Preferred citation: S. Dolatshahi and M.T. Kortschot. The effect of fibre orientation on the zero-span testing of paper. In **Advances in Pulp and Paper Research, Oxford 2009**, *Trans. of the XIVth Fund. Res. Symp. Oxford, 2009*, (S.J. I'Anson, ed.), pp 931–946, FRC, Manchester, 2018. DOI: 10.15376/frc.2009.2.931.

THE EFFECT OF FIBRE ORIENTATION ON THE ZERO-SPAN TESTING OF PAPER

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ABSTRACT

In this study, a new technique for producing almost fully aligned paper sheets was developed, and the resulting sheets were used to test the validity of the theory most commonly used to relate zero-span tensile strength to individual fibre strength. The standard theory predicts that a zero-span test of a sheet with randomly oriented fibres should yield a breaking load equal to 3/8 of the load that would be observed if all the fibres were aligned in the direction of loading. It is widely used, in spite of the fact that the underlying assumption of affine deformation is questionable under true zero-span conditions. The results obtained here suggest that the fibre strength may be overestimated because inclined fibres in a zero-span grip actually contribute more than the theory predicts. However, the results also suggest that this effect may be confounded because other factors lead to a variable contribution of individual fibres to the zero-span strength of the sheet.

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INTRODUCTION

The strength of a paper sheet is an important mechanical property, and hence the mechanism of sheet failure has been extensively studied. For many years, the relative contribution of fibre breakage and bond breakage in determining sheet strength was a source of debate, however, in 1958, Van den Akker *et al.*[1] found that a considerable percentage of fibres are in fact broken during tensile failure of paper, even in sheets where the degree of bonding is only moderate. This study confirmed earlier observations made by Clark [2] and Graham [3], and established the significance of fibre strength to the failure of a sheet of paper. Consequently, there has been a considerable effort in the literature to find reliable means of measuring fibre strength.

It is possible to directly measure the strength of single fibres in a microtensile test provided they are sufficiently long and slender. In this method, the fibre is gripped at both ends in a miniature tensile tester, usually with the aid of a small bead of glue applied to the fibre ends. Though simple in principle, this method is tedious and time-consuming. It involves extreme care in preparation of the test specimens and requires testing of a great number of fibres for the results to be statistically significant. [4]

The main alternative method of measuring fibre strength involves testing a sheet of paper using a pair of jaws that grip the sheet with no free span, widely referred to as the *zero-span* test. Hoffman-Jacobsen suggested that the zero-span test would result in a failure load directly proportional to fibre strength in 1925. [5] Since then, there have been many studies of zero-span tests and improvements to the equipment (e.g.[6, 7]) Cowan and Cowdrey used an instrument capable of testing at both zero-span and very short spans to measure not only fibre strength, but also measures of fibre bonding, length and orientation. [8] In summary, the zero-span test has proven to be a relatively low cost and reliable measure of pulp properties, and is widely used in mills and research labs. [9]

In spite of the versatility and wide adoption of zero-span testing in industry, numerous studies have discussed and sometimes disagreed on the fundamental relationship between zero-span strength and fibre strength. Zero-span strength may be affected by variations in fibre length, the degree of bonding, non-uniformity of fibre strength, fibre curl and kink, and imperfect stress transfer in the grips [6, 10, 11, 12] All of these factors may be important, depending on the pulp being tested and the conditions used, but none of the previous studies have questioned the fundamental theory needed to compute the effect of imperfect fibre alignment on the zero-span results. In this study, we will focus only on the effect of fibre orientation on the zero-span strength. As a starting point, we will discuss the standard theories of Van den Akker [1] and Cox [13] upon which most subsequent studies rely.

If it were possible to test a sheet of paper with fully aligned fibres, it would be a relatively simple matter to compute the fibre strength as the load at failure divided by the total cross-sectional area of fibres broken during the test. Stone and Clayton tested thin microtomed sections of wood, but although this produces a sheet of oriented fibres, they concluded that the bonding between the fibres had a great influence on the results.[14] Fully aligned paper sheets are not available, so it is normal to test handsheets, where the fibre orientation is essentially random. In order to convert a zero-span failure load into equivalent fibre strength for random orientation handsheets, the effect of fibre misalignment must be dealt with analytically.

