Tests for z-direction fibre orientation in paper

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SUMMARY

Fibres that acquire a z-direction tilt in the forming process help bond adjacent strata of the paper sheet, increasing z-direction shear. Fibre tilt manifests itself as a measurement difference when directionally sensitive tests are conducted “toward headbox” or “toward reel.” Seven of eight different paper grades ranging in grammage from 73 to 268 g/m² were found to show this difference for Scott-internal-bond tests, directional-brightness tests, or both. Test results were compared for 180° rotations in the machine direction and cross-machine direction. Three-eights of the rotations showed significant directional effects at the 75–100% confidence level, including roughly equal numbers of Scott bond and brightness tests. However, the two tests did not reinforce each other strongly, possibly because of depth variations in z-direction tilt. A model emphasizing tilt of MD fibres caused by rush or drag conditions was well supported by Scott-bond testing. Directional effects in CD testing appear to require a more complex model based on cross flows in the forming section.

KEYWORDS
Fibre tilt, grain, felting, z-direction, directionality, running direction, extension, shear, Scott internal bond, brightness, tape pull, fibre pull, ply-bond, sheet-splitting, Student’s t-test, confidence, significance, Fourdrinier, rush, drag, cross flows

INTRODUCTION

Paper property differences in the two machine directions (MD+ and MD-) often arise in connection with ply-bond strength and are attributed to the presence of tilted fibres (1-3). Aaltio has made the connection between tilted fibres and ply adhesion, and used x-ray diffraction to demonstrate a correlation (1). Zhao and Pelton have measured nearly 50% reduction in peel force with MD reversal and also attribute the effect to fibre tilt (2). MacGregor has used the amount of fibre pickup during directional tape pulls to characterize the effects of rush and drag on fibre tilt (3).

Although paper is a highly stratified material, hydrodynamic forces in the forming process of a Fourdrinier machine are likely to cause one end of an MD-oriented fibre to migrate a greater distance toward the wire side. Paper made under drag conditions is likely to have fibres with ends closest to the reel lying closer to the wire side (3). Tilt is reversed for papers made under rush conditions. Fibres with segments tilted only a few degrees can intersect multiple fibre layers. By forming bonds within adjacent layers, fibres tie the layers together, increasing z-direction properties (4). If a convenient fibre-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 directional sensitivity of traditional paper tests that potentially probe the volume of a sheet of paper. Demonstration of directional sensitivity of well-understood tests would help to characterize fibre 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, ultimately leading to control of fibre tilt.

EXPERIMENTAL

Tests

Tests that have been performed to date include Scott-internal-bond strength (5) and directional brightness (6) (henceforth, “Scott bond” and “brightness”). Both tests have a directional component. For Scott bond, the motion of a pendulum that strikes 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. Replicate samples in close physical proximity are required for this purpose.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. At the same time, the brightness test may not penetrate far beneath the surface of darker, heavier sheets. This makes it more representative of fibre tilt at the surface, similar to a tape-pull test.

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 labelled 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 labelling conventions used. An arrow pointed to the edge of a sheet labelled MD+ and away from the edge labelled 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. Samples were pre-conditioned and subsequently conditioned and tested at TAPPI standard temperature and relative humidity (7).

Testing
The testing program used the power of averaging to allow detection of small differences in the presence of significant variation. This was particularly necessary for Scott-bond testing. The Scott-bond test is notoriously variable, and the inclusion of multi-ply samples with many possible failure modes makes it even more so. Our hypothesis is that different failure modes respond in the same way if not the same degree to fibre segments having the same general tilt. If so, test results indicate an average material response to an average fibre tilt. If different failure modes respond to tilted fibres in opposite ways, or if fibre tilt exists but is distributed randomly, the likelihood is that no directional effect will be observed.

The typical sample contained 50 consecutive sheets, spaced by 27.9 cm (11 in.) in the MD. Considering a sample as 10 units of five 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 five replicates of 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 to 10 cm (spacing within a single sheet) and intermediate variation on a scale of 1 to 10 m (spacing within multiple sheets). To compensate 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 typically 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 close proximity. Five locations were selected: the four corners and the centre of the sheet. Because no brightness readings were 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 in Table 1.

