MULTI-STAGE TENSILE STRAINING DURING DRYING OF SC PAPER

By

J. Kouko[a] and P. Kekko[b]
[a]VTT Technical Research Centre of Finland
[b]Metso Paper
Finland

ABSTRACT

During multi-cylinder drying on a pasper machine, the paper web is under stress in the machine direction, whereas the cross direction is more or less free. The web shrinks due to drying and contracts due to web draws. The machine speed, dryness and tension level determine the speed difference between drive groups, which in turn determines the level of MD straining. Straining and stresses during drying have a significant influence on the elastic properties of paper. The objective of this study was to investigate the effects of multi-stage straining during drying on the tensile properties of dried paper.

Oriented SC paper samples were prepared on a pilot paper machine with varying levels of draw between the press and the press cylinders. Never-dried SC paper samples were then dried in a C-Impact laboratory tensile tester. The tensile force, strain, surface temperature and dryness of the samples were measured during drying.

The design of the trials was full factorial (multivariate), which enabled the use of statistical methods in the data analysis. Two of the five straining tests were performed on a pilot paper machine during sample preparation, and three of the five during drying on a laboratory tester. The draws were combined in order to form two separate 3^4 full factorial designs. It was concluded that the use of a fractional factorial design instead of a full factorial design would lead to equally statistically good results, but would also be biased towards the most powerful factor term.

The measured tension of the paper samples during drying was affected by the straining, dryness and tension relaxation of the paper. The straining and drying history of the paper also influenced the tensile properties. Increased straining generally led, almost linearly, to decreased strain at break of the dried paper. The tensile stiffness of the dried paper and the drying tension at the end of drying (final drying tension) were increased considerably by straining. Although a certain level of strain is needed to ensure wet web runnability, straining has a detrimental effect on a number of dry paper web properties. Straining strategy improvements can be made by controlling the dryness of straining. The C-Impact tensile tester was found to realistically simulate the paper drying process at paper machine conditions.

INTRODUCTION

Stress and strain during drying are known to significantly influence the tensile properties of paper [1–4], and variables such as pulp composition, pulp beating and fiber orientation are known to influence paper shrinkage and drying stresses [4–6]. A web dried under restraint will have a higher modulus of elasticity, higher tensile strength and better dimensional stability than a web allowed to shrink during drying [1]. The difference in paper properties are due to different drying stresses, different stress concentration levels, and changes in crystallinity index, fiber orientation and other fiber properties [7–8]. Various explanations are given regarding the effects of restrained drying on fiber properties [9–14], although fiber-level effects are not discussed in this work.

The process of paper web drying on a paper machine after wet pressing comprises three phases: (1) the heating period, (2) the constant rate period and (3) the falling rate period. During the heating period the temperature of the web increases to the level of adiabatic saturation. During the constant rate period, the web is saturated with water. The constant rate period proceeds until all free water has been removed from the voids between the fibers, i.e. the critical moisture content is reached. In the falling rate period the temperature of the web continues to rise until the paper is dry [3].

Arlov and Ivarsson found that the stress-strain properties of a paper sheet depend on the dimensional changes of the web during drying [15]. The dimensional changes were performed by pilot paper machine draws and felt tensions as well as free drying of paper samples. During multi-cylinder drying on the paper machine the web is under stress in the machine direction, whereas the cross direction is free. The web shrinks due to drying and contracts due to web draws. Machine speed, dryness and tension level determine the needed speed difference between the drive groups, which in turn determines the MD straining [1]. The draw should be as low as possible to retain the strain potential of the paper for further converting and printing processes [1, 16].

The following definitions are used to describe the mechanisms involved in paper drying:

