Fiber Orientation and Degree of Restraint During Drying

Effect on Tensile Anisotropy of Paper Handsheets

VANCE SETTERHOLM and EDWARD W. KUENZI

Abstract: The combined influence of fiber orientation and restraint during drying on handsheets showed that stretch-dependent properties were influenced principally by restraint during drying while tensile strength was influenced more by fiber orientation.

Keywords: Fibers · Orientation · Drying · Constraining · Handsheets · Tensile strength · Modulus of elasticity · Paper · Papermaking

THE combined effects of restraint during drying and fiber orientation determine the mechanical anisotropy and, ultimately, the utility of paper. These effects have long been recognized in the industry as important variables, yet we know of no quantitative studies simultaneously relating these variables to basic strength and elastic properties in tension or to anisotropy in paper. Most paper machines are relatively inflexible in their ability to alter fiber orientation and restraint during drying (across the web). We hope that this report will give added incentive to new paper machine designs by demonstrating the remarkable flexibility and range of tensile properties available from a single pulp. Another related objective is to illustrate the manner in which the principles and application of engineering mechanics can serve the paper industry by pointing the way toward designing products based on a knowledge of the basic mechanical properties of paper.

In the study reported here, fiber orientation ratios were established for paper handsheets subjected to various levels of restraint during drying. The fiber orientation and restraint levels were related to tensile strength, modulus of elasticity, and strain at failure.

MATERIALS AND METHODS

Pulp

The pulp used was a western softwood bleached kraft, beaten in a standard beater to a Canadian Standard freeness of 580 ml. After beating, a quantity of the fibers was dyed with Du Pont's Fiber Black. An amount of dyed fiber equal to 0.25% of the total weight of fiber in the slurry was added to be used for subsequent determination of fiber orientation.

Forming Handsheets

The method used to form handsheets with varying fiber orientation was a modification of Steenberg's technique (*1*) for simulating cylinder machine operation. His apparatus was essentially an inverted small-sheet machine, which moved the pulp over a stationary mold about 10 cm^2 in area. Our primary modification was to move a much larger (226 cm^2) area mold through a stationary pulp slurry (Fig. 1).

The mold or forming device was fitted with a 13- × 18-cm piece of paper machine wire and attached to a rubber tube which acted as a siphon. The tube was connected to a rotor-type hydraulic vacuum pump. The device was operated at a nominal vacuum of about 58 cm Hg.

Fibers were deposited on the wire when the mold was drawn up by hand through a large vat containing a slurry of pulp. The pulp consistency was maintained at about 0.03%. The length of time that the mold was left in the slurry determined the thickness; the speed with which it was drawn through the slurry determined the average angle of fiber orientation. This simple apparatus, although adequate for the purposes intended, required skill in manipulation to obtain sheets that were uniform in weight and had similar orientation of fibers. Attempts had been made initially to use our experimental fourdrinier machine for preparation of webs with varying fiber orientation. While a paper machine has the advantage of producing quantities of test material of uniform weight, it has the disadvantage of producing distinctly one-sided sheets, i.e., with an uneven distribution of fines from top to bottom and a tendency toward more fiber alignment on the wire side.

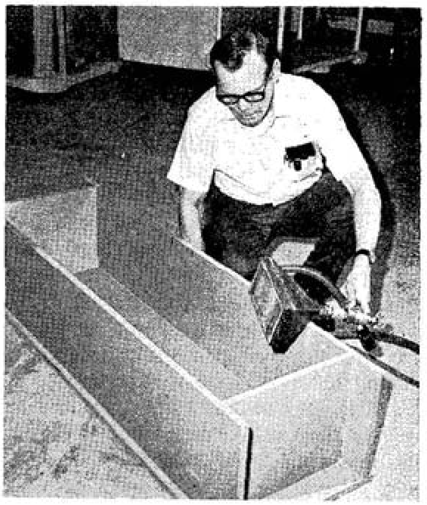

Fig. 1. Apparatus wed to form handsheets varying in degree of fiber orientation. The mold was drawn through the slurry by hand.

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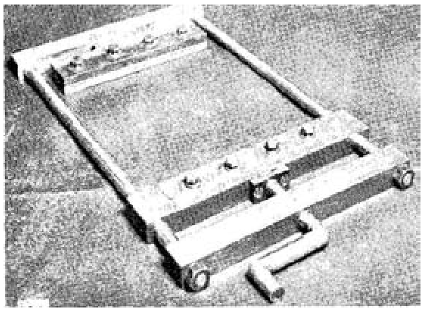

Fig. 2. Frame used to control restraint during drying.