Data Handling
The largest variation in test results comes from sheet two-sidedness as opposed to the directionality of interest. This suggests that each side’s test results should be considered separately or averaged with symmetrically equivalent results from the other side. The latter was selected for this work because it provided another opportunity for noise reduction through averaging.

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 sheet must be rotated and translated between tests to accommodate the four measurements shown.) The diagonal lines represent the simplest possible model for tilted fibre segments, for ease of illustration. Although no fibre is expected to run through the thickness of the sheet at a constant angle, it is assumed that fibre segments present a dominant, more-or-less uniform fibre tilt throughout the volume of possible Scott-bond failure. As an example of the notation in Figure 3, the quantity \( WS_{MD^+} \) represents the Scott-bond test result when the pendulum swings toward the MD+ direction and impacts a platen taped to the wire side.

There are two ways to average felt and wire-side measurements to remove two-sidedness from consideration. \( WS_{MD^+} \) and \( FS_{MD^-} \) can be averaged to provide a result.
for the symmetry where the Scott-bond action tries to “raise” the tilted fibres toward the vertical. $W_{MD}$ and $F_{MD}$ can then be averaged to provide a result for the symmetry where Scott-bond action tries to “flatten” the tilted fibres toward the horizontal. The difference in these two averages can then be calculated and used as an indirect measure of fibre tilt. Note that the Scott-bond tests being averaged would, if they could somehow be performed at the same time, resemble a novel test for interlaminar shear. Therefore, we refer to the differences between the averages as the shear metric for Scott-bond directionality. For tests in the MD, the shear metric is given by Equation [1],

$$\Gamma_{MD} = \frac{[W_{MD} + F_{MD}]}{[W_{MD} + F_{MD}]} \quad [1]$$

A parallel equation for $\Gamma_{CD}$ uses CD test results.

A second approach to averaging two-sided test differences considers the platens in Figure 3 that are directly opposite one another, as opposed to diagonally opposite. In this case, the Scott-bond action of one of the platens is to “raise” the tilted fibres while the other tries to “flatten” them. If the tilted fibre distribution is as shown in Figure 3, the averaging will tend to cancel the effects of the tilt. The two averages that can be calculated from the four measurements will be equal, or nearly so, and the Scott-bond directionality will vanish. Nevertheless, the following metric, Equation [2] can be calculated for tests in the MD:

$$\Lambda_{MD} = \frac{[W_{MD} + F_{MD}]}{[W_{MD} + F_{MD}]} \quad [2]$$

$\Lambda_{MD}$ and its partner $\Lambda_{CD}$ will be referred to as extensional metrics to differentiate them from the shear metrics of Equation [1]. While the extensional metrics may be small for the tilted-fibre model in Figure 3, they may be large for tilted-fibre slopes that vary in the $z$-direction. Table 2 lists possible relationships between values of $\Gamma$ and $\Lambda$ along with their interpretation. Although Equations [1] and [2] were presented with respect to Scott-bond, they may also be applied to directional brightness measurements.

### Statistical Analysis

The two bracketed terms in Equations [1] and [2] are each the sum of two test results from specimens taken in close proximity. If one or both of the test results is faulty, that pair is excluded from the analysis. Approximately 50 successful pairs for each term are averaged. The magnitude of the difference between averaged values is the value of the metric. Application of the Student’s $t$-test produces a significance value $\alpha$ 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.

### RESULTS

Table 3 shows the $t$-test confidence that the metrics of Equations [1] to [2] are non-zero. Values above $75\%$ confidence are shown in bold. Twenty-four of 64 applications of the metrics showed significance at this level. Only 10 of 64 showed significance at the $95\%$ level or higher.

The most noteworthy features of Table 3 are as follows:

1. MD Scott-bond is the only test showing significant directionality for the shear metric with no significant directionality for the extensional metric ($\Lambda = 0$ in 8 of 8 cases).

2. In all other testing, the confidence levels associated with the shear and extensional metrics tend to correlate. High or low confidence are common to both shear and extensional metrics in 20 of 24 comparisons, including 15 of 16 directional-brightness comparisons ($\Gamma = \Lambda$).

