A LABORATORY METHOD FOR BIAXIAL STRAINING OF PAPER DURING DRYING

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ABSTRACT

During the paper drying process, it is possible to make large changes to the paper properties by straining the paper web. As an example, laboratory studies have shown that an 8% strain increase, from -4% (shrinkage) to +4% (stretch), can give a relative increase in tensile stiffness of as much as 500%! The strain at break is reduced to the same extent and the tensile strength can be doubled.

Based on pioneering work by Brecht and Lindem, a new apparatus was developed. The apparatus described in this paper is capable of controlling the stresses and strains of the paper independently in two mutually perpendicular directions during drying. The function of the apparatus is described and its potential for producing reproducible results has been evaluated.

To investigate whether stress or strain could be used as a controlling parameter for paper properties, two experiments with different drying strategies were carried out. In both cases, the final strain during drying was found to be the controlling parameter for the in-plane mechanical properties evaluated.

INTRODUCTION

During the paper-drying process, it is possible to make large changes to the paper properties by straining the paper web. As an example, laboratory studies have shown that an 8% strain increase, from -4% (shrinkage) to +4% (stretch), can give a relative increase in tensile stiffness of as much as 500%! The strain at break is reduced to the same extent and the tensile strength can be doubled (Setterholm and Kuenzi 1970). The strain during drying is also known to affect compression properties (Meyers 1967), dimensional stability (Nordman 1958) and surface properties (Lindem 1991).

In conventional paper machines, the paper web can be stretched in the machine direction to different extents by varying the speed, for example between different dryer groups. Over the dryer cylinders the pressure from the dryer fabric prevents the paper from shrinking in the cross machine direction. Between each pair of dryer cylinders, the paper web passes a free draw where there are no forces acting on the edges of the web. This allows the paper to shrink in the cross machine direction. The degree of shrinkage can be affected by for example varying the dryer construction (longer free draws increase the total web width shrinkage) and pulp characteristics (increased refining increases shrinkage). The conditions in the free draw results in higher cross directional shrinkage at the edges than in the centre of the paper web (Viitaharju and Niskanen 1993). Consequently also a profile in paper properties is unavoidable in the cross machine direction (Hansson et al. 1989). Shrinkage results in a higher grammage and a grammage compensation must be introduced to obtain a uniform cross machine grammage profile. If the compensation is made by reducing the slice opening of the headbox, transverse flows are induced. Such flows can cause deviations in fibre orientation angle, which in turn can cause runnability problems during converting due to twist curl and twist warp.

Obviously there are several good reasons for controlling the strain in the paper, both in the machine direction and in the cross machine direction during drying. In order to obtain fundamental knowledge of how different combinations of strains in the two directions influence the final paper properties there is a need for improved laboratory methods. Uniaxial strain and stress experiments have been performed in several investigations, but only a few studies deal with biaxial strain and stress. The term "biaxial" in this context means that loading is imposed in the plane of the paper in mutually two perpendicular directions. Based on pioneering work by Brecht et al. (1956) and by Lindem (1994) a new apparatus was developed. The apparatus, described in this paper, is capable of controlling the stresses and strains of the paper independently in two mutually perpendicular directions during drying. The function of the apparatus is described and its potential for providing reproducible results is evaluated.

MATERIALS AND METHODS

Nomenclature

Table 1 lists terms, definitions, symbols and units used in this investigation. Moisture ratio was used to characterise the moisture content of the paper. The advantage of using moisture ratio rather than dry solids content is the linear representation of the evaporated moisture. For example, an increase of 10% dry solids content in the interval from 35 to 45% corresponds to 5 times more evaporated moisture (Δ mr) than an increase of 10% in the interval from 85 to 95%, as shown in **Figure 1**.

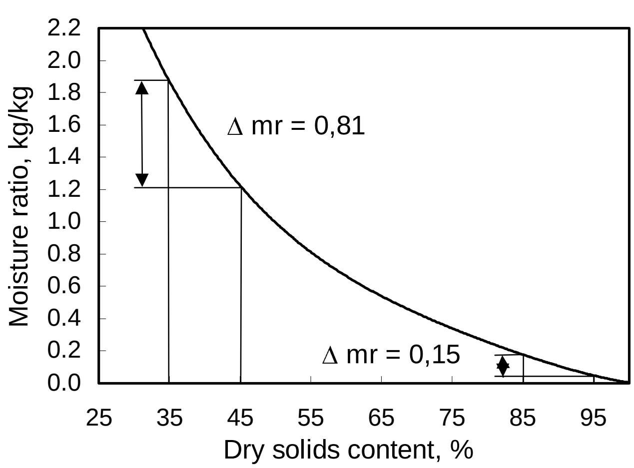

Figure 1. Relation between moisture ratio and dry solids content.

Table 1. Terms, definitions, symbols and units used.

Term	Definition	Symbol	Unit
Machine direction	Direction in the running direction of the paper machine.	MD	-
Cross machine direction	Direction transverse to MD in the plane of the paper.	CD	-
Strain	Elongation divided by original length. A positive strain means that the material is elongated and a negative strain means a reduction in length.	ε	%
Stress	Force measured during drying divided by test piece width.	σ	N/m
Final strain	Total amount of strain after finished drying.	$\varepsilon(F)$	%
Final stress	Total amount of stress after finished drying.	$\sigma(F)$	N/m
Specified strain	The paper was stretched or allowed to shrink to a pre-determined value at the beginning of the drying process. When the pre-determined strain was reached it was held constant.	$\varepsilon(S)$	%
Specified stress	Stress was allowed to build up to a pre-determined value by restraining the shrinkage in the initial part of the drying process. When the pre-determined stress was reached it was held constant by allowing shrinkage.	$\sigma(S)$	N/m
Grammage	Determined on conditioned test piece after drying.	*w*	g/m^2
Moisture ratio	Mass of moisture in a test piece divided by mass of dry matter.	*mr*	kg/kg
Dry solids content	Mass of dry matter in a test piece divided by the sum of mass of moisture and mass of dry matter.	*d*	%

Sheet Making

A bleached kraft softwood pulp, beaten to 25.0 SR (SCAN- C 19: 65) in an industry-like refiner, was used. Paper was made on STFI´s pilot paper machine EuroFEX (Roding and Norman 1986). The anisotropy in Tensile stiffness (MD/CD) for a restrained dried sample of the paper was 2.3 and the grammage 60.7 g/m^2 measured at 23°C and 50% relative humidity. The wet papers were pressed in the pilot machine to a dry solids content of 42.4%, which is equal to a moisture ratio of 1.36 kg/kg.

