed a strong extensional or shear effect using one test were not likely to show it using the other. Only the CD testing of tagboard resulted in strong agreement for both tests and metrics. When Scott-bond and brightness confidence values were compared no combination of measured values that was correlated gave an r^2 value as high as 0.1. As a result, the question of which test gives the better indication of extensional and shear effects in paper becomes more relevant.

The average of the 10 highest confidence values for Scott bond from Table 2 was 94.0%, and the average for the 10 lowest was 8.4%. By contrast, the 10 highest and lowest confidences for brightness averaged 87.1% and 24.5%, respectively. The dynamic range of each test as expressed by the ratio of high to low averages was 11.2 for Scott bond and 3.6 for brightness. Brightness appears to be less discriminating of directional effects than Scott bond, and therefore less preferred.

Extensional vs. Shear

The single most striking observation to be made from Table 2 is the comparison between the extensional and shear metrics for MD Scott-bond testing. The three heaviest papers and envelope showed strong evidence for an MD shear effect. The same papers showed strong evidence against an MD extensional effect. No papers had a more significant extensional effect than shear effect. This result is reasonable because the Scott-bond test applies strong shear stresses to the sheet just prior to fracture initiation. It may be that in this MD test the simple model of tilted fibers in the MD-Z plane is best demonstrated. In all other tests, there were directional effects of more complicated and unknown origin than explained by the simple model in Figure 3, or even by the more sophisticated model of MacGregor [1].

CONCLUSIONS

Scott internal bond strength and directional brightness tests had significant differences when papers were tested in plus (+) and minus (–) MD and CD directions. The differences were not the same for each paper or for each test metric. Roughly 400 measurements per sample were used to obtain statistically significant results for both MD and CD testing.

A simple fiber-tilt model was consistent with results of MD Scott-bond testing. Prior to fracture initiation, the Scott-bond test creates shear stresses, and a metric emphasizing shear had strong significance for the heaviest papers tested. A metric emphasizing extensional forces did not show significant directional effects for MD Scott-bond testing. CD Scott-bond values and both MD and CD brightness values had no strong differentiation between shear and extensional metrics. Unexpectedly, CD test results had a similar number of directional effects as did MD test results. This suggests that a complete description of directional effects in papers is more complicated than can be explained by a simple fiber-tilt model.

FUTURE WORK

Comments in this work have been based on application of the Student's *t*-test without thorough investigation of the suitability of the data for this test. Other comparisons of results have been of a speculative nature to stimulate thought and deserve careful statistical analysis. This is now underway.

If directional test effects in paper can be characterized and related to projections of fibers in the Z-direction, it would be useful to have a simple test for Z-direction fiber orientation. The ability to measure in-plane fiber orientation angles has been a boon to the control of such problems as diagonal curl, stack lean, and twist warp [7]. If it were possible to measure fiber tilt angles through the thickness of paper, it would provide the papermaker a similar tool that could be used to help tune the Z-direction mechanical properties of the product. We are investigating possible refinements of optical tests now used for in-plane fiber orientation to determine if Z-direction fiber-orientation measurements are possible [8, 9]. Progress will be reported at the conference.

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