3. Half of the 32 comparisons show no metrics significantly different from 0 ($\Gamma = 0, \Lambda = 0$).

4. Only 1 of 32 comparisons (Linerboard 268) results in $\Gamma = 0, \Lambda \neq 0$.

Because fibre tilt may improve important structural paperboard mechanical properties, the three linerboard results are of particular interest. Linerboards 214 and 209 have similar MD metrics except for Scott-bond shear, $\Gamma_{MD}$ in Table 3. Linerboard 214 behaves as though there were a dominant MD fibre tilt in the Scott-bond fracture zone (Fig. 3). Linerboard 209 behaves as though there was no MD tilt in the fracture zone. Otherwise, Linerboards 209 and 214 share similar MD brightness metrics. Linerboard 268 is like 214 with respect to tilt in the fracture zone, but shares no other MD metrics in common with either Linerboard 214 or 209. These three distinct MD behaviours from the three linerboards, all potentially related to their mechanical performance, have motivated additional testing of the samples reported elsewhere (4).

Table 4 contains the grand-average values of the terms used to calculate the
Table 4.
Grand averages of Scott-bond and brightness test values and corresponding metrics.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Grand average, (J/m²)</th>
<th>Scott bond metrics, expressed as a % of the grand average</th>
<th>Brightness metrics, expressed as a % of the grand average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MD</td>
<td>CD</td>
<td>ΓMD</td>
</tr>
<tr>
<td>Linerboard 268</td>
<td>168.3</td>
<td>174.4</td>
<td>1.5%</td>
</tr>
<tr>
<td>Cylinder board</td>
<td>217.4</td>
<td>235.9</td>
<td>-3.4%</td>
</tr>
<tr>
<td>Linerboard 214</td>
<td>167.6</td>
<td>168.8</td>
<td>-2.9%</td>
</tr>
<tr>
<td>Linerboard 209</td>
<td>196.5</td>
<td>199.4</td>
<td>0.1%</td>
</tr>
<tr>
<td>Tagboard</td>
<td>588.3</td>
<td>556.9</td>
<td>-0.2%</td>
</tr>
<tr>
<td>Envelope</td>
<td>441.2</td>
<td>428.9</td>
<td>3.0%</td>
</tr>
<tr>
<td>Copy</td>
<td>203.0</td>
<td>194.3</td>
<td>0.3%</td>
</tr>
<tr>
<td>Z-fold printing</td>
<td>370.2</td>
<td>373.4</td>
<td>1.0%</td>
</tr>
</tbody>
</table>

This large difference probably reflects both increased anisotropy of the heavier samples and tendency of the brightness signal to come from the surface of dark papers. This could be important in explaining differences between brightness and Scott-bond metrics. By comparison, Scott bond was found to be 4% higher in the CD than in the MD for heavier samples, with the situation reversed for lighter grades. Scott-bond anisotropy is of the same order as the directional metrics when both are expressed as a percentage. It is tempting to think that tilted fibre differences in the MD and CD influence the Scott-bond anisotropy; however, there is no apparent correlation between metrics and anisotropy.

Several plots of the metrics are of interest. Figure 4 shows that for most brightness tests, shear and extensional metrics plot close to the 45° line, indicating $\Gamma \approx \Lambda$. Table 2 indicates that for this condition, the brightness test is non-directional for testing in Equations (1) and (2). Metrics are expressed as a percentage of the corresponding grand average. Values in bold underline are associated with statistically non-zero metrics. Averages are of interest because they suggest possible relationships between tests and orientations. As expected, CD brightness was higher than MD brightness in all samples (8). In the four heaviest and most opaque papers, the difference was significantly greater than in the four lightest, brightest samples (17% vs. 2%). This large difference probably reflects both increased anisotropy of the heavier samples and tendency of the brightness signal to come from the surface of dark papers. This could be important in explaining differences between brightness and Scott-bond metrics. By comparison, Scott bond was found to be 4% higher in the CD than in the MD for heavier samples, with the situation reversed for lighter grades. Scott-bond anisotropy is of the same order as the directional metrics when both are expressed as a percentage. It is tempting to think that tilted fibre differences in the MD and CD influence the Scott-bond anisotropy; however, there is no apparent correlation between metrics and anisotropy.

