Z-direction fiber orientation in paperboard

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ABSTRACT: This work evaluated the use of conventional tests to show beneficial attributes of z-direction fiber orientation (ZDFO) for structural paperboards. A survey of commercial linerboards indicated the presence of ZDFO in one material that had higher Taber stiffness, out-of-plane shear strength, directional dependence of Scott internal bond strength and directional brightness. Laboratory handsheets were made with a specialized procedure to produce ZDFO. Handsheets with ZDFO had higher out-of-plane shear strength than handsheets formed conventionally. Materials with high out-of-plane shear strength had greater bending stiffness and compressive strength because of their ability to resist shear deformations.

Application: Mills might be able to increase the strength of paper by redirecting more fibers in the z-direction, at little added materials cost.

Compressive strength greatly influences the performance of structural paperboard products. Papermakers generally try to improve this property by modifying pulp furnish, grammage, density, drying restraint, and in-plane fiber orientation. In this study, we provide insights for improvement of compressive strength by measurement and introduction of z-direction fiber orientation (ZDFO). ZDFO (equivalent to fiber felting, fiber tilt, or anfractuous fibers) describes the spatial orientation of fiber segments that have an out-of-plane spatial component. We believe that ZDFO can play an important role in improving compression behavior of structural paperboard without the expense of additional fiber.

ZDFO alters z-direction (ZD) properties and enhances compressive properties. Habeger and Whitsitt developed a compressive strength model that incorporates ZD properties [1]. Uesaka and Perkins [2] modeled compressive strength as an instability phenomenon that is strongly influenced by out-of-plane shear behavior. Buckling is the primary compression failure mode for low-density paperboard. Fellers [3] noted that ZDFO produced higher Scott internal bond strength, bending stiffness, and compressive strength, as well as lower density. ZDFO improves compressive strength by resisting shear dislocation, which occurs during compressive failure [4].

Studies have examined the effect of in-plane fiber orientation [5] and have shown the importance of fiber alignment for stiffness and strength improvement. In that work, preferential fiber alignment, rather than random orientation, produced higher fiber packing efficiency, which led to more inter-fiber bonding.

Shear forces within the headbox slice are responsible for layering in paperboard [6]. Shear has a stronger effect on long fibers than on short fibers, so that with current papermaking technology, fiber tilt might be produced more easily with short fibers than with long [7]. Blends of pulp fibers, flexible and inflexible, also might help to produce fiber tilt [8].

Finger and Majewski [9] used a tape pull test to demonstrate ZDFO and develop a basic model consisting of essentially straight fibers with tilt through the sheet thickness. Radvan [10] showed that paper and paperboard are primarily layered structures. Radvan's work suggested that ZDFO exists in poorly formed regions because of flocculation induced early in the forming section. Pulsating drainage has been used to create ZDFO [11] by forcing the fibers downward shortly after landing on the wire. Headbox turbulence [12] and foaming action on the wire [13] also have been used to produce fiber tilt. High-consistency forming increased felting as determined by higher Concora medium-test strength, compressive strength, and Scott internal-bond strength [14]. An additional benefit of ZDFO is improved drainage, as suggested by Radvan et al. [15]. Despite these efforts to produce felted structural paperboard, no commercial equipment has been specifically designed to create such a product.

Direct observation of ZDFO is problematic. Tape pull [9], microscopy, and sheet splitting [16] have been used to characterize the three-dimensional (3-D) structure of paper in two dimensions (2-D). Cellulose fibers are semicrystalline materials and therefore can be analyzed using X-ray diffraction methods [17,18]. However, early efforts were only marginally successful because they were not sensitive to kinking and curling of fibers, which are components of ZDFO. In the 1990s, development of powerful synchrotron X-ray sources allowed radiographs of paper samples at micron resolutions. Multiple radiographs of a sample taken at different angles can be combined to reconstruct its inner structure at a micron scale [19]. This technique, microtomography, is useful for characterizing internal void sizes in paper related to porosity. Interpretation of the results in terms of ZDFO is more difficult. Samuelsen et al. reported practically no cases of interconnections between fiber layers in a paper volume of 85 × 300 × 50 μm³ [20]. Hasuike et al. analyzed microscope images of paper cross sections separated by 8 μm to measure ZDFO in a comparable volume of 200³ μm³ [21]. Unfortunately, these approaches were limited to such small volumes that they cannot be used to characterize the practical importance of ZDFO to macroscopic mechanical properties.

In this work, we examined three commercial paperboards for evidence of ZDFO based on results from conventional tests. Because one linerboard indicated presence of tilt and had superior out-of-plane shear strength, we made laboratory handsheets with ZDFO to show that tilted fibers were the source of improved properties. The connection between ZDFO and conventional tests is indirect. However, large samples of paper were tested to give the results statistical validity. Use of conventional tests enables other laboratories to extend this research until such time that direct measurements of ZDFO over large volumes of paper are available. The tests we performed were Scott internal bond, tensile strength and stiffness, compressive and out-of-plane shear strengths, Taber stiffness, and directional brightness.

The distribution of ZDFO in terms of the number of tilted fiber segments and their angles are important parameters, but are not addressed in this exploratory work. For example, a straight 3 mm fiber would need approximately 7° of tilt to extend from felt-to-wire side in a paperboard of 200 g/m². Binding of three fiber layers via fiber tilt might be sufficient to beneficially influence the paperboard performance. This may be accomplished by a fiber segment approximately 0.5 mm long and 7° tilt.

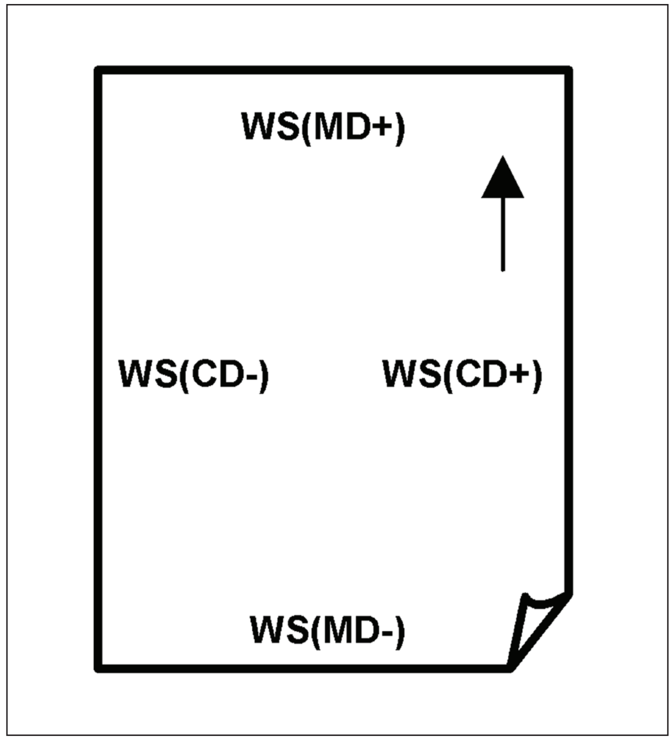
MATERIALS

We examined the properties of three commercial paperboards from earlier work for evidence of ZDFO [22]. Furnish, paper machine variables, and directionality, either toward the reel or toward the headbox, were not known. We defined one end of the material as the reel end, denoted as MD+ (**Fig. 1**). Specific knowledge of reel or headbox end was not needed; labeling was used to guarantee that specimens were tested in the desired direction. Cross-machine directionality (CD) is based on unintended cross flows on the wire and was described in a previous study [22]. We also made three types of laboratory handsheets for testing from the following materials:

1. 100% eucalyptus fiber (control).
2. 90% eucalyptus fiber, 10% rayon fiber (by weight).
3. 90% eucalyptus fiber, 10% carbon fiber (by weight)

METHODS

Fiber used to make the laboratory handsheets was Brazilian plantation-grown eucalyptus received in dry-lap form. The eucalyptus fiber was reconstituted in a 50 L laboratory pulper at 10% consistency, followed by dewatering to 30% consistency. The resulting Canadian standard freeness was 610 mL.



1. Notation for directionality of specimens. WS—wire side; FS—felt side (not shown). MD– is toward the headbox end of the machine direction (MD), and MD+ is toward the reel end. Cross-machine direction (CD) terms are defined similarly with respect to the front and back sides of the paper machine.