The effect of fibre orientation on the modulus and strength of a paper sheet was first studied in detail by Cox. [13] Cox's theory is based on the concept of "affine deformation", where every part of a sheet has a strain field identical to that of the whole. The theory further assumes that fibres carry only axial load. For a fibre at an angle θ to the direction of externally applied load, the sheet strain in the θ direction is first computed, and then the resulting axial fibre load is projected back into the direction of applied load. The process is repeated for fibres at all angles, and the result is that the modulus (or strength) of a random sheet is related to the integral of $cos^4\theta$ for all fibres crossing a particular cross section and works out to be 1/3 of the fibre modulus (or strength). Using this theory, the strength is simply calculated as the modulus times the critical strain, which would be governed by failure of the fibres aligned in the direction of applied load. The Cox theory thus treats fibres as line segments with no width, It has been reviewed and presented in a straightforward manner by Jayaraman and Kortschot. [15]

Van den Akker applied the theory of Cox to a sheet being tested under zero-span conditions. Because Poisson contraction is restricted by the rigid grips, the same computation for randomly oriented fibres leads to a prediction of zero-span strength of 3/8 of the fibre strength rather than 1/3. Van den Akker suggested that the fibre strength should be 8/3 of the zero-span strength of a handsheet to account for the random orientation of fibres. This factor has been used widely, and is included, for example, in the Page Equation.[16] Even under "true" zero-span conditions, where the gap between the jaws of the tester is, at least in principle, infinitesimally small, this computation assumes affine deformation of the network holds and that the contribution of individual fibres is related to their axial load projected into the direction perpendicular to the clamp line. For example, a fibre crossing the clamp line at 60° is expected to contribute only 6.25% of its potential using this calculation. However, if the gap between the clamping jaws under ideal zero-span conditions is essentially zero, it seems unreasonable to assume that the contribution of a misaligned fibre would be so low. Fig. 1 provides a scanning electron microscope (SEM) image of a fracture line from a zero-span test, and it is clear that many fibres were gripped and ultimately fractured parallel to the grip line. Such fibres actually have an effectively larger cross sectional area, albeit a lower tensile strength perpendicular to this because of their anisotropy. However, the underlying assumption that such fibres are basically one-dimensional line segments and contribute only the loading-direction component of axial force does not seem reasonable.

In this study, we investigate the hypothesis that under zero-span conditions,

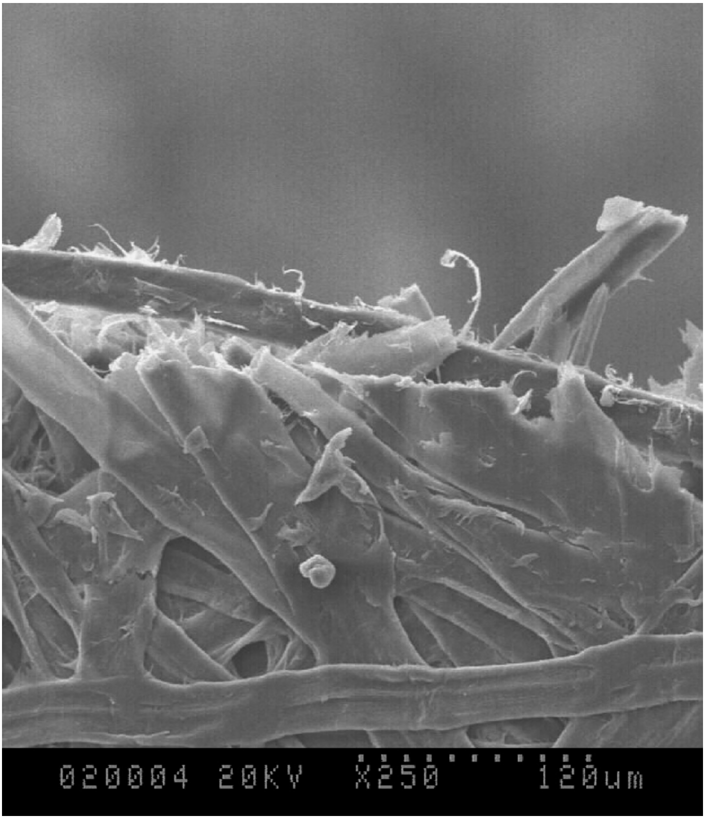

Figure 1. Scanning electron micrograph of a zero-span fracture line in a random handsheet of kraft pulp fibres.

the conventional theory underestimates the contribution of inclined fibres to the observed zero-span breaking load of the sheet.

EXPERIMENTAL METHODS

One method of testing the validity of Van den Akker's theory is to perform the zero-span test on highly aligned handsheets, so that the effect of misaligned fibres is negligible. There have been many attempts to produce highly aligned sheets in the past, but none have resulted in sheets with sufficiently aligned fibres to serve the current needs. In order to produce such handsheets, a new device was developed based on the deposition of a thin stream of pulp solution thickened with a small amount of polyethylene oxide on a rotating vacuum screen. This novel method has the ability to produce sheets with an extremely high degree of fibre alignment.