Several plots of the metrics are of interest. Figure 4 shows that for most brightness tests, shear and extensional metrics plot close to the 45° line, indicating $\Gamma \approx \Lambda$. Table 2 indicates that for this condition, the brightness test is non-directional for testing on one if not both sides of the sheet.

Figure 5 shows the comparable plot for Scott-bond data. In this case, five of eight CD test metrics show a tendency to follow the 45° line, indicating non-directional Scott-bond testing from one or both sides. MD test metrics plot horizontally, indicating a common fibre-tilt direction seen by tests from both sides, as suggested by Figure 3.

Figure 6 shows a plot of Scott-bond MD shear metrics compared with the corresponding brightness CD shear metrics. Excluding one outlier (Linerboard 268), there is a surprisingly good correlation considering the radically different nature of the two tests.

**ANALYSIS**

Analysis is focused on the tilt of fibres, its distribution through the sheet’s thickness, and its MD-CD anisotropy. The core
assumption is that non-zero test metrics indicate fibre tilt.

Scott-Bond Testing

Figure 3 presented a heuristic model of MD-oriented fibre segments tilted at a fixed angle with respect to the plane of the sheet. Consistent with the model, MD Scott-bond testing showed four instances in Table 3 where the shear metric ($\Gamma_{MD}$) was different from zero while the extensional metric ($\Lambda_{MD}$) was not. This observation, primarily in heavy boards, suggests that the four sheets have a dominant MD fibre-tilt direction within the Scott-bond fracture zone. The other four sheets either lack MD-tilted fibres or have them distributed in such a way that the average tilt is near zero.

The picture generated from Scott-bond testing in the CD is more complicated. Fibres in forming flows directed a few degrees from the MD can move perpendicular to the wire, or nearly so, as seen from the wire’s frame of reference. Fibres in these flows experience a rush condition with respect to their CD motion that can exceed the rush or a drag experienced with respect to their MD motion. A CD-oriented fibre in a cross flow can have more tilt than a neighbouring MD-oriented fibre not in a cross flow. A nearby CD fibre in an opposing cross flow can have comparable tilt of opposite sense. This leads to the possibility of highly tilted CD fibres with zero average tilt. These considerations can begin to be important for cross flows of only one-half degree. MacGregor has shown CD tape pulls with significant fibre pullout but without major difference from one CD direction to the other (3). Much information about forming conditions is needed to characterize the situation.

In Table 3, Z-fold Printing and Tagboard are interesting in showing a significant CD shear metric with an insignificant MD metric. This could be explained if the tilt effect from cross flows were greater than from rush or drag; for example, if the paper had considerable fibre misalignment but was made with low rush.

Linerboard 268, the outlier in Figure 6, was the only sample with an insignificant CD shear metric but a finite CD extensional metric. Table 2 indicates this condition is associated with opposite senses of fibre tilt on opposite sides of the sheet. It is possible in a multiply sheet that two plies associated with oppositely directed cross flows could produce this effect. The effect would be seen by testing in the CD. In the MD, fibre tilt might be controlled by rush or drag and be the same for both plies.

Tagboard and cylinderboard have comparable values for both CD shear and CD extensional metrics. In Figure 5, they plot as two points on the 45° line well away from the origin. Table 2 indicates that this condition implies test values that are non-directional on one side of the sheet but highly directional on the other. This could be another manifestation of the complex interaction between fibre tilts when cross flows are involved.

Scott-bond is regarded as a mid-plane delamination test (5), and this interpretation is consistent with results from MD testing. In CD testing, non-vanishing extensional metrics require explanation in terms of two-sided distributions of fibre tilt. This suggests the possibility that fracture zones are less localized during CD Scott-bond testing than during MD testing.

Directional Brightness Testing

Figure 6 shows a correlation between CD brightness and MD Scott-bond shear metrics. The brightness signal derives primarily from surface fibres that are perpendicular to the incident light beam. The light beam in a CD-brightness test tends to reflect forward at the gloss angle when it encounters surface fibres oriented in the CD. However, MD-oriented fibres tend to reflect the light vertically toward the brightness detector (8). For this reason, the correlation in Figure 6 is physically reasonable: both MD Scott-bond and CD brightness emphasize the contributions from MD-oriented fibres. The conventional interpretation of regression r-squared suggests that 70% of the variation in MD Scott-bond shear metric is accounted for by the corresponding CD brightness metric.