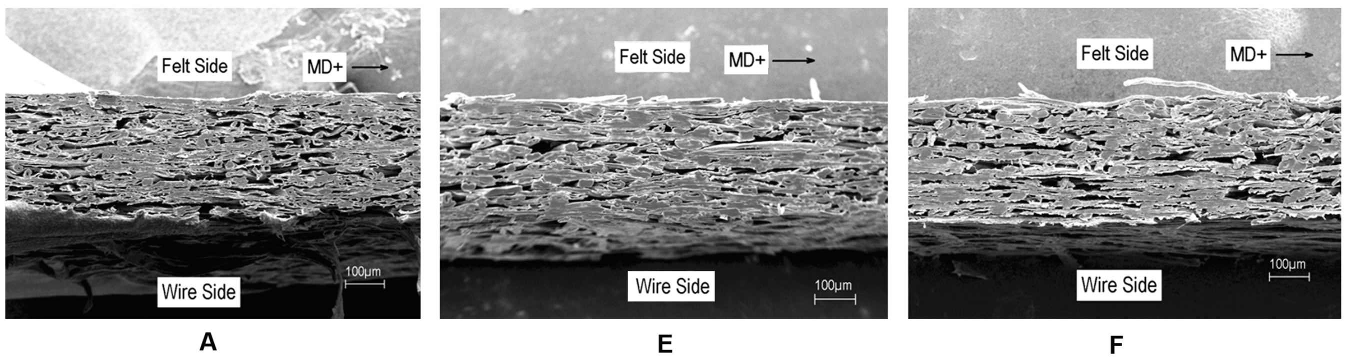
The weighted average fiber length was 0.57 mm. Either of two synthetic fibers (rayon or carbon) was added to the cellulose pulps, depending on the experiment. Rayon fibers were nominally 15 μm in diameter, 3 mm long, and had density in the range 1.480 to 1.540 kg/m³. Straight, stiff carbon fibers were nominally 7 μm in diameter, 3 mm long, and had a density of 1.800 kg/m³. Neither rayon nor carbon fibers bonded to the eucalyptus fibers. Rayon fibers had low bending stiffness and were easily intertwined with the eucalyptus fibers. They were used to show the effect of nonbonding, flexible fibers in the fiber network, in contrast with the effect of nonbonding, stiff carbon fibers used to produce 3-D structure.

All handsheets formed for the study were produced at a target grammage of 205 g/m². For each set of six handsheets, 24.6 g of ovendry material, either 100% eucalyptus fiber or 90% eucalyptus fiber and 10% synthetic fiber, was processed in 2 L of tap water for 5000 revolutions in a British disintegrator. The resulting stock was further diluted to 4.8 L and agitated until dispensed for each handsheet.

The handsheets were formed on a sheet mold modified according to TAPPI T 205 sp-02 "Forming handsheets for physical tests of pulp." The standard 40 cm deckle tube was replaced by an acrylic tube 102 cm in height. The suction normally provided by the standard TAPPI water leg was replaced using a ball valve and piping to a 90 L vacuum tank. Additionally, the shaft of the perforated stirrer was lengthened and the handle positioned such that when fully inserted, the

Materials	Grammage (g/m^2)	Caliper (mm)	Density (kg/m^3)
Linerboard A	268	0.41	660
Linerboard E	209	0.30	688
Linerboard F	214	0.33	645
Handsheet—control	224	0.40	560
Handsheet—10% rayon	223	0.42	530
Handsheet—10% carbon	211	0.44	480

I. Materials examined in this study.



2. Scanning electron microscope (SEM) cross-sectional images of each commercial linerboard. MD+ is toward the reel end.

stirrer stopped 3.8 cm above the forming wire. During the forming of a typical handsheet, the deckle tube was backfilled with 90 cm (17.9 L) of tap water and 800 mL of stock was added. The stirrer was moved through five complete up-and-down cycles and allowed to rest 3.8 cm above the forming wire. The ball valve was opened, allowing the water to drain to the vacuum tank maintained at 85 MPa (63.5 cm Hg). The sheet was then couched, pressed, and ring-dried according to TAPPI T 205 sp-02.

The longer tube was used to bring the initial forming consistency of a 205 g/m^2 handsheet into the same range as a standard TAPPI handsheet at 60 g/m^2 (0.02% consistency). At a lower consistency, the fibers are less likely to flocculate, allowing them to be repositioned by other means. The perforated stirrer was positioned just above the forming wire as a means to attempt to “push” the fibers into a vertical orientation just before depositing on the wire. The reduced cross-sectional area of the perforated stirrer was anticipated to increase the flow velocity and increase the momentum of fibers when hitting the wire. Likewise, increased vacuum was anticipated to increase the flow velocity.