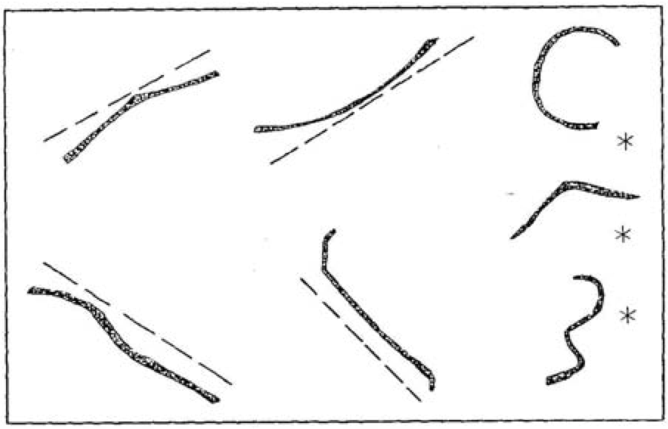

Fig. 3. Various fiber configurations encountered. Dotted lines show angles recorded. The asterisks indicate configurations not recorded.

With the vacuum turned off, handsheets were easily removed from the wire of the forming device using a blotter and gentle hand pressure. Six sets of five or six handsheets representing a wide range of fiber orientation were made. The moisture content of the wet sheets was estimated to be about 80%. Before drying these wet samples, reasonable care was taken to make handling procedures uniform. Any differences in drying prior to clamping specimens in the drying frame would be expected to reduce the comparability of results. In addition, one set of handsheets having randomly oriented fibers was made on a British mold. The dry handsheets varied in weight from 30 to 60 g/m^2.

Method of Restraint During Drying

One handsheet from each set was allowed to dry without restraint so that maximum shrinkage could be measured. The remaining sheets were dried in a special frame (Fig. 2) designed to facilitate control over sheet length during drying. Each sheet was subjected to some measure of restraint by the frame during drying. In this report, the term "restraint during drying" is used to describe states of tension ranging from slight shrinkage allowance through a condition where the wet handsheet is actually stretched and held before drying. In Table I, values for net change in dimension are preceded by a plus sign when the sheet was stretched before drying, or a minus sign to indicate allowance for shrinkage.

Before drying, reference marks were placed on the wet handsheets to be used later for measurement of dimensional changes during drying. The handsheet edges to be clamped were ironed dry to avoid rupture at the clamp as drying stresses were developed. Immediately after placing the wet sheet in the frame, the distance between the clamps was adjusted to give the desired amount of restraint during drying. This assembly was placed in a drying oven maintained at 65°C with the wet sheet held in a vertical plane to minimize the tendency to sag that could occur if the sheet were held in a horizontal position.

After drying, handsheets were placed in a room maintained at 50% RH and 23 °C. Measurements of dimensional change were made when the sheets reached a constant weight.

Fiber Orientation Measurements

The term "fiber orientation" is usually used to denote the directionalism in paper as indicated by a ratio of machine to cross-machine tensile strength. In this report, however, it is used in the much more limited sense of the "in-plane'' geometric arrangement of fibers. However, considering that all fibers are more or less curved creates a problem of describing fiber geometry within a sheet of paper in simple terms. An arbitrary solution to the problem was adopted which proved to be very simple and useful. This system is based on visual inspection and angular measurement of dyed fibers. The angular direction of a curved fiber was considered to be an imaginary straight line that best fit the curved fibers. Certain shapes of extreme curvature were disregarded. Some typical examples of fiber configuration that were counted, as well as ones that were not counted, are shown in Fig. 3. Those marked with an asterisk were not counted. Fiber orientation was then expressed as the average cotangent of the angle that the fibers made with the length direction of the handsheet. This is referred to as the fiber orientation ratio.

It was also found that the fiber orientation ratio is affected very little by whether we group by 5 or 10° intervals when recording data. For example, all fibers falling in a range from 85 to 95° can be summed up at 90°.

Tension Tests

Two specimens from each sample were used to obtain tensile strength, modulus of elasticity, and strain-to-failure data. Since

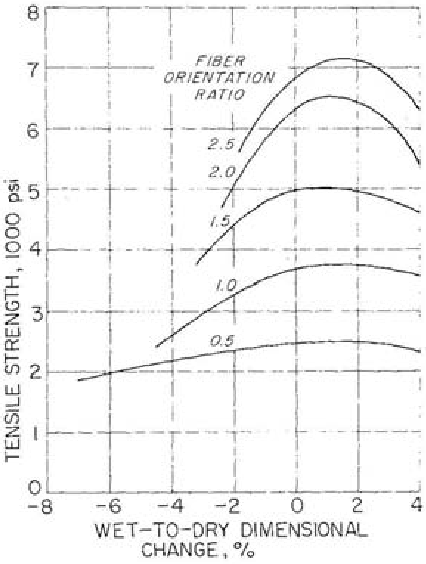

Fig. 4. Relationship between tensile strength and wet-to-dry dimensional change for several levels of fiber orientation.

determining fiber orientation is a very time-consuming process, the sample used for tests was very small. Necked specimens and a tensile strain gage described by Jewett (2) were used for tensile strength evaluations. The loads were applied at a fixed crosshead travel of 0.1 in./min. The span or distance between the grips was 4 in.

DISCUSSION

The anisotropy or directionalism which modern-day papers exhibit is purely a chance phenomenon associated with machine manufacture. To a certain extent each type of paper machine produces a product having its own characteristic degree of mechanical anisotropy. We can usually distinguish, for example, between fourdrinier and cylinder machine-made paper by the ratio of machine to cross-machine tensile strength. The directionalism of paper results chiefly from variations in fiber orientation and restraint during drying, and these are largely the uncontrolled and natural result of other variables in the papermaking process.

In spite of the somewhat capricious origins of directionalism in paper, its influence is by no means insignificant. It affects tension and compression properties, tearing resistance, folding endurance, dimensional stability, water absorption, and, in varying measure, the manufacture or use of nearly all paper products.

Table I. Effect of Fiber Orientation and Restraint During Drying on Tensile Properties of Handsheets

Fiber orientation ratio	*Change in length (restraint), %*	*Average thickness, mil*	*Basis weight, g/m^2*	*Density, g/cm^3*	*Tensile strength, psi*	*Modulus of elasticity, 1,000 psi*	*Strain at failure, %*
2.46	−1.8	5.5	57.2	0.409	5,220	300	5.0
2.62	−1.2	5.1	56.2	0.400	4,240	399	3.2
2.64	0.0	5.1	53.3	0.413	6,500	759	2.6
2.62	+1.3	4.9	51.3	0.411	7,000	947	2.2
2.60	+3.6	5.1	49.9	0.382	6,060	909	1.4
2.02	−2.0	4.5	45.5	0.398	4,650	260	5.1
2.06	−1.4	4.8	49.4	0.405	4,350	332	4.5
2.07	−0.4	4.8	51.3	0.421	5,080	549	3.3
1.93	+1.2	5.1	55.3	0.428	6,400	845	2.3
2.12	+3.6	5.1	51.8	0.396	5,380	819	1.5
1.53	−3.2	4.5	45.5	0.398	3,670	181	6.2
1.51	−2.0	5.9	65.5	0.438	4,540	347	5.2
1.34	−0.2	3.9	41.6	0.417	3,600	438	3.1
1.72	+1.6	4.1	42.5	0.403	5,180	672	2.1
1.52	+3.6	5.2	53.8	0.401	5,450	997	1.4
1.00	−4.4	3.5	29.8	0.332	2,010	98	5.6
1.00	−3.4	3.4	31.8	0.369	2,380	128	5.6
1.00	−1.8	3.6	35.7	0.392	2,940	258	4.5
1.00	−0.4	3.8	41.6	0.432	3,750	438	3.1
1.00	+1.6	4.7	46.0	0.388	3,660	473	2.4
1.00	+3.8	3.8	37.7	0.386	2,970	488	0.9
0.67	−5.6	3.9	35.7	0.359	1,760	82	7.0
0.71	−4.6	4.0	36.7	0.372	1,860	120	6.7
0.79	−2.2	5.2	55.7	0.423	2,920	247	4.8
0.76	−0.4	3.5	35.7	0.401	2,260	270	2.8
0.67	+1.6	3.5	33.7	0.380	2,580	378	1.8
0.78	+4.0	3.6	32.8	0.359	2,130	340	1.1
0.57	−7.6	5.6	60.6	0.423	1,740	78	9.6
0.57	−3.8	4.9	49.4	0.411	2,000	159	5.5
0.58	−1.8	3.7	35.7	0.380	1,710	178	3.4
0.52	−0.6	4.7	53.3	0.444	2,110	274	2.8
0.63	+1.4	4.4	47.4	0.423	2,360	352	1.9
0.64	+4.0	4.5	45.5	0.400	2,230	354	1.2

Tensile Strength

To examine the interacting effects of fiber orientation and restraint during drying on tensile strength, a three-dimensional model was constructed from data in Table I. Using this model it was relatively easy to prepare a graph showing smooth curves of strength vs. restraint during drying for several degrees of fiber orientation. Figure 4 shows that fiber orientation has a much greater influence on tensile strength than does restraint during drying (wet-to-dry dimensional change). Increasing the fiber orientation ratio from 0.5 to 2.5 resulted in a threefold increase in strength, whereas the range restraint during drying only increased strength by 30–40%. The more oriented the fibers in handsheets, the greater the increase in strength due to restraint during drying. A somewhat more pictorial representation of these data is shown in Fig. 5, which is a three-dimensional graph of the strength orientation and restraint data. As a general rule, increasing the restraint during drying will increase tensile strength. For any pulp handsheet there is a limit to the increase, and for these handsheets the limit was reached when they were stretched about 1% and held until dry. Stretching beyond 1% tended to reduce strength, possibly due to a reduction in the amount of fiber-to-fiber bonding.

While it might be argued that drying restraint also may change the fiber orientation, attempts made to show changes in orientation by time-lapse photography during drying did not confirm this. These findings, however, do not rule out the possibility of changes in orientation of fibrils and smaller microscopic particles.

A consideration of tensile strength and fiber orientation inevitably leads to a question of what strength paper would have if all of the fibers were to be oriented to the same angle. One estimate, at least at the limit, can be gained by considering values for strength and density of individual fibers. If fiber strength is taken as 100,000 psi as reported by Jayne (*3*), and fiber density as 1.5 g/cm^3, then a handsheet with a density of 0.4 g/cm^3 and having all fibers lying in the test direction might have a tensile strength in the vicinity of 26,700 psi [100,000/(0.4/1.5)] if all fibers were stressed to failure in unison. It will be shown later that this appears to be a reasonably good estimate.

To better understand how fiber orientation affects tensile strength, a graph of orientation vs. strength was made on log paper as shown in Fig. 6. The strength values for handsheets were taken from Fig. 5 for a restraint or "wet-to-dry dimensional change" of ±1%. This plot also shows tensile strength orientation data for paper made on our experimental fourdrinier paper machine from a bleached softwood kraft pulp. The density of the paper was about 0.75 g/cm^3. These represent tests made at various angles to the machine direction and a calculation of fiber orientation based on the measurement of number and angle of dyed fibers in the paper. Figure 6 shows that the data for handsheets and those for the machine-made paper both exhibit linearity and that both lines have the same slope. The somewhat greater strength value for the machine-made paper, at a given fiber orientation ratio, is probably due to a number of interacting variables related to formation and fiber bonding. On the basis of density alone, an even larger spread between the lines would be expected. However, it seems likely that the density of the machine-made sample was achieved in part by compacting the sheet without increasing the amount of fiber-to-fiber bonding. Therefore, the spread between data lines for handsheets and machine-made paper has no particular significance. The fact that the two lines are parallel is more important because it indicates that the influence of orientation on strength for handsheets is the same as for machine-made paper.

The third line drawn on Fig. 6 is for data reported by Zehrt (*4*) from a study of factors affecting the tensile strength of structural lumber. The line plotted is that of an interaction formula fitting data for tensile strength of Douglas-fir having various slopes of grain. It is quite remarkable that the slope of this line is nearly identical to that of lines for our test handsheets and machine-made paper. However, experimental data for the Douglas-fir line fall between 6000 and 16,000 psi, and thus the values on either side of the