Materials

Northern softwood bleached kraft pulp obtained from the National Institute of Standards & Technology (Reference Material 8495) was used. The pulp consists of 68% White Spruce, and 32% Lodgepole Pine with trace amounts of Balsam Fir. The average fibre length was determined to be 1.3 mm using a Fibre Quality Analyzer (Optest). The as-received kraft pulp bales were disintegrated with 10,000 revolutions in a Durant disintegrator prior to beating. Both beaten and unbeaten kraft sheets were tested, and the pulp for beaten sheets was prepared by soaking 30 grams of pulp in water overnight, and beating to 8000 revolutions in a PFI laboratory beater according to TAPPI standard T248.

In order to test a different, and more uniform set of fibres, several samples were also made using loose rayon fibres (bright, regular, 3 denier fibres). The fibres were 6.3 mm in length, and were obtained from the Claremont Flock Corporation where they had been cut to length from endless tow filaments manufactured by Acordis Kelheim GmbH.

Handsheets

Handsheets were made from kraft pulp (with 0 and 8000 revolutions of beating) and rayon fibres, following TAPPI standard T-205 sp-95. The basis weight of the samples was set at either 20 or 60 g/m^2 for both the rayon and the kraft pulp. Four handsheets were made for each condition.

Fully aligned handsheets

The device used to produce fully aligned handsheets is depicted in Figure 2, and consists of a syringe pump that deposits a thin stream of pulp slurry on a rotating drum. A viscous aqueous solution containing 0.7% high molecular weight (4,000,000) polyethylene oxide was added to dilute pulp slurry (0.01% to 0.1% oven dry fibres by weight) to provide a pulp suspension with sufficient extensional viscosity that surface tension could not cause the thread of suspension coming from the syringe pulp to bead prior to deposition on the drum (see Fig. 2). One percent of the fibres were dyed with chlorazol black so that fibre orientation could be quantified using simple scans of the sheet. The viscosity of the final solution and concentration of pulp fibres were adjusted to maintain individual fibres in a homogeneous suspension, and to assure the

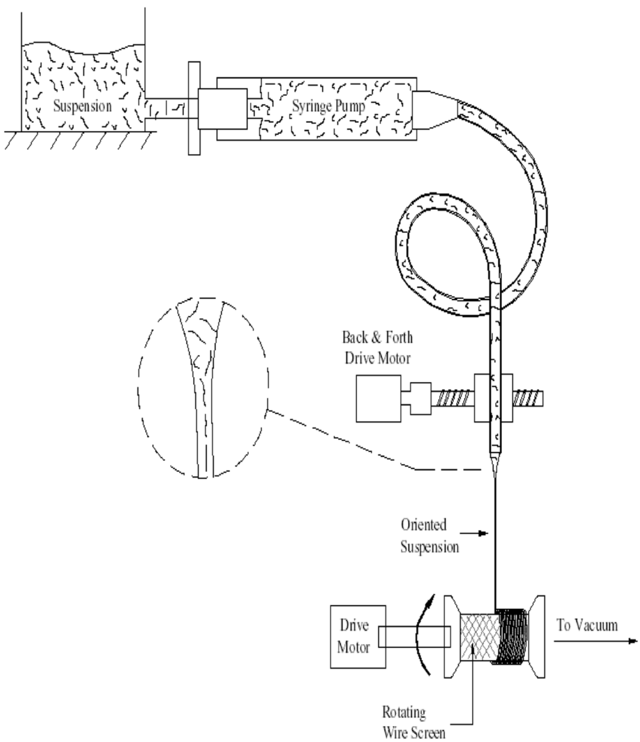

Figure 2. Apparatus for producing fully aligned handsheets. The suspension flows under the influence of gravity and its own tensile strength freely through the air for several centimeters before being deposited on a rotating porous drum.

absence of fibre bundles and knots. The viscous slurry was pumped using a syringe pump at a constant flow rate of 5.3 ml/min. After emerging from the nozzle, which had an internal diameter larger than the fibre length to avoid clogging, the stream flowed several centimeters through the air under the influence of gravity and tensile stress in the stream itself. The stream was laid down on a rotary drum one inch in diameter that was covered with a stainless steel woven wire cloth (150 Mesh). The suction was applied from inside the drum using a commercial Shop Vac, draining the water and the PEO from the suspension. The speed of the rotating drum was controlled by a variable speed motor and was typically 300 rpm. The difference in velocity between the surface of the drum and the stream emerging from the syringe pump caused the free stream to elongate by a factor of at least 10, producing highly oriented pulp fibres as illustrated in Figure 2. The stepper-motor-driven linear motion slide was used to scan the nozzle back and forth at 0.84 cm/sec.