One factor limiting the correlation could be the different z-direction depths that are probed by the two tests. Directional-brightness testing is strongly influenced by the surface, especially in the case of dark and heavy sheets. Light that travels many fibre layers beneath the entry surface is less likely to return to that surface and contribute part of the brightness signal. In Table 3, 15 of 16 directional-brightness comparisons showed coincidences between shear and extensional metrics. For these cases, a dominant direction for fibre tilt is missing from one or both surfaces (Table 2). The heavier papers tested were found likely to have a dominant tilt angle on one side, but the three lightest papers did not have a dominant tilt angle when tested on either side.

MD Scott-bond testing of the same samples didn’t reveal any two-sidedness for heavy or light papers. This supports the interpretation that directional brightness is more a surface test than Scott bond. However, the correlation in Figure 6 also suggests that there were no major tilt differences between the depths at which the two tests measured. By comparison, MacGregor found that tape pulls of lightweight papers yielded greater fibre pull-out from one side than the other, but not vanishing in either case (3).

No correlation was observed between MD brightness and CD Scott-bond metrics. Both tests showed two-sidedness. All MD brightness tests indicated that at least one side of the sheet was non-directional; i.e., $\Gamma \approx A$. When CD Scott-bond testing agreed, a different side was generally non-directional. We conclude that fibre tilt in the CD is too complicated to provide brightness and Scott-bond results in confirmation of each other. Both tests provide numerous instances of significant test directionality, often for different samples. This could reflect the different depth-sensitivity of the brightness test coupled with high ply-bond variability of the CD Scott-bond test.

Scott Bond vs. Brightness

MD Scott-bond was the only test that provided readily interpretable results consistent with a simple model for fibre tilt in the MD (Fig. 3). Although CD brightness shear metrics correlated with MD Scott-bond shear metrics (Fig. 6), they did not select the same tests as having statistically significant non-zero values (Table 3). The average of the 10 highest confidence values for Scott bond was 93.8%, and the average for the 10 lowest was 8.4%. By contrast, the 10 highest and lowest confidences for brightness averaged 89.1% and 24.6%, 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. Part of the problem using brightness testing in this application is the uncertainty of the depth from which the signal is generated. In a dark and heavy sheet, the
CONCLUSIONS

HCSs with lower molecular weight interacted more effectively with pulp fibres with less adsorbing onto the fibre, leaving more degraded HCSs to interact with the dissolved and colloidal substances in the liquid phase, resulting in better DCS controlling performances. The degraded HCSs with pure configurations, i.e., the totally linear or the totally branched, seemed to have separate particular properties, in that the degraded linear HCS had very good performance in controlling microstickies, while the degraded branched HCS had very good performance in paper strengthening.

Table 2
Effect of degraded HCSs (0.2% odp) on paper strengths.

<table>
<thead>
<tr>
<th>HCS</th>
<th>Tensile index (N.m/g)</th>
<th>p value</th>
<th>Burst index (kPa.m²/g)</th>
<th>p value</th>
<th>Folding times Average</th>
<th>p value</th>
<th>Tearing index (mN.m²/g)</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>26.47</td>
<td>1.00</td>
<td>1.66</td>
<td>1.00</td>
<td>12</td>
<td>1.00</td>
<td>9.27</td>
<td>1.00</td>
</tr>
<tr>
<td>Degraded HCSs</td>
<td>27.05</td>
<td>0.75</td>
<td>1.68</td>
<td>0.86</td>
<td>8</td>
<td>0.09</td>
<td>8.45</td>
<td>0.07</td>
</tr>
<tr>
<td>Degraded HCSs</td>
<td>26.94</td>
<td>0.60</td>
<td>1.76</td>
<td>0.48</td>
<td>7</td>
<td>0.05</td>
<td>7.63</td>
<td>0</td>
</tr>
<tr>
<td>Degraded HCSs</td>
<td>33.28</td>
<td>0</td>
<td>1.66</td>
<td>0.98</td>
<td>11</td>
<td>0.70</td>
<td>9.08</td>
<td>0.64</td>
</tr>
</tbody>
</table>

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