Scott internal bond tests (Scott bond) were conducted according to TAPPI T 569 om-07 “Internal bond strength (Scott type),” with two exceptions. First, each specimen was identified by side and directionality, as in Fig. 1. Directionality was defined by the anvil of the test swinging toward the reel (MD+) or toward the headbox (MD–). Second, each test consisted of 50 replications instead of the normal five replications. The 25 mm × 25 mm specimen size helped justify the need for the additional replications. Scott bond failure depends on both local bond weakness and proximity to the top test surface. It would be possible to have no difference in the MD– and MD+ Scott bond tests and still have fiber tilt in other planes of the sheet. Occasionally, 55 replicates were performed, instead of 50, on 11 sheets to compensate for occasional bad tests where failure occurred in one of the tape bonds instead of within the specimen.

Directional brightness tests were conducted according to TAPPI T 452 om-08 “Brightness of pulp, paper and paperboard (directional reflectance at 457 nm),” with the same two exceptions as for Scott bond tests; directionality was noted and 50 replications were performed instead of five. The projection of the incident light beam on the specimen defined the direction; light traveling toward MD+ produced a MD+ test result. The 50 replications were completed as five replicates on each of 10 consecutive sheets pulled from the sample stack.

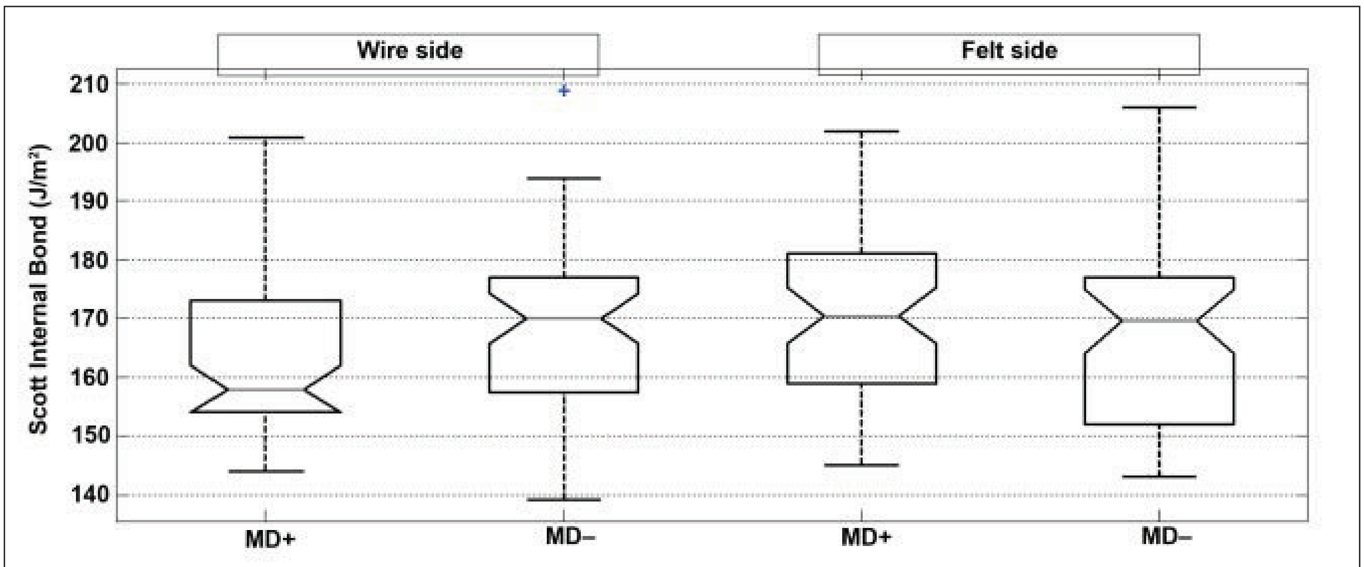
Out-of-plane shear tests were performed according to the double-notch shear (DNS) method developed by Nygårds et al. [23]. The shear lap was 2 mm in our tests, and notches were placed to the approximate middle of specimen caliper. The cuts predetermined a failure surface. As in the earlier discussion for Scott bond, fiber tilt may be present elsewhere, even if not found in the failure surface. ZDFO near center of cross-section is most beneficial for compressive strength and bending stiffness.

Tensile tests were conducted according to TAPPI T494 om-06 “Tensile properties of paper and paperboard (using constant rate of elongation apparatus).” For commercial linerboards, the tensile specimens were 25 mm wide × 100 mm long; for handsheets, the specimens were 15 mm wide × 100

		Linerboard		
Property		**A**	**E**	**F**
Tensile strength index (N·m/g)	MD[a]	53.6 (3.0)	68.5 (4.3)	66.3 (5.0)
	CD[b]	26.4 (1.4)	33.8 (1.5)	30.8 (1.2)
Tensile stiffness index (kN·m/g)	MD	3.99 (0.11)	4.58 (0.16)	4.84 (0.25)
	CD	3.02 (0.11)	2.95 (0.07)	3.25 (0.16)
Comprehensive strength index (N·m/g)	MD	29.8 (0.9)	33.7 (1.3)	33.8 (3.0)
	CD	18.7 (1.1)	19.9 (1.8)	20.1 (1.4)
Taber stiffness index (kN·m/g)	MD	5.54 (0.53)	7.67 (0.71)	7.95 (0.47)
	CD	2.44 (0.21)	3.43 (0.44)	3.03 (0.24)
DNS[c] index (N·m/g)	MD	9.11 (1.47)	8.32 (0.85)	11.83 (1.23)
	CD	5.23 (0.41)	5.28 (0.29)	5.49 (0.43)

[a]Machine direction. [b]Cross-machine direction. [c]Double-notch-shear.

II. Mean mechanical properties for each paperboard; standard deviations in parentheses.



3. Linerboard F Scott-Bond. MD– is toward the headbox and MD+ is toward the reel end.

mm long; and 10 replicates were performed for each case. Initial stiffness was calculated by fitting force-displacement data with a hyperbolic tangent model [24].

Short-span compression tests were conducted according to TAPPI T826 om-04 "Short span compressive strength of containerboard." Taber stiffness tests were conducted according to TAPPI T489 om-04 "Bending resistance (stiffness) of paper and paperboard (Taber-type tester in basic configuration)." Both compression and Taber tests had 10 replications per sample. Ultrasonic measurements were made by Sonisys using their 3D-UTI tester (Sonisys Corporation, Atlanta, GA) [25].

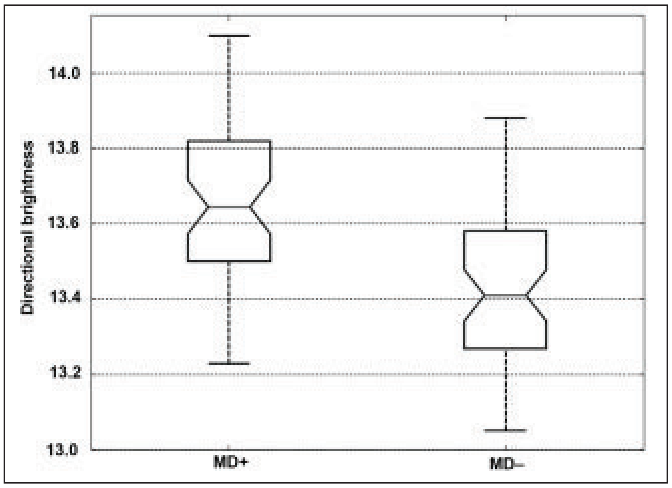
RESULTS AND DISCUSSION

Table I lists the physical properties of the commercial linerboards and the laboratory handsheets. The commercial linerboards were unbleached kraft, single-ply materials. **Figure 2** shows edgewise scanning electron microscope (SEM) photographs for each commercial linerboard. No ZDFO differences were evident.

Table II lists measured mechanical properties for each commercial linerboard in this work and provides some rationale for their selection. The general result of Table II is that linerboard F is superior to linerboards A and E in both MD and CD tests. Paperboards E and F are similar in strength and stiffness indices, while paperboard A is typically lowest. For Taber tests, samples E and F are quite similar and are stiffer than sample A, whereas for DNS tests sensitive to interlaminar shear strengths, sample F outperforms E and A. The three samples therefore display a broad range of mechanical perfor-

Paper	Mean Scott-Internal-Bond (J/m²)	Number of Tests
E	197.7	407
A	171.3	403
F	168.0	416
Minimum significant difference = 2.5 (J/m²)		

III. Tukey analysis of Scott-Bond tests.



4. Directional brightness for Linerboard F, wire side. MD– is toward the headbox and MD+ is toward the reel end.

Linerboard			
Measurements[a]	A	E	F
E_z (MPa)	75.69	47.96	57.84
E_{md} (GPa)	7.80	7.75	9.44
E_{cd} (GPa)	3.71	3.73	3.88
$G_{md\text{-}cd}$ (GPa)	2.10	2.13	2.26
$\nu_{md\text{-}cd}$	0.20	0.23	0.23
$\nu_{cd\text{-}md}$	0.44	0.50	0.60

[a]E is Young's modulus in the direction indicated by the subscript,
G the shear modulus in the plane of the sheet, and
ν the Poisson's ratio in the plane of the sheet.

IV. Ultrasonic measurements for each linerboard.

mance and are excellent candidates to study for possible existence of ZDFO.

Scott bond tests were used as an indicator of ZDFO in the three samples. Based on the general idea that ZDFO involves a tilt of fibers through the thickness, Scott bond tests of papers containing ZDFO should have different values when testing is "toward headbox" (MD–) or "toward reel" (MD+). When all Scott bond data are pooled, analysis of variation of the data showed statistically significant differences based on linerboard (A, E, or F) but not on direction or side. This result confirms that Scott bond does not have an inherent bias toward direction or side.

Based on a Tukey analysis of Scott bond (**Table III**), all three linerboards were statistically different from each other. Differences between linerboards A and F were small but significant.

Figure 3 is a boxplot of linerboard F Scott bond strength by side (felt or wire) and direction (MD+ or MD–). The centerline of the boxplot denotes the median value; upper and lower horizontal boundaries denote data quartiles; vertical whiskers denote the extent of the data; outliers are denoted by +; the notches represent a measure of uncertainty about the median for a box-to-box comparison (at the 5% significance level). Each test direction and side had similar Scott bond strengths, except for wire side, MD+. Only linerboard F had any differences in Scott bond strength based on MD direction. Though a large number of replications were needed for statistical significance, the test was able to provide indirect evidence that linerboard F had ZDFO.

ZDFO found by the Scott bond test may be regarded as existing near the center of the linerboard as opposed to either of the two surfaces. We found directional brightness, **Fig. 4**, had sufficient resolution to identify fiber tilt near the surface of unbleached paperboards, because light did not penetrate far beneath the surface before it was absorbed.

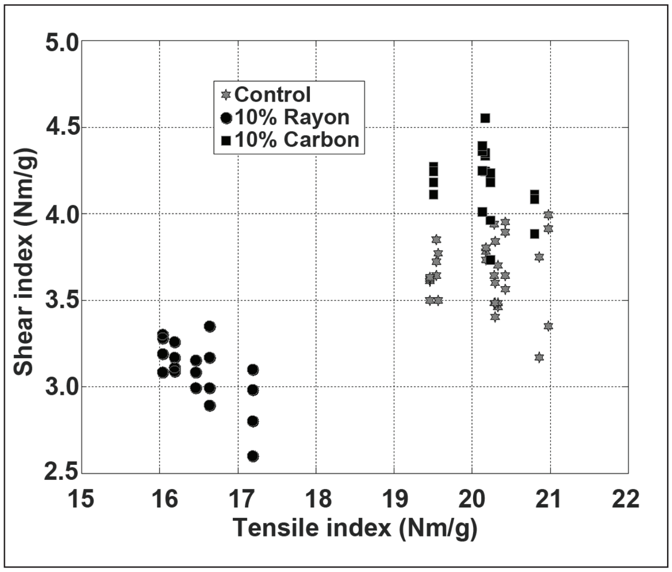
As in Scott bond testing, no directional differences between felt and wire sides were determined for linerboards A and E. For linerboard F, directional brightness depended on MD+ and MD– for the wire side, similar to results using Scott bond strength.

Table IV lists the ultrasonic measurements of samples A, E, and F. Similar to Table II, linerboard F has the highest in-plane stiffness values relative to the other two. Linerboard F did not have the highest E_z, out-of-plane stiffness, but was still higher than linerboard E, which had the greatest in-plane strengths. E_z depends on many variables and is not a good indicator of ZDFO when comparing different paperboards. In the mill environment, E_z may be a good choice as a process parameter to identify relative changes in fiber tilt from day to day. No other independent ultrasonic properties indicated the presence of fiber tilt.

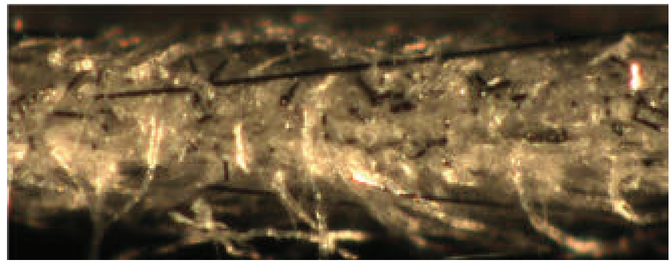
At this point, we believed that linerboard F had evidence of ZDFO with the following properties:

- 19% higher DNS index, compared with the average for linerboards A and E (Table II)
- 8% difference between Scott bond test directionality, compared to 0% statistical difference for linerboards A and E (Fig. 3)
- 2% difference between directional brightness directionality, compared to 0% statistical difference for linerboards A and E (Fig. 4)

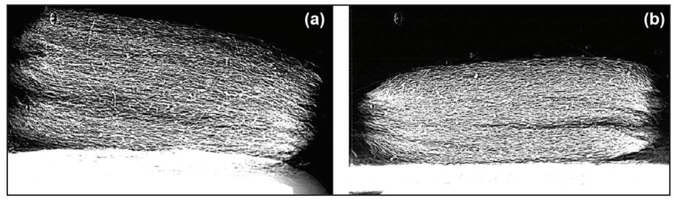
Our second goal was to create sufficient ZDFO in laboratory handsheets to achieve property improvements similar to those measured in linerboard F. Our approach was to use stiff synthetic fibers to guide neighboring cellulose fibers toward



5. Tensile strength index vs. double-notch-shear (DNS) index for handsheets.



6. Light microscope cross-section image of a handsheet with 10% carbon fiber.



7. X-ray radiographs of eucalyptus handsheets containing 10% carbon fiber (a) or rayon fiber (b). The scale of the images is 1,400 µm horizontal by 840 µm vertical.

a vertical configuration during the handsheet forming process. Attempts to use noncellulose fibers to create 3-D structures in paper have been tried in the past [26], but, to our knowledge, research using modern synthetic fibers does not exist.

The basic idea was to create a 3-D structure during handsheet forming to disrupt the tendency of cellulose fibers to stratify. The handsheet former described earlier was designed to accomplish this. As straight, stiff carbon fibers descended in the modified forming tube, they tended to land vertically on the forming screen and fiber mat and then fall over, creating an open 3-D network that could be filled in by cellulose fibers that arrived later. These fibers acquired ZD tilt by conforming to the network, which was no longer stratified. When rayon was used in place of carbon, descending rayon fibers conformed to the existing fiber mat. The tendency to stratify was preserved.

DNS and tensile-strength tests were performed on each set of handsheets. **Figure 5** shows the results. As expected, bonding reduction in handsheets with 10% rayon fibers decreased tensile and shear indices. On average, tensile loss was 18% and shear loss was 16%. Surprisingly, handsheets with 10% carbon fibers had no loss of tensile index and an increase in shear index of 14%. Our interpretation was that the 3-D structure offered different opportunities for bonding, so that relative bonded area was not compromised despite the 10% reduction in cellulose fiber content. Because tensile strength is related to relative bonded area, it did not decrease. Also, carbon fibers created the desired 3-D structure, increasing the shear index of the handsheets due to ZDFO. As measured by the DNS test, the 14% increase in shear index for the handsheets was comparable to the 19% increase in shear index for linerboard F in comparison to linerboards A and E.

Figure 6 shows a light microscope cross-section of a handsheet containing 10% carbon fiber. Individual carbon fibers are seen as black and straight in comparison with cellulose fibers. One carbon fiber can be seen spanning nearly the entire horizontal field of view, with a cellulose fiber draped across it near its leftmost extent. Another short black fiber segment left of center appears to be the end of a longer fiber generally perpendicular to the image. During handsheet forming, carbon fibers extending above the fiber mat provide an inviting structure for cellulose fibers to drape over, providing enhanced DNS strength and minimal loss of in-plane tensile strength despite the penalty imposed by nonbonding carbon material.

Figure 7 shows enhanced synchrotron X-ray radiographs taken through the edge cross-section of eucalyptus handsheets containing carbon and rayon fibers. Sample preparation is described elsewhere [19,27]. Vertical projections of carbon fibers are common in Fig. 7a. Because the fibers are 3 mm long, these are projections of fibers that generally extend into the plane of the image. They must be horizontal or slightly tilted to fit inside the sheet. Note that tilting of carbon fibers is not significant to the reported results. Either tilted or horizontal carbon fibers can create the open 3-D network later occupied by cellulose fibers referred to as ZDFO. The resolution of the image is unfortunately not sufficient to show these. Rayon fibers in Fig. 7b are not as stiff as carbon fibers and are harder to differentiate from cellulose fibers. The general appearance is one of stratification. As given in Table I and shown in Fig. 7, both carbon and rayon fibers tended to increase bulk and caliper in the laboratory handsheets. The increase from carbon fibers is greater, supporting the argument for an open fiber network allowing ZDFO. Strata are well-interwoven in Figure 7a, but are more distinct in Figure 7b. Also, Figure 7b has a large crack clearly separating adjacent fiber strata. This defect is not believed to result from sample preparation. It may be a reflection of poor ZD bonding, which would have a detrimental effect in compression and Taber tests.

SUMMARY AND CONCLUSIONS

Using conventional mechanical property tests, we found performance differences in a group of three commercial linerboards that strongly suggest the importance of ZDFO. In support of this finding, we were able to produce handsheets with ZDFO using 10% addition of stiff carbon fibers. Though the fibers do not bond with cellulose, they form a 3-D network that disrupts the tendency of the cellulose fibers to stratify. X-ray images showed that carbon fibers did not stratify in handsheets, but showed rayon fibers to be stratified and integrated in the cellulose network. Tensile-strength testing indicates that the network produces enough extra bonding sites to compensate for the carbon-fiber substitution. DNS testing indicates that the network produces enough ZDFO to improve the shear index by 14%. This was comparable to the shear-index enhancement in the best of the three commercial linerboards tested.

Taken together, these results suggest that ZDFO sufficient to couple more than two fiber strata should reduce propensity to buckling and delamination that occur during compression failure in commercial paperboard. Using noncellulosic fibers to create 3-D structures is one method to create a felted mat. Future work will explore methods to create ZDFO in commercial papermaking systems. **TJ**

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AUTHOR INSIGHTS

We were intrigued by the fact that some paper properties test differently depending on whether the test direction is toward the headbox or toward the reel. In examining what this indicates about fibers tilted in the z-direction, we see an opportunity to improve paper strength by changing fiber tilt, without incurring additional materials costs.

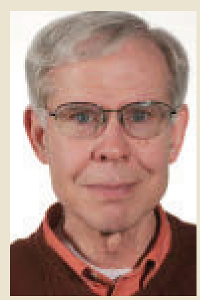
This study compliments previous research by characterizing fiber tilt for a wide range of commercial papers in a statistically significant way. We extended previous research by developing a method to produce fiber tilt in handsheets.

For this study, we tried to generate fiber tilt by trying many modifications of standard handsheet practice. Then, we had success by adding stiff, synthetic carbon fibers to the furnish. It was most surprising to find that one could replace 10% of the weight of a handsheet with a nonbonding synthetic fiber and still find an increase in strength!

For the present, mills should be aware of the potential strength benefits that come from tilted fibers. Simple, directional tape peels may help a mill understand the role of fiber tilt in its current product performance.

Lord Kelvin said: "If you cannot measure it, you cannot improve it." We are still looking for a direct measurement of tilted fibers in paper.

Considine



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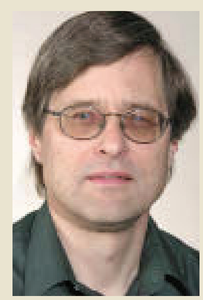

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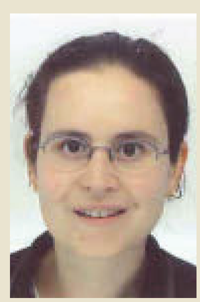

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