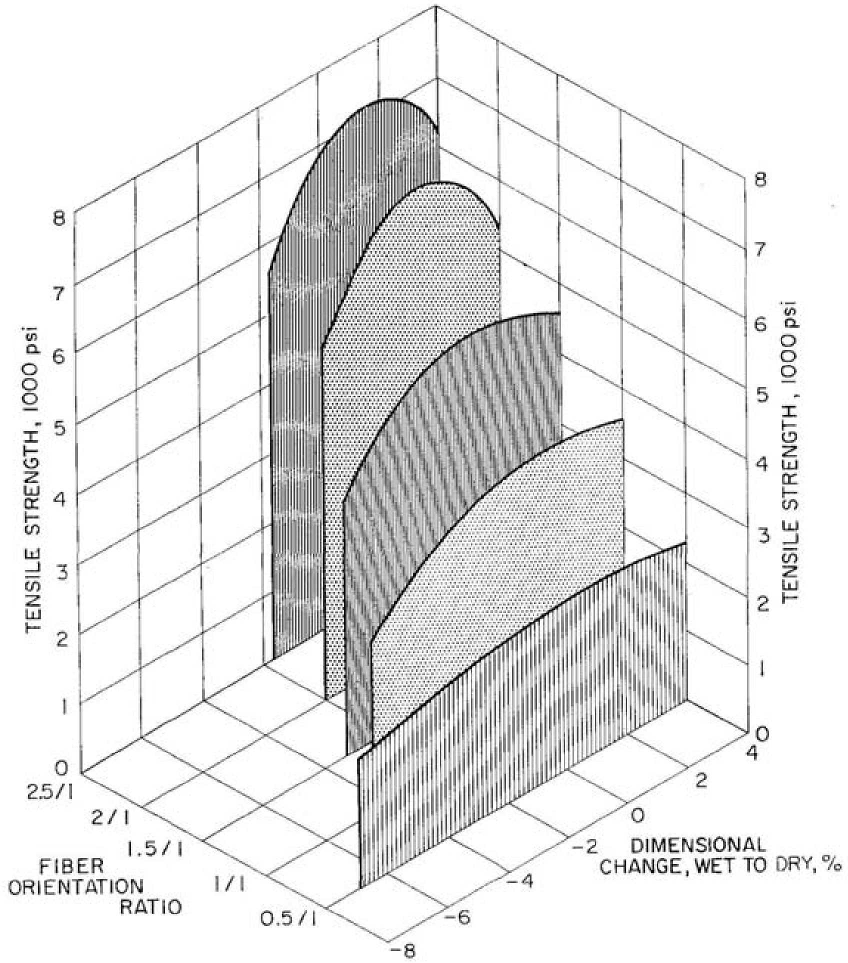

Fig. 5. Three-dimensional view of relationship between tensile strength, restraint during drying, and fiber orientation.

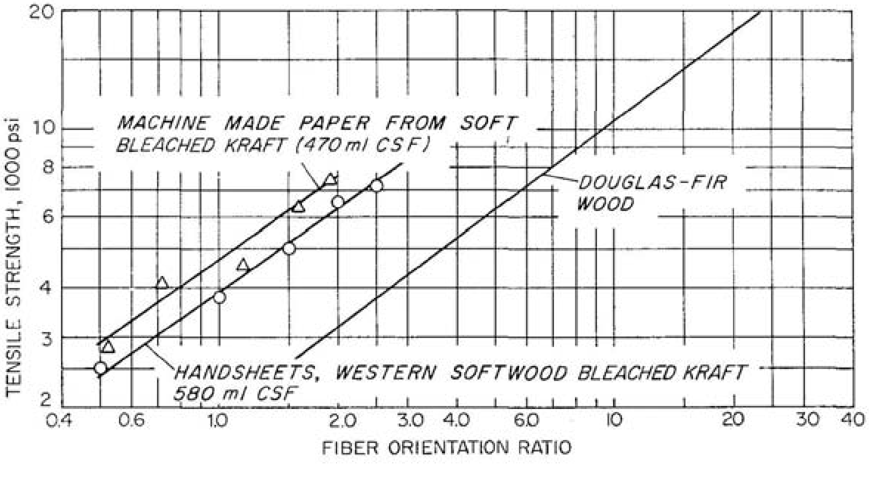

Fig. 6. Relationship between tensile strength and fiber orientation for handsheets, machine-made paper, and Douglas-fir.

range amount to a projection of the data. This projection, however, is somewhat confirmed on the lower side by the perpendicular-to-grain strength of Douglas-fir, which Zehrt found to be 340 psi. Thus it would appear that, for the same degree of fiber orientation, paper has much a higher tensile strength than Douglas-fir.

The wood samples had a density of around 0.5 g/cm^3 and were tested at a moisture content of 10% based on the OD weight. Consequently, the difference between the lines for wood and paper does not appear to be attributable to moisture or density differences. It seems more appropriate to question whether the data are truly comparable because wood and paper having the same degree of orientation obviously do not have fibers arranged in the same manner. A fiber orientation ratio of 1.0 refers to paper with an "average" or random distribution of fibers in all directions. Using the same terminology with wood, an orientation ratio of 1.0 is equivalent to a slope of grain of 45°. While this on the average is the same as that of paper with an orientation ratio of 1.0, its behavior is likely to be quite different.

On the other hand, the fibers in the pulp handsheets contained about 85 % cellulose and 15% hemicellulose while the Douglas-fir contained only about 40% cellulose, the remainder being made up of 29% hemicellulose, 28% lignin, and 3% extractives. Thus with a 2-to-1 advantage in cellulose, it perhaps is not surprising that the tensile strength ratio for equivalent fiber orientation is the same (2/1) as the ratio of cellulose content.

While the foregoing discussion is pertinent to the data presented, it tends to obscure the more practical implications and reasons for including these data with test results of paper materials. Through the use of the interaction formula derived by Norris (*5*) and evaluated by Zehrt (*4*), we have a means of estimating tensile strength in the principal direction of paper with perfectly oriented fibers. In addition, and obviously much more significantly, we will demonstrate the feasibility of applying principles of engineering mechanics to practical paper problems. The equation used is as follows:

$$\frac{1}{F_\phi^2} = \frac{\cos^4\phi}{F_1^2} + \left[\frac{1}{F_{12}^2} - \frac{1}{F_1F_2}\right] \times \sin^2\phi\cos^2\phi + \frac{\sin^4\phi}{F_2^2}$$

where

F_ϕ = Tensile stress at an angle ϕ to the grain

F_1 = Tensile stress parallel to the grain

F_2 = Tensile stress perpendicular to the grain

F_{12} = Shear stress parallel to the grain

Given experimental values of ϕ and F_ϕ, values of F_1F_2 and F_{12} are determined by a best-fit calculation using the method of least squares. An initial guess at F_1, F_2, and F_{12} is made by the operator and the computer program calculates successive corrections until the correction is smaller than some preassigned value. The curve obtained using the Norris formula (*5*) is shown in Fig. 7. The solid circles represent handsheet data in the experimental ranges while the open circles represent projected data for the handsheets from Fig. 6.

It is interesting to observe that the formula calculates F_1, the strength parallel to fibers of a perfectly oriented handsheet (at a density of 0.4 g/cm^3), as 26,700 psi, which is about the same value predicted from fiber strength and density

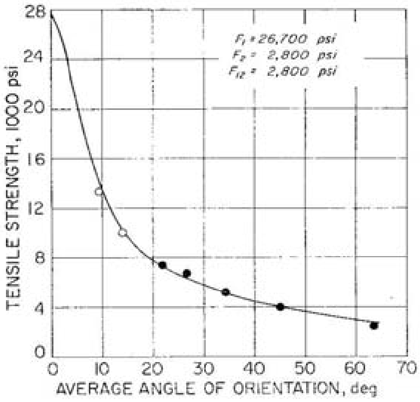

Fig. 7. Calculated and experimental tensile strength values. The curve was obtained by using the Norris formula (5). Solid circles represent handsheet data in experimental ranges, and open circles represent projected handsheet data from Fig. 6.

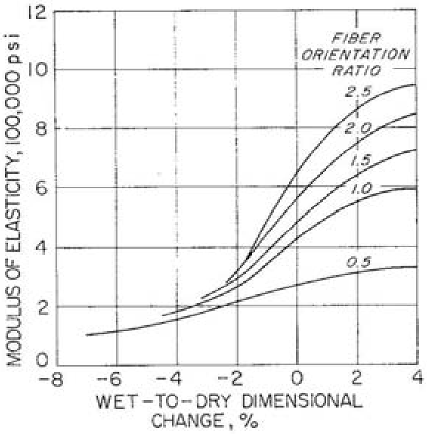

Fig. 8. Relationship between modulus of elasticity and wet-to-dry dimensional change for various fiber orientation ratios.

data. The tensile strength at right angles to the axis of a perfectly oriented handsheet (F_2) would be 2800 psi. This seems like a difficult value to verify. The shear strength (F_{12}) of 2800 psi agrees very well with shear strength values of 200 kg/cm^2 (2840 psi) reported by Setterholm *et al.* (*6*).

Whether these values are perfectly correct is perhaps less important than the knowledge that tensile strength at various angles can be related through a mathematical expression. The close fit of the calculated and experimental results (Fig. 7), the close prediction of shear strength, plus the knowledge that this expression holds for Douglas-fir, increase our confidence in extending our estimates beyond the range of experimental data. These results are, however, by no means conclusive.

Modulus of Elasticity

Stretch-dependent properties such as modulus of elasticity were as dependent on restraint during drying as they were on fiber orientation differences over the range examined in this report. This is not to say that fiber orientation does not exert a strong influence on the stretch characteristics of paper. Figure 8 shows the relationship between modulus of elasticity and wet-to-dry dimensional change (degree of restraint) for five levels of fiber orientation from 0.5 to 2.5. At the lower level of orientation, drying under restraint increased the modulus of elasticity by 250,000 psi, while at the higher level of orientation the restraint during drying increased elasticity by 600,000 psi. On a percentage basis, however, these were comparable increases of about 300%.

While tensile strength data show peak values at or near 1% stretch (Fig. 4), the modulus of elasticity at this point is still increasing. In this and other ways we see a different shape to curves for modulus of

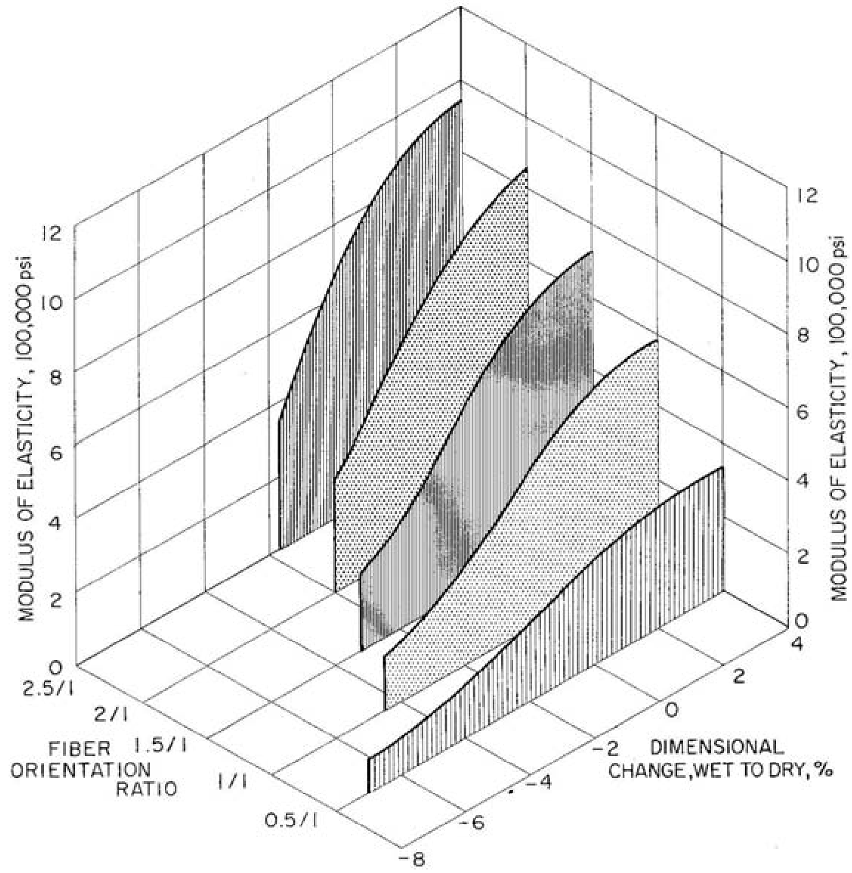

Fig. 9. Three-dimensional view of relationship between modulus of elasticity, fiber orientation, and restraint during drying.

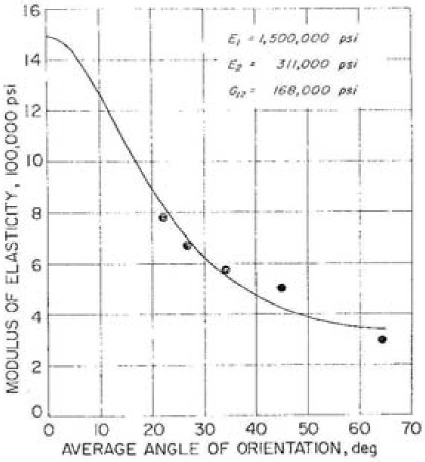

Fig. 10. Calculated and experimental modulus of elasticity values.

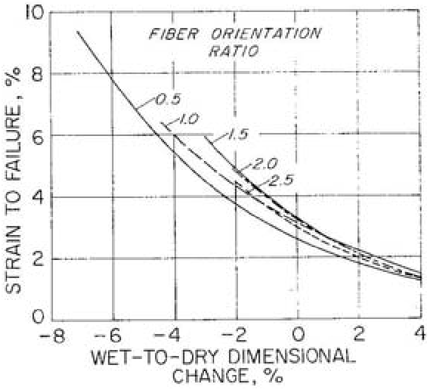

Fig. 11. Relationship between strain to failure and wet-to-dry dimensional change for several fiber orientation ratios.

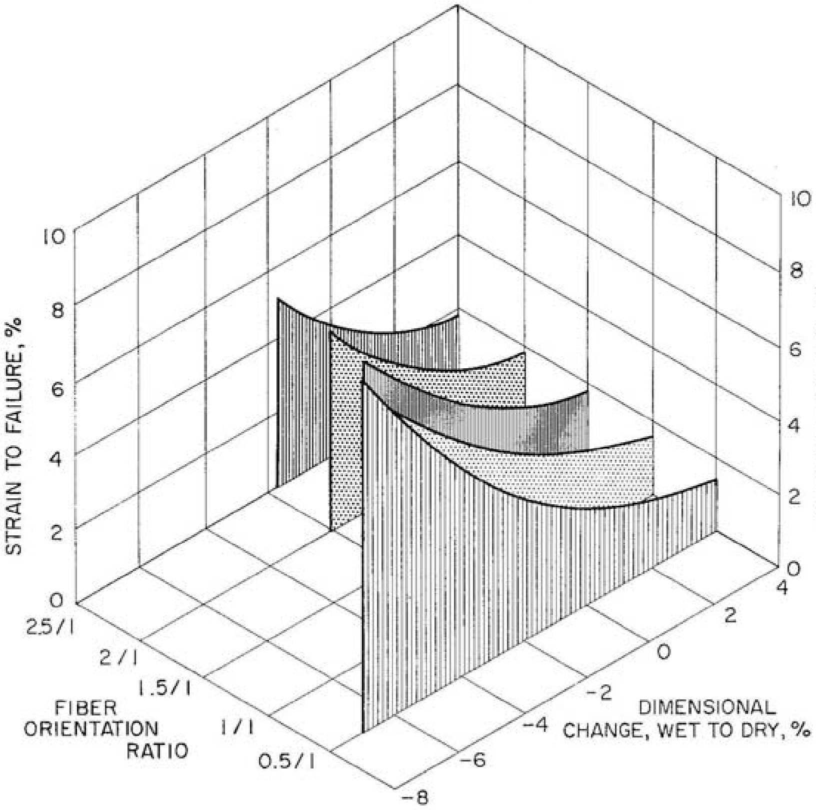

Fig. 12. Three-dimensional view of relationship between strain to failure, fiber orientation, and restraint during drying.

elasticity vs. restraint than for strength vs. restraint for the various levels of fiber orientation. This is best illustrated by comparing Figs. 5 and 9, which shows that there need not be any fundamental relationship between strength properties and the elastic or viscoelastic properties of paper. Thus, care should be taken when predicting strength properties from sonic modulus-of-elasticity data. Frequently it may be practical to do so, but when both restraint and fiber orientation are subject to change in paper, the practice would seem risky at best.

A mathematical analysis of the relationship between modulus of elasticity and fiber orientation of handsheets was made using equations for orthotropic laminates (7). According to the theory, the modulus of elasticity at any degree of slope of grain (fiber orientation) is dependent on shear modulus, Poisson's ratio, and modulus of elasticity parallel and perpendicular to the fiber direction of perfectly oriented handsheets as shown in the following expression:

$$\frac{1}{E_\phi} = \frac{\cos^4 \phi}{E_1} + \frac{\sin^4 \phi}{E_2} + \left[\frac{1}{G_{12}} - \frac{2\mu}{E_\phi}\right] \sin^2 \phi \cos^2 \phi$$

where

E_ϕ = modulus of elasticity at some angle ϕ

ϕ = fiber orientation or slope of grain

E_1 = modulus of elasticity parallel to fiber axis of perfectly oriented handsheet

E_2 = modulus of elasticity perpendicular to fiber axis of perfectly oriented handsheet

μ = Poisson's ratio

G_{12} = shear modulus associated with distortion of the 1–2 plane

Using a procedure similar to that described for estimating tensile strength by best-fit curve, Fig. 10 was prepared. The modulus-of-elasticity values used to fit the curve were taken from Fig. 8 and were chosen at the level of restraint which gave maximum strength (about 1% stretch).

Examination of Fig. 10 shows that the modulus of elasticity for a perfectly oriented handsheet (E_1) at a density of 0.4 g/cm^3 is 1,500,000 psi. This agrees fairly well with the modulus of elasticity of wood having the same density. On a density basis, this handsheet modulus of elasticity corresponds with a fiber modulus of elasticity of 5,600,000 psi which agrees somewhat with data presented by Jentzen (*8*).

The modulus of elasticity across the fibers (E_2) was estimated at 311,000 psi. No estimate is offered as to the correctness of this value. The shear modulus G_{12} of 168,000 psi agrees well with values reported by Setterholm *et al.* (*6*).

If we assume that these data are reasonably accurate, what is the significance of these findings? Perhaps most important, they provide additional evidence that certain theories or design criteria for wood also can be applied to paper. In addition to the potential of engineering applications, this approach can broaden our knowledge of paper behavior more quickly than point-by-point incremental accumulation of data. A few tests of paper for different levels of fiber orientation could be used to describe elastic properties over a wide range of fiber orientation values.

While small changes in fiber orientation in the region of perfect parallel alignment result in substantial differences in modulus of elasticity, the magnitude of change is not nearly as great as that exhibited by tensile strength when fiber orientation is changed. Changes in modulus of elasticity or stiffness of paper are better controlled by varying the degree of shrinkage or restraint during drying.

Strain at Failure

The most unexpected result of this study was the relationship between strain-at-failure stretch values and the orientation–restraint variables. Although it is well known that drying restraint will reduce the stretch of paper, the data presented in Fig. 11 show that fiber orientation has only a small influence on tensile stretch. It appears that stretch in these handsheets is governed almost entirely by tension during drying. Figure 12, which gives a three-dimensional view, shows that handsheets having the lower Orientation ratios are most sensitive to differences in the level of restraint.

If these results are typical of paper behavior, some explanation for these phenomena, should be developed, because high stretch is a quality often sought by paper users. One tentative suggestion is that restraint improves the uniformity of stress between fibers so that when failure occurs, it occurs rather abruptly and simultaneously in many fibers.

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