Paper Properties

Tensile stiffness index, tensile index, strain at break and tensile energy absorption, TEA, were measured according to SCAN- P 67:93. Two papers were dried to produce 12 test pieces for each test point and direction. Confidence intervals (t-distribution) with 95% confidence limits are reported for all measurements. Tensile stiffness index was also evaluated by ultrasonic velocity measurements in eight in-plane directions of the paper (Linblad 1996).

Laboratory Method for Biaxial Straining of Paper during Drying

Figure 2 shows a schematic drawing of the apparatus used. The wet paper was fastened on all four sides in clamp packages. On two adjacent sides of the paper, the clamp packages was moveable by stepper motors. Load cells recorded the forces in the paper during drying. The strain in the paper was measured in two perpendicular directions by strain sensors. The drying was achieved without any surface contact, with a heated plate beneath the paper.

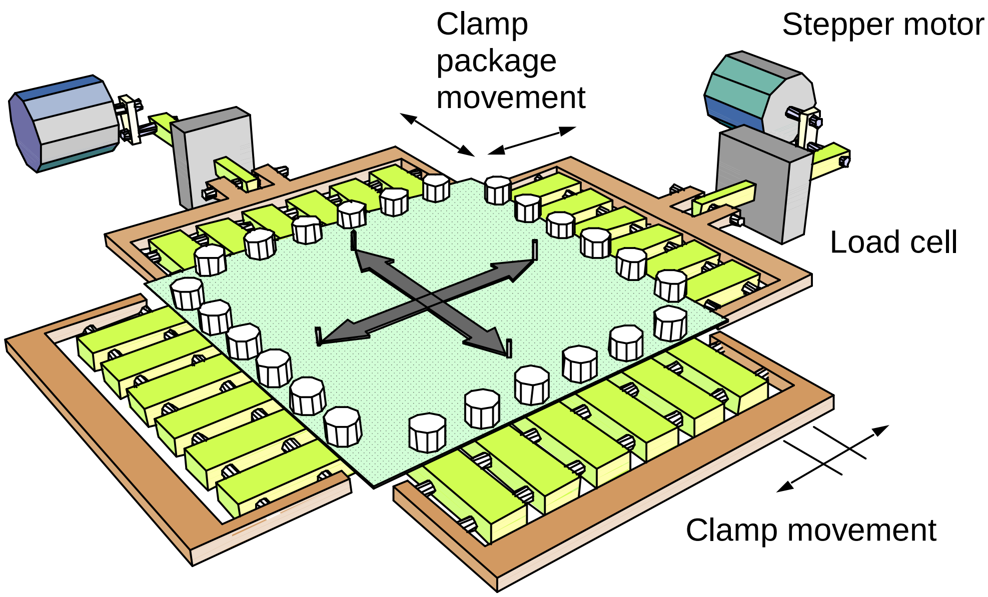

Figure 2. Schematic drawing of the biaxial straining apparatus.

A mounting plate assured that the wet paper was flat and prevented drying during the mounting procedure, **Figure 3**. The clamps moved downwards in a vertical motion to avoid damage to the paper. Needles attached to strain sensors were pushed through the wet paper into a cork backing in the mounting plate. Finally the mounting plate was removed, the heating plate raised to position and the drying of the paper was started.

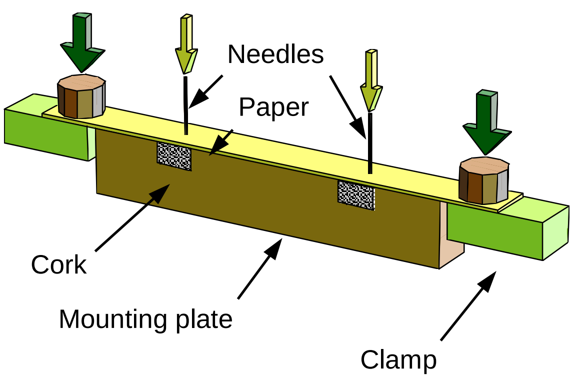

Figure 3. Schematic description of the mounting procedure.

Drying was carried out without any surface contact, by a heated plate, 150 mm ×150 mm, positioned 20 mm below the paper. The surface temperature of the heated plate was adjustable between 23°C and 150°C. The temperature during each experiment was chosen to achieve the desired drying time. The experiments were performed in a conditioned room at 23°C and 50% relative humidity. The moisture ratio of the paper during drying was not measured directly on the paper but by a calibration procedure.

The paper was fastened on all four sides in clamp packages. Each clamp package consisted of six clamps. Each clamp was moveable sideways, being mounted on rods parallel to the paper sides with ball bearings. On two adjacent sides of the paper, the clamp packages were moveable perpendicular to the paper sides by stepper motors. This arrangement made it possible to control the strain in the two perpendicular directions of the paper independently and simultaneously. Since six discrete loading points on each side achieved the deformation of the paper, the strain field is inhomogeneous near the clamps. The size of the paper between the clamps was 170 mm ×170 mm. An area of 120 mm ×120 mm in the middle of the paper was considered to have a strain field sufficiently uniform for physical testing. The surface temperature of the clamps was adjustable between 23°C and 90°C. The temperature was chosen to dry the area under each clamp with at the same drying rate as the area used for physical testing. A lower drying rate would have lead to breakage of the paper close to the clamps. Too high a drying rate would have caused the inhomogeneous area close to the clamps to increase and thus reduce the area with an even strain field.

An example of the clamp movements in a typical straining situation is shown in **Figure 4**. The paper was stretched in the 1-direction and allowed to shrink in the 2-direction. As a result of the stretching, the filled clamps were spread out. As a result of the shrinkage, the unfilled clamps were moved closer together.

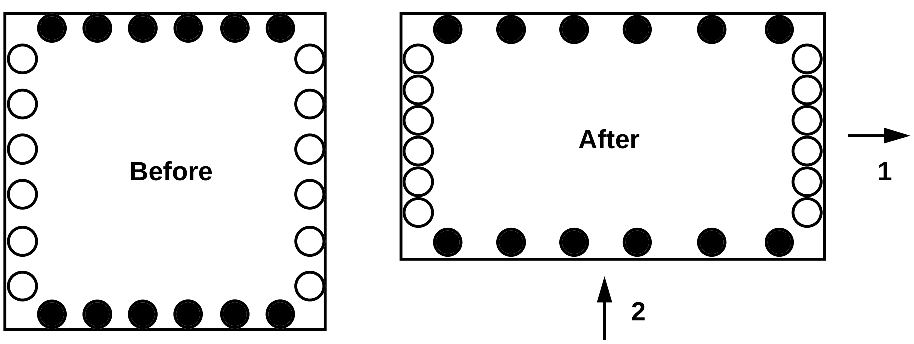

Figure 4. Movements of the clamps when stretching the paper in the 1-direction and allowing shrinkage in the 2-direction.

Strain was measured directly on the paper by strain sensors equipped with needles pushed through the wet paper. One pair of sensors was used for each perpendicular direction of the paper. **Figure 5** shows the pair of strain sensors used for measuring strain in the b- direction. This pair also had to be able to adapt to strains in the a- direction without the measurement in the b-direction being affected. This was achieved by using two shafts in each strain sensor. For movement in the measuring direction (b), the sensors rotated around shaft B. For movement in the perpendicular direction (a), the sensor rotated around shaft A. Only rotation around shaft B affected the strain transducer. The force needed to move the sensor (about 4 grams) was low enough not to damage the paper. Each strain sensor was calibrated individually with a mechanical calibrator having a resolution of 0.01 mm.

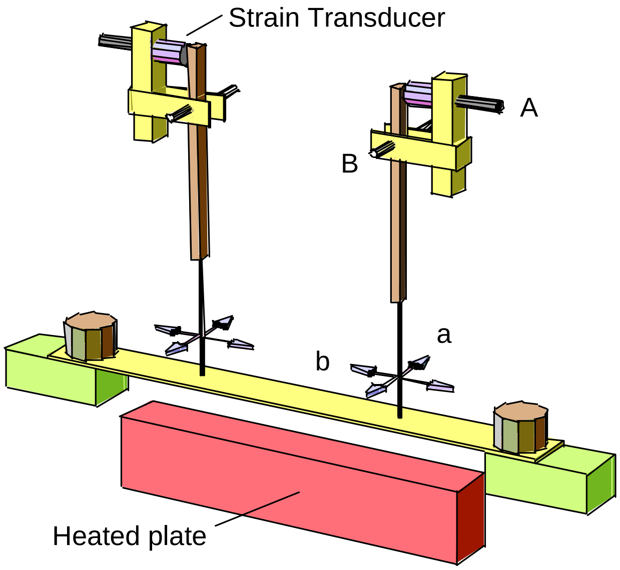

Figure 5. Principle for strain measurement in one direction.

Straining could be performed under either load control or strain control. Under load control, the stress in the paper was kept at a given level, allowing either shrinkage or stretch during drying. Under strain control, the paper was stretched or allowed to shrink to a given level of strain. Under a true strain control, the material should be compressed to a negative value of strain. Since compression of the paper was not possible, the paper's own ability to shrink during drying was used to reach the desired level of strain. The stress and strain were controlled by load cells and stepper motors connected to the moveable clamp packages. In the experiment reported in this paper, the step length was 0.0012 mm and the straining speed 0.30%/s.

RESULTS AND DISCUSSION

Heating

The surface temperature of the heating plate mainly influences the drying time as shown in **Table 2**. Drying times shorter than 300 seconds were not possible to evaluate in the laboratory dryer. The change in tensile stiffness index and strain at break with increasing drying time was not significant. The relatively long drying time used here compared to the drying time on a real paper machine is not likely to influence the results. A surface temperature of 100°C was used in the experiments. A longer drying time would have led to a time-consuming method. A shorter drying time would have led to a lower accuracy of the calibration curve.

Table 2. Heating plate surface temperature

Surface temp., heating plate, °C	Drying time, s	Tensile stiffness index, MNm/kg	Tensile index, kNm/kg	Strain at break, %
23	4500	10.5 ±0.30	38.3 ±1.60	2.24 ±0.19
50	1000	10.4 ±0.16	37.5 ±0.83	2.24 ±0.14
100	300	10.0 ±0.18	36.1 ±0.66	2.18 ±0.18

The moisture ratio of the paper during drying was not measured directly on the paper but was determined by a calibration procedure. A calibration curve was made by varying the drying time while keeping the drying conditions constant. For each drying time, six papers were dried and the moisture ratio for each paper at the desired drying time was determined gravimetrically and plotted versus time. **Figure 6** shows the calibration curve for moisture ratio versus drying time. After an initial constant drying rate the falling rate stage, period began after about 200 seconds. The variation in in-going moisture of the paper samples used was considered to be small. The coefficient of variation (standard deviation divided by average) for the moisture ratio of 12 samples stored in a plastic bag for one month was 0.032%.

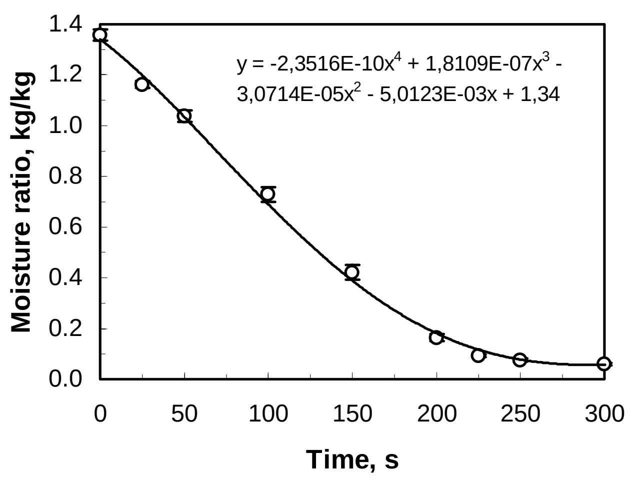

Figure 6. Moisture ratio versus drying time.

Clamping System

To evaluate whether the clamping system influenced the paper properties, six papers were dried without allowing any strain during the drying process. From each paper, 11 test pieces were cut from 11 positions according to **Figure 7**. The tensile stiffness index and strain at break for each position are also shown in Figure 7. No deviation from the mean value could be seen for tensile stiffness index. For strain at break there was a small deviation closest to the clamps. In subsequent experiments only test pieces from positions 3- 9 were used.

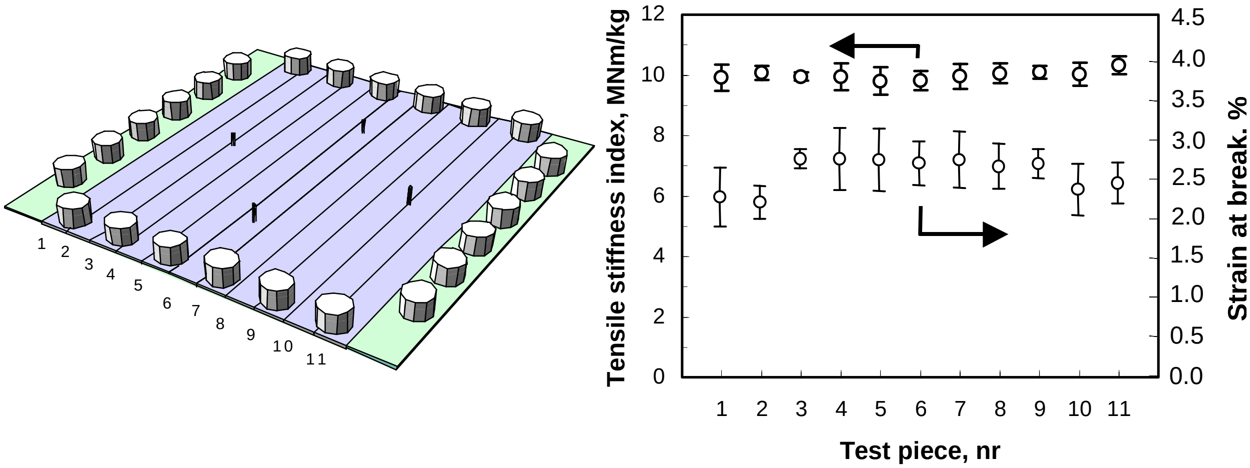

Figure 7. Description of how the test pieces were cut out and the corresponding property profile.

System for Measuring Strain

With reference to Figure 5, **Figure 8A** shows the deviation in per cent strain created in the measurement of the strain in the a-direction when the pair of strain sensors were also subjected to a strain in the b-direction. **Figure 8B** shows the corresponding data thing for the pair of strain sensors not shown in Figure 5. The deviation was measured by moving each pair of strain sensors perpendicular to their measuring direction. Open and filled circles represent the two strain transducers in each pair of strain sensors. The measured errors were considered to be random and small enough not to affect the results.

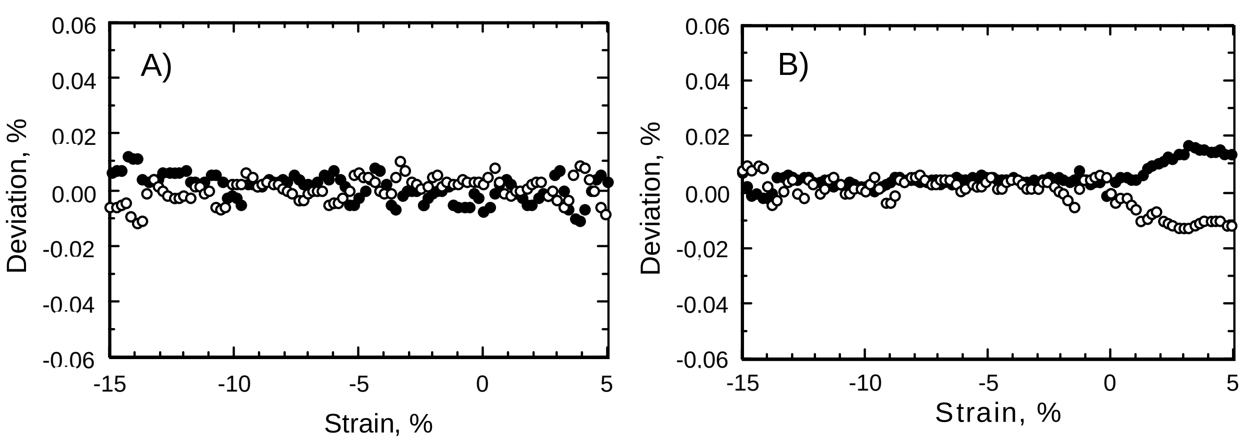

Figure 8. Deviation in the strain in the measuring direction versus strain in the non-measuring direction.

Definition of Free Shrinkage

When a paper is dried it strives to shrink and, if no forces are acting on the paper, the shrinkage is often referred to as free shrinkage. When the paper's own ability to shrink during drying was utilised in the experiments, for example to reach a desired level of negative strain (shrinkage) under strain control, this should preferably have been carried out as free shrinkage. In practice, drying the paper with low stress achieved this. Initially no strain was allowed, and this caused a stress to build up in the paper. When the stress reached a pre-determined level (specified stress), the stepper motors were activated to keep the stress constant.

Figure 9 shows that the specified stress influenced the final strain. When the specified stress was lower, the final strain was less in both MD and CD. **Figure 10** shows the influence of the specified stress on the tensile stiffness index and strain at break of the paper. The tensile stiffness index decreased and the strain at break increased with decreasing specified stress. To achieve a true free shrinkage, the specified stress should be 0 N/m. For practical reasons the smallest possible stress was 1 N/m. The shapes of the curves in Figure 10 indicate that the difference in stiffness and strain at break is negligible between 0 and 1 N/m. Consequently a stress of 1 N/m was used to produce papers with free shrinkage.

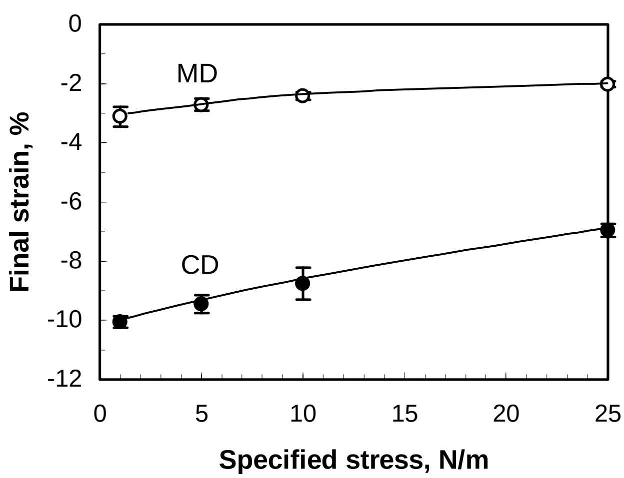

Figure 9. Strain versus stress during drying.

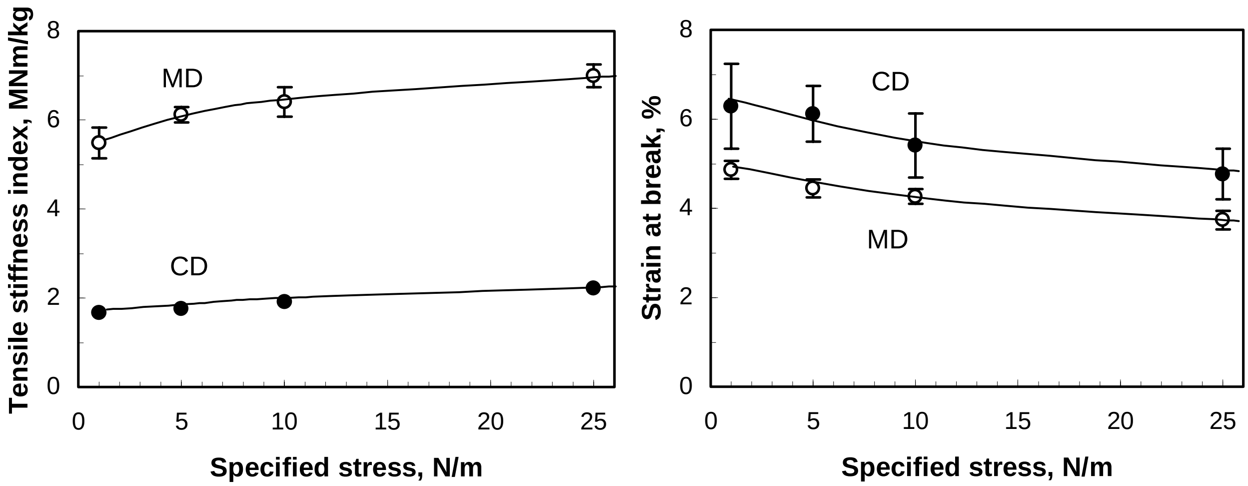

Figure 10. Tensile stiffness index and strain at break versus stress during drying.

Drying Strategies

To demonstrate the possibilities of the laboratory method, we give examples using three different drying strategies.

Restrained drying. When the strain is zero during the entire drying process, the strategy is often referred to as restrained drying. **Figure 11** shows how the stress was built up in a restrained dried paper. The stress increased exponentially with decreasing moisture ratio. The final stress was higher in the MD than CD.

Free shrinkage. **Figure 12** shows that the strain decreased exponentially with decreasing moisture ratio. The final strain was lower in the CD than MD (higher CD shrinkage).

MD stretch and CD shrinkage, **Figure 13**. In the MD 2% stretch was imposed at the beginning of the drying process. Thereafter no further change in strain took place. In the CD -4% strain (4% shrinkage) was allowed and thereafter no further change in strain took place. As a result of the stretch in MD, the paper contracted about 0.8% in CD.

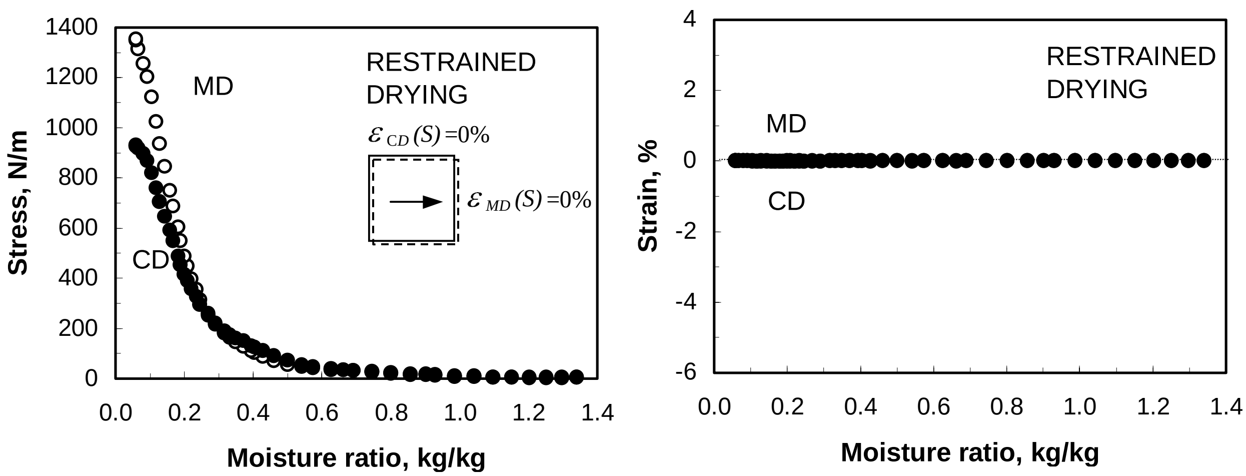

Figure 11. Restrained drying in MD and CD. Stress and strain versus moisture ratio.

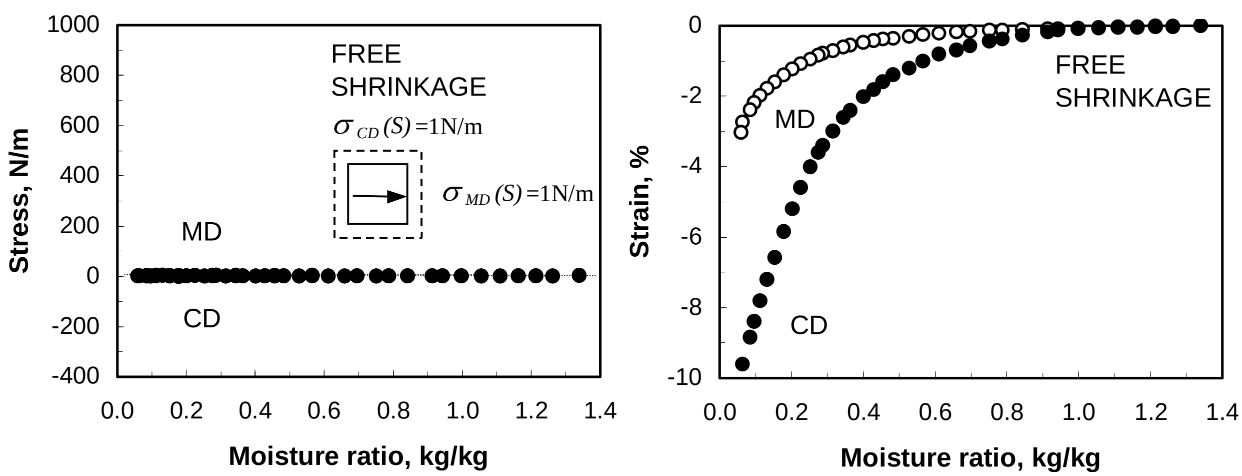

Figure 12. Free shrinkage in MD and CD. Stress and strain versus moisture ratio.

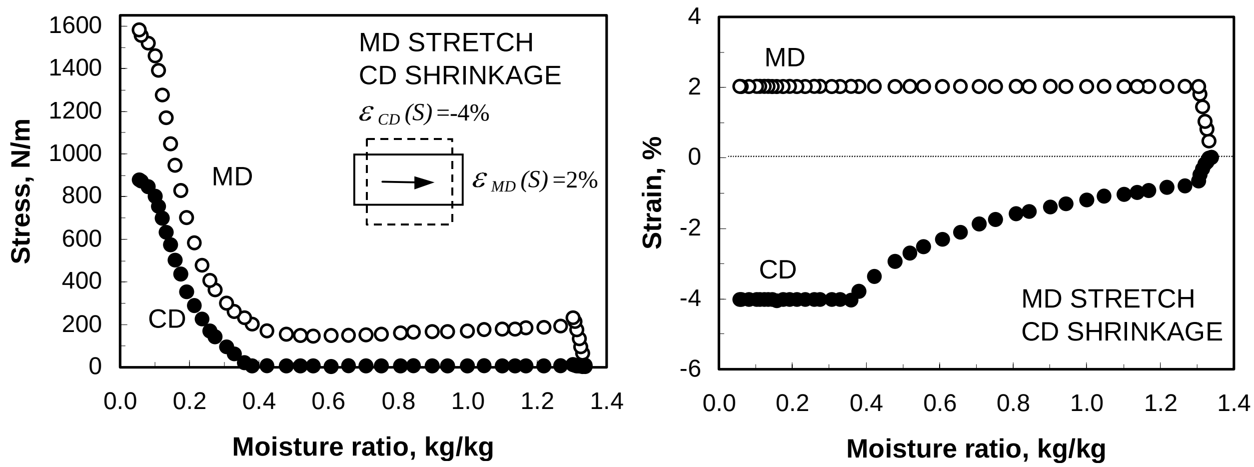

Figure 13. Two per cent stretch in MD and four per cent shrinkage in CD. Stress and strain versus moisture ratio.

Figure 14 shows the effect on tensile stiffness index (TSI) of the different drying strategies in Figures 11- 13. The results are expressed as a polar plot. The tensile stiffness index was very sensitive to the strain imposed in the paper during drying (specified strain). If shrinkage was allowed, the TSI was reduced, and when the paper was stretched, the TSI increased.

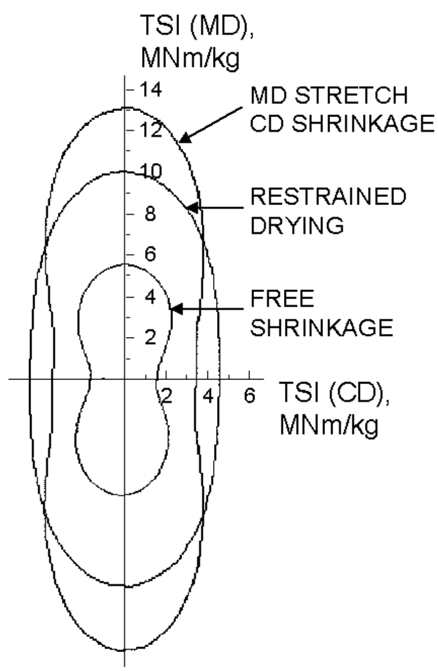

Figure 14. Tensile stiffness index (TSI) due to the drying strategies in Figure 11- 13.

Drying with Specified Stress and Strain

To investigate whether stress or strain could be used as a controlling parameter for the paper properties two experiments with different drying strategies were carried out. Papers were dried either under a specified stress or under a specified strain.

Drying with specified stress. The specified stress was not immediately imposed on the wet paper but was allowed to build up by restraining the shrinkage in the initial part of the drying process. When the specified stress was reached, it was held constant by allowing the paper to shrink. The left-hand graph in **Figure 15** shows the relation between specified stress and final strain for MD and CD. For the highest specified stress in MD and CD, the paper was dried under restraint. When the specified stress was reduced, the final strain decreased logarithmically.

Drying with specified strain. The paper was allowed to shrink immediately from the beginning of the drying. When the pre-determined strain (specified strain) was reached, no more shrinkage was allowed and a stress started to build up. Figure 15 shows that the more shrinkage that was allowed the lower was the final stress reached at the end of the drying process.

The arrows in Figure 15 illustrate the difference between the two drying strategies studied. Consider, as an example, drying with a specified stress of 100 N/m in the CD. When 100 N/m was reached the paper shrank almost 4% during the remaining drying time to maintain the specified stress of 100 N/m. When drying to the same specified strain (–4%) the final stress was built up to about 750 N/m. Obviously the relation between stress and strain is dependent upon the type of drying strategy used.

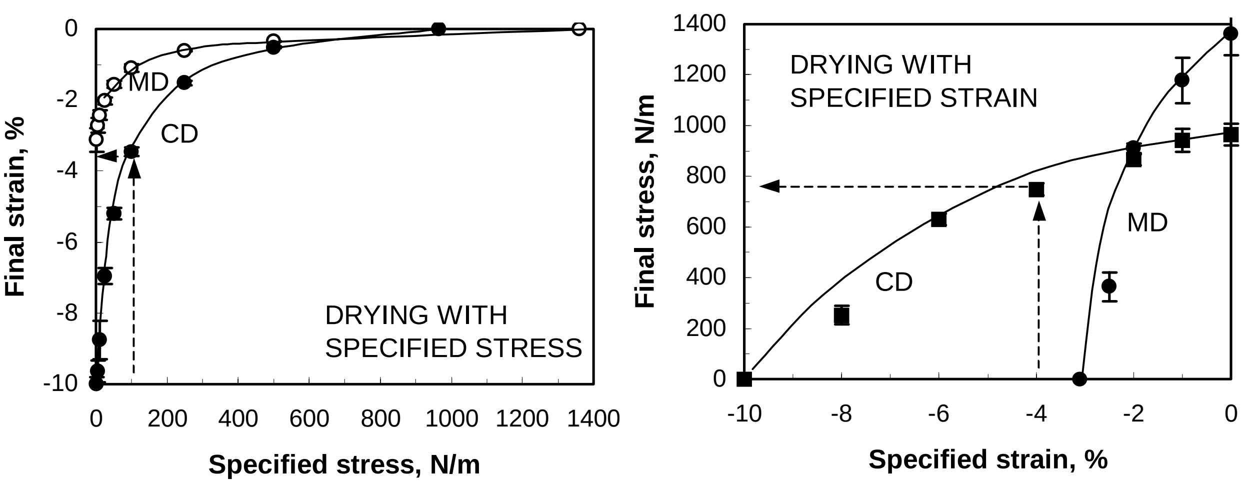

Figure 15. Strain versus stress during drying when drying under a specified stress and when drying to a specified strain.

In **Figure 16**, tensile stiffness index is plotted versus both stress and strain. When stiffness is plotted versus stress, different relations are obtained depending on whether the test is performed with specified stress or specified strain. On the other hand, if stiffness is plotted versus strain only one relation is obtained, regardless of whether the drying was performed with specified stress or specified strain. Obviously strain is the controlling parameter for tensile stiffness index, not stress.

Another observation regarding the results in Figure 16 is that it did not make any difference for the tensile stiffness whether the shrinkage took place at the beginning or at the end of the drying process. When drying to a specified stress, the shrinkage took place in the final part of the drying process, and when drying with specified strain the shrinkage occurred at the beginning. In both cases, strain was the controlling parameter for the tensile stiffness index.

Note that the lack of any dependence of drying strategy on the relation between tensile stiffness index and final strain only applies for the experiments performed. The independence is not for example valid in a situation where stretch is imposed at different moisture ratios as investigated by Htun (1986).

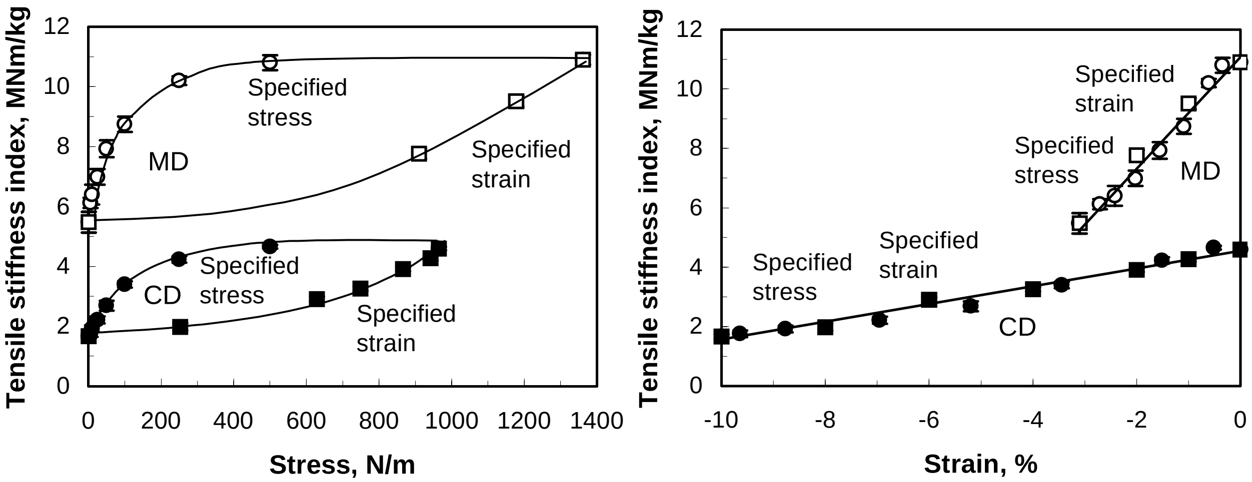

Figure 16. Tensile stiffness index versus stress and versus strain during drying for MD and CD. Drying was carried out with specified stress and with specified strain.

For strain at break, tensile index and tensile energy absorption, TEA, strain was the controlling parameter, **Figure 17.** All four in-plane mechanical properties evaluated followed linear relations when plotted versus strain in the same way as in Figure 16. The slope of the relations was different in the MD and CD. For example, the slope in tensile stiffness index was 1.9 MNm/kg/% in MD and 0.3 MNm/kg/% in CD. On the other hand, the relative change from free shrinkage to restrained drying was larger in the CD (175%) than in the MD (80%).

Setterholm and Kuenzi (1970) also found that the slope of tensile stiffness, strain at break and tensile index was dependent on the fibre orientation. Strain at break had the same value in both MD and CD when restrained dried. This result was in agreement with results of Htun and Fellers (1982).

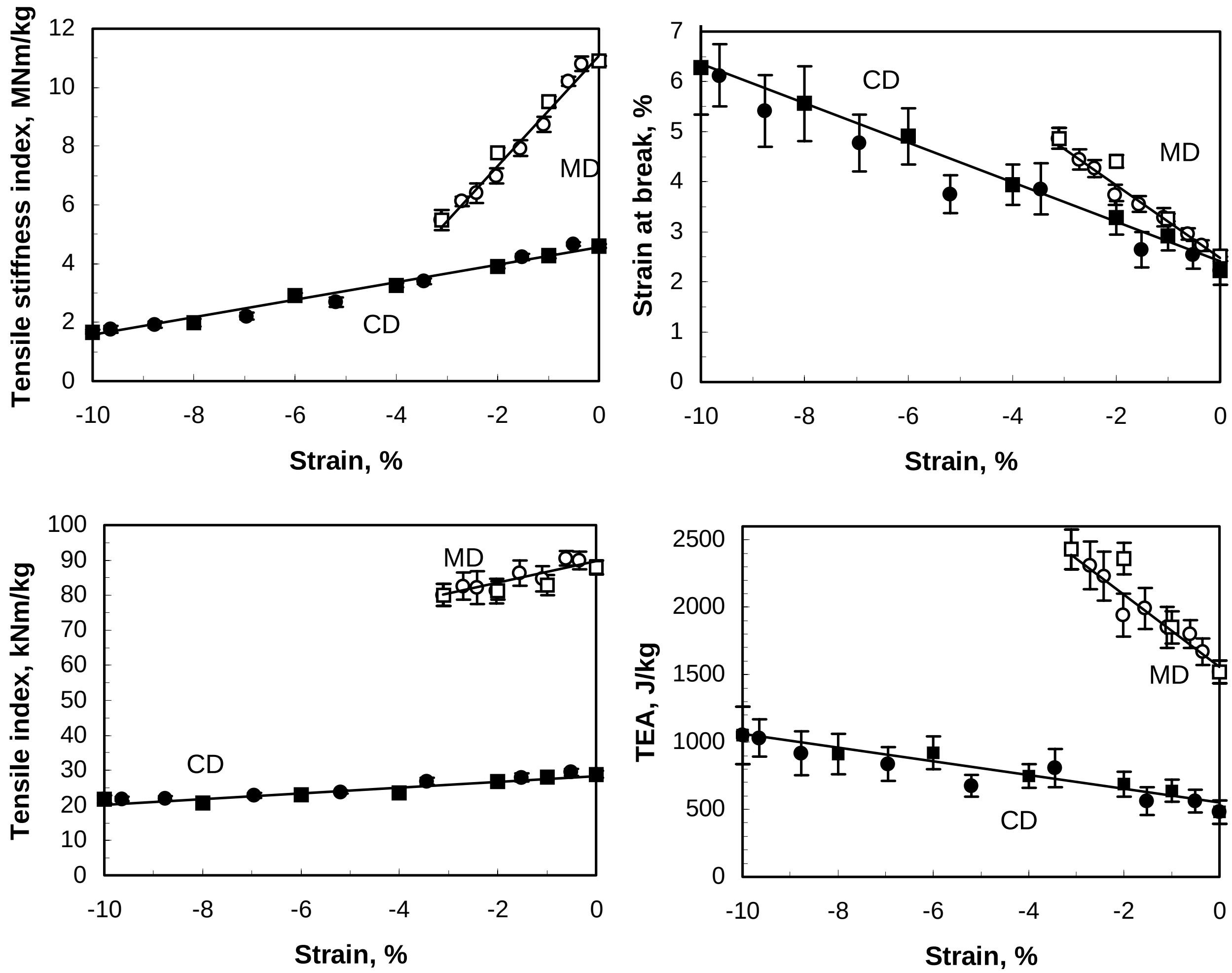

Figure 17. Tensile stiffness index, strain at break, tensile index and tensile energy absorption versus strain. Drying was carried out with both specified stress and specified strain.

CONCLUSIONS

An apparatus is described that is capable of controlling the stresses and strains of the paper independently and simultaneously in two perpendicular directions during drying.

The function of the apparatus and its potential for producing reproducible results have been evaluated and found to be satisfactory.

The strain imposed on the paper during drying was found to be the controlling parameter for the studied properties and drying strategies.

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