Once approximately 0.05–0.08 grams of oven-dried fibres were laid down on the moving wire, the resulting strip of highly aligned paper (140 mm × 20 mm) was stripped from the screen. Prior to stripping, the sheet was washed with at least 400 ml of distilled water with the vacuum running to dissolve and remove any residual PEO in the sheet. FTIR scans of the washed sheets did not show any evidence of residual PEO. The basis weight of the resulting sheet was typically 20 g/m^2 and this sheet was stripped and transferred on a blotter sheet to a standard conditioning room at 50% relative humidity and 23°C. There it was dried without restraint.

To make oriented rayon fibre sheets with sufficient integrity to be handled when dry, it was necessary to change the ratio of drum speed to transverse feed in order to deliberately misalign the fibres by between 3 and 5 degrees. The theory suggests that the mechanical properties of such a sheet would be virtually identical to those of a fully oriented sheet.

Mechanical testing

Both zero-span and single fibre tests were conducted on the NIST kraft pulp and rayon pulps.

Single fibre tests

Single fibre tensile tests were carried out on a micro tensile tester with a 50 g load cell. The jaws of the tensile tester consist of two flat plates, one of which is connected to the load cell, while the other was moved by hand turning a very fine threaded rod. Load was recorded on a continuous strip chart recorder, and the strain was not recorded. The load cell was calibrated using small weights ranging from 1–10 g, prior to testing.

Individual fibres were picked with a pair of tweezers from a bundle of moist fibres under the microscope. During this operation an attempt was made to choose fibres randomly and to avoid choosing only long, straight fibres. The fibres were mounted on black paper specimen holders for good contrast, as shown in Figure 3. The fibre was laid across the gap of the tab and its two ends were carefully glued on to the tab with small beads of LePage 11 epoxy. The length of the fibre section between the two glue joints was set at 1mm for the kraft fibres, and at 3 mm for the longer rayon fibres. The samples were made and kept at 50% R.H. prior to testing.

The paper specimen holders were taped to the grips of the machine, and just prior to testing, the side tabs were cut so that only the fibre itself would carry load between the grips.

Single fibre tests were carried out on 63 rayon fibres and 15 kraft fibres, following the procedure described above. Load-elongation data for 28 kraft fibres was also obtained from tests conducted at the USDA Forest Service,

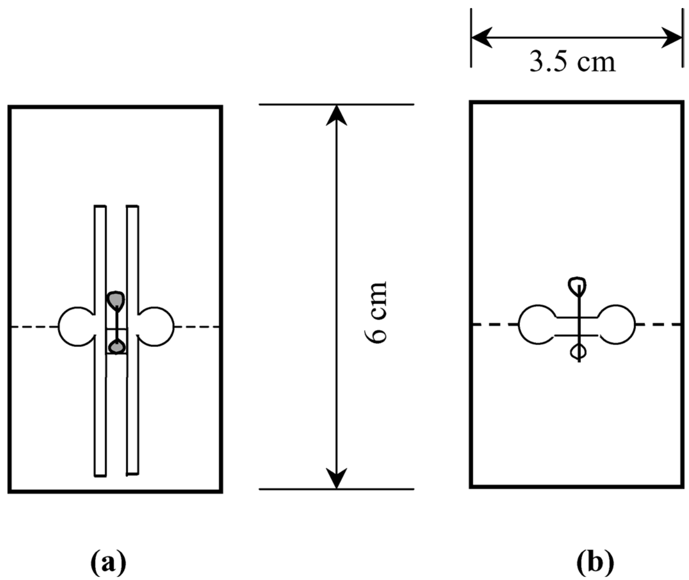

Figure 3. Black paper tabs for mounting individual fibre. (a) For shorter kraft fibres, long flexible tabs were used to ensure axial loading of the fibres even if their original alignment was not perfect. (b) For the much longer rayon fibres, this was not necessary.

Utilization of Southern Forest Resources Unit. The results of the USDA tests were in good agreement with those obtained in our lab, but were conducted on a more advanced instrument capable of measuring strain at failure and the cross section of each fibre being tested.

The cross-sectional areas of the 28 kraft fibres tested at the USDA Forest Service were measured by confocal microscopy. The area of the lumen was subtracted from the total cross-sectional area of the fibre, and the fibre strength was reported as the failure load divided by the cross sectional area of *solid cellulose* in kg/mm^2. The average cross-sectional area of individual rayon fibres was determined from an SEM image of a polished cross section of an epoxy disc containing a small clump of fibres from an aligned rayon sheet. An additional benefit of being able to form almost fully aligned sheets is that the sheets may be embedded in epoxy and polished for cross-sectional area characterization, without any concern about the effect of misalignment on the resultant measurement. The rayon fibres are solid, and hence the fibre strength was reported in the conventional way.

Zero-span testing

Zero span testing was conducted on a Pulmac Z1000 B2. Prior to testing the sheets, the alignment of the jaws of the tester was characterized by clamping a strip of aluminum foil at full pressure in the jaws. The marks left by the two jaws were then observed by a scanning electron microscope (as shown in Figure 4). The image suggests that there was a very slight misalignment of about 5–10 μm between the lower jaws of the tester used in this study at the time of testing. This was attributed to some previous accidental damage of the tester, but tests of standardized sheets showed that the machine produced results within normal operating limits.

The clamping pressure was optimized prior to testing specimens by plotting the strength of a standard 60gsm handsheet made from the NIST kraft fibres at a variety of pressures. The recorded strength was virtually constant in the range 70–95 psi, and consequently 85 p.s.i. was used for subsequent tests.

20 mm × 80 mm kraft and rayon specimens were used for the experimental work, and each of five strips from the sample was tested in seven different locations.

The thickness of a sheet may be calculated as the grammage/density. If the density of cellulose is used in this equation, the equivalent thickness of cellulose in the jaws of the zero-span tester may be calculated. The zero-span strength of the sheet, expressed in units of force per unit cross-sectional area of cellulose, can be subsequently obtained from the equation [1]

$$(Zero\text{-}span\ Strength)\ ZS = \frac{F}{t.15} \quad (kg/mm^2)$$

where the width of the jaws of the zero-span tester is 15mm, and F is the load at failure.

The density of cellulose has been taken as 1.55 gr/cm^3, for all the calculations. The value of ZS may be compared directly to the value of individual fibre strength, which was also computed as the failure load divided by the area of solid cellulose.

RESULTS AND DISCUSSION

The fibre orientation distribution in the sheets made with the new method was determined using a high resolution scanned image of the sheet with 1% of the fibres dyed black. Figure 5 shows a scanned image of a typical portion

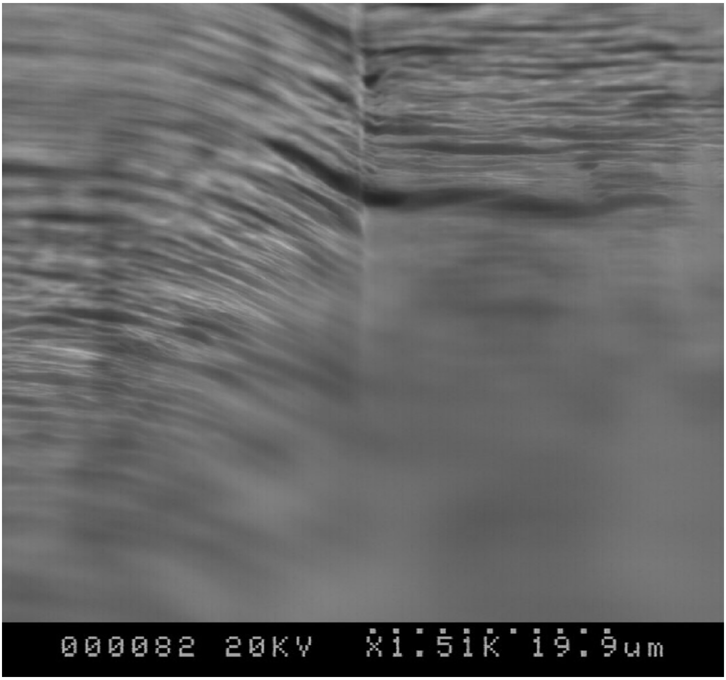

Figure 4. Slight misalignment of the zero-span jaws is illustrated by an oblique SEM image of a piece of aluminum foil clamped but not tensile tested.

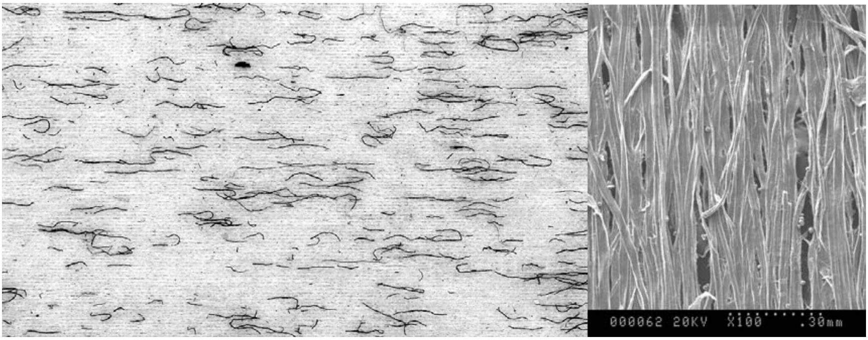

Figure 5. An optical scan and SEM of a highly aligned sheet made from beaten kraft fibres on the aligned sheet former.

of an aligned sheet made with softwood bleached kraft, together with an SEM image of the surface of the sheet. It is clear that the sheet is almost perfectly aligned and in Figure 6, the distribution of fibre orientations in this sample is presented. Orientation was computed with a Matlab program that fit each isolated fibre with an equivalent ellipse having the same area and the

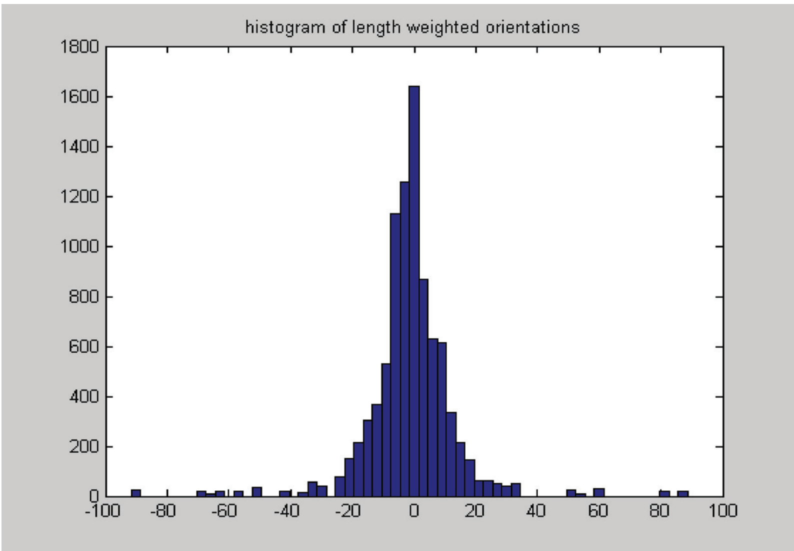

Figure 6. Distribution of fibre orientation in a highly aligned sheet made with beaten kraft pulp.

same second moment of area. The orientation of the major axis of this ellipse was then reported as the fibre orientation. The average fibre orientation angle obtained with this method was typically about 7°. To the best of the authors' knowledge, no other techniques are capable of producing such a highly aligned sheet.

Some fibre kink and curl is evident, but a randomly placed transverse line intersects the vast majority of the fibres at 90 degrees. In any case, kink and curl would be expected to affect both the oriented and the random handsheets in a similar way. Since the $\cos^4$ of angles less than about five degrees is approximately one, the misalignment visible in Fig. 5 is expected to have little effect on the results.

The results of both single fibre tests and zero-span sheet tests are reported in kg/mm^2 of cellulose. In other words, forces were divided by the amount of cellulose only, in order to present a simple and fair comparison between sheet and fibre strength.

Both aligned and randomly oriented sheets were tested in a zero-span test, and results are reported in Table I. Each zero-span strength value is an

Table I. The results of single fibre and zero-span tests

Single Fibre Strengths:	*kraft fibres = 92 ± 48 kg/mm²*	*rayon fibres = 35 ± 18 kg/mm²*
Sample	*Zero-Span strength (kg/mm²)*	*Ratio of ZS to Fibre Strength*
Kraft Handsheet (Unbeaten)	21.6 ± 3	0.23
Kraft Handsheet (Beaten to 8000 revs)	24.5 ± 3	0.26
Kraft Aligned Fibre Sheet (Unbeaten)	34.2 ± 2	0.37
Kraft Aligned Fibre Sheet (Beaten to 8000 revs)	38.2 ± 3	0.41
Kraft Aligned Fibre Sheet (Beaten to 8000 revs) and oriented at 45° to the grip line	25.6 ± 3	0.28
rayon – Handsheet	12.7 ± 2	0.36
rayon – Aligned Fibre Sheet	19.3 ± 3	0.54
rayon – Aligned Fibre Sheet and oriented at 45° to the grip line	12.0 ± 1	0.34

average of results from tests conducted on five or more sheets, and each sheet was tested in at least seven different locations. The aligned sheets were also inserted into the zero-span tester at an angle of 45° to the grip line, to obtain a value for strength where all fibres are gripped at a 45° angle.

A comparison of the various results reported in Table I yields insight into the zero-span tests and its relationship to fibre strength. According to Van den Akker, the contribution of *N* randomly arranged fibres to the final load at failure should be 3/8 of the fibre strength.[1] Here we see that while the rayon handsheets do meet this requirement, the kraft handsheets fall far short of it. More importantly, the zero-span strength of the highly aligned sheets should be equal to the single fibre strength. In fact, for both the rayon and kraft fibres, the zero-span result for the highly aligned sheet is much lower than the fibre strength: 54% and 41% of the fibre strength respectively.

Many researchers have commented on the various factors that can affect the zero-span strength, as discussed previously. Any non-uniform stress in the grips would lead to reduced fibre strength, as would fibre curl, fibres ending very close to the grip line and so on. Less well understood is the effect of fibre non-uniformity on the load sharing at the moment of failure. The single fibre tests produce a huge standard deviation in both strength and failure strain. The strain was measured in the USDA Forest Service tests of 28 NIST fibres and was found to be .026 ± .011. Consequently, if 1000 fibres are gripped perfectly and the assembly is tested to failure, it is not reasonable to expect all fibres to carry a load corresponding to their ultimate strength at the point of sheet failure. This issue was discussed previously by El-Hosseiny and Bennett[10]

All of these factors lead to a zero-span strength measurement that is expected to be lower than the single fibre strength. It is important to point out however, that single fibre strength measurements are extremely difficult to perform reliably, and hence the zero-span measurement is still very useful in providing a relative measurement of fibre strength.

In order to investigate the central hypothesis of this study, that the theoretical treatment of zero-span strength underestimates the contribution of misaligned fibres, the zero-span measurements of aligned sheets can be compared to those of random handsheets or aligned sheets mounted at an angle to the applied load. For example, if the zero-span strength of an aligned handsheet is assumed to represent the fibre strength reduced by a number of factors that affect both the aligned and random handsheets equally, then the zero-span strength of a random handsheet should be 3/8 of this value. In other words,

$$ZS_{random} = \frac{3}{8} ZS_0 \qquad \text{(Theory)}$$

where ZS_{random} represents the zero-span strength of a random handsheet, and ZS_0 denotes the zero-span strength of a fully aligned sheet with fibres lying parallel to the direction of loading. In practice, Table I shows that for both beaten and unbeaten random handsheets:

$$ZS_{random} = 0.63\ ZS_0 \qquad \text{(Experiment)}$$

For rayon handsheets, the ratio was 0.67. In all cases, the discrepancy is significant, and supports the hypothesis that misaligned fibres carry more load than predicted by the Van den Akker/Cox approach It should be noted that the stress transfer from the grip surface to the centre of the sheet has been found to depend on fibre orientation, and this may have affected the strength ratios observed. [12]

The basic hypothesis was further investigated by testing oriented handsheets with the fibre direction aligned at 45° to the jaw line. Fibres lying at 45° in an isotropic sheet are supposed to contribute only 25% of their axial strength. Failure in this case is controlled by the failure strain of the 0° fibres. When all fibres in an oriented sheet are lying at 45°, the original Cox theory would yield an expected ratio of sheet strength to fibre strength of $\cos^2 45°$ or 0.5. (This result is obtained because there are fewer fibres crossing the failure line, and their axial load at the moment of failure must be projected back into the direction of applied load.) However, the results show that for rayon fibres, $ZS_{45} = 0.63\ ZS_0$, and for kraft fibres, $ZS_{45} = 0.68\ ZS_0$. This again suggests that misaligned fibres, well gripped by very accurate zero-span jaws, can contribute more than the load-direction component of axially loaded line segments.

The results for the comparison between rayon handsheet results and the single fibre tests suggest that previous studies may have been simultaneously measuring the effect of two independent factors: the random orientation should reduce the strength by only 30 or 40%, but there is additional strength loss because of a number of other factors that prevent all fibres in a zero-span test from being simultaneously stressed to the failure point. The combination of these factors led to a strength reduction (in comparison to single fibre tests) of almost exactly 3/8 for the rayon handsheets tested in this study, but it appears that this may be a coincidence.

CONCLUSIONS

The zero-span test has proven to be a remarkably quick and useful way of characterizing relative fibre strength with minimal effort. However, the results of the present study suggest that the simple adaptation of the Cox equations may not adequately capture the mechanisms of load transfer within the jaws in a true zero-span test. If this were the only difference between the ideal and experimental conditions, it could lead to an overestimation of single fibre strength, since the contribution of misaligned fibres is apparently under-represented by the theory. However, in our tests of highly aligned sheets, the maximum zero-span strength obtained was between 40% and 50% of the strength that would be expected based on results obtained for individual fibres. There, are of course, many factors that could affect this, as detailed in the quite extensive literature on the subject, but whatever the root cause, it must be the case that not all fibres were simultaneously stressed to their ultimate strength. Given the variability in measured single fibre properties, this is not unexpected.

ACKNOWLEDGEMENTS

The authors would like to thank Amy Lin for preliminary work on the apparatus and for developing the algorithm used to characterize fibre orientation. We would also like to thank Les Groom of the USDA Forest Service for assistance with single fibre tests. Finally, the authors would like to thank the Natural Science and Engineering Research Council of Canada for financial support.

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Transcription of Discussion

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Ulrich Hirn Graz University of Technology.

I was wondering, have you also made wet zero-span tests because there is this theory that there is stress transfer from fibre-to-fibre bonds, and so you should actually measure wet zero span to account for fibre strength. So I was wondering if you were doing that?

Mark Kortschot

No, we just focused on the dry strength measurements because in this case we were just trying to isolate the effect of misalignment, the whole thing could have been done wet. The oriented papers would probably fall apart if we wet them. They would not stick together very well, although we could probably wet them after they are in the grips perhaps. So it is a good suggestion, thanks, but we didn't do that.

Norayr Gurnagul FPInnovations

Mark, can you make a comment on the impact of the single-fibre micro-fibrillar angle on your observations?

Mark Kortschot

I used the words "structural hierarchy" to say that, when we were looking at the structure at this network level, maybe we can ignore the structure at the lower level. So in this case we are treating the fibres as just units with strength in them. I think that is okay. The fibrillar angle is probably one of the reasons that lead to the range of fibre properties so that, when you are testing individual fibres with different fibril angles, they have quite different strengths and moduli. That is why you have to test so many and that is what makes the tests so difficult to do. When you put an assembly of fibres like that into a zero-span (or any other mechanical test), what happens is that you do not fail them all simultaneously as the theory presumes, but the stiffest ones fail first – lower strain to failure – and that is one of the reasons that inhomogeneity is one of the things that can lead the strength in an assembly of fibres to be less than what you would expect by just averaging the strength of the individual fibres. I think that for the purposes of micro-mechanics testing, we can treat the fibres as just individual units. We do not have to worry about what the fibril angle is except that it provides a variety of fibre properties which provides variation in assembly properties and causes problems when we are trying to test the assembly.

Douglas Coffin Miami University

I think of the zero-span as the upper limit that you can achieve in a given sheet or network as you change bonding, and you are not going to get above that. I wonder, given that it is not a measure of fibre strength, is there is a way to make a sheet that is going to have a tensile strength above zero-span? Given what you have done, is it possible to form a structure that can be stronger than zero-span?

Mark Kortschot

No, I do not think so. I think in an open sheet I have less problem with the idea that the modulus of a full sheet is based on the axial contribution of the fibres, axial deformation of the fibres, although surely bending and shearing of the fibres might be important as well. The basic Cox's theory is that you know the sheet has affine deformation, every part of the sheet deforms as every other part, the fibres all axially stretched and we can do the maths based on that. I do not have any fundamental problem with that for a full-size sheet. It is just that when we are grabbing individual fibres which have quite a significant width compared to the grip, that caused me to have a problem. So the answer to your question is no, I think zero-span is still going to form that upper limit.

Steve I'Anson University of Manchester

I was thinking about the fact that fibres only contribute axially. That makes sense where you have a finite span because, if they were to contribute other than axially, it would be due to bending or something like that. When you have a short-span, that is actually smaller than the width of the fibres, then the non-axial contribution comes from the modulus or the strength going perpendicular to the axis.

Mark Kortschot

That is right!

Steve I'Anson

So this is what it is about really, isn't it? I was just wondering whether you had any ideas for how graduate students could measure the strength of fibres perpendicular to the axis?

Mark Kortschot

It is very interesting, yes. I don't know what happens if you put one of our aligned sheets in sideways, maybe you'll get little bit more off-axis. But it is also not just the perpendicular, it comes back to Norayr's question about fibril angles. When we grab an individual fibre across the jaws, then we do not know what the fibril angle is but it is anisotropic; it has anisotropic properties. So its properties at 45 degrees are different than the axial properties as well, which would factor into the contribution of that fibre. The properties of the fibres themselves are not as high at 45 degrees as you would expect. If it was an isotropic fibre, then actually I think it would contribute even more than the test showed. I think a fibre is quite a bit weaker at the 45 degree angle but the cross-sectional area is also larger. If I grab it and break it at 45 degrees, it is hard to know exactly what it contributes, but I would not like to do those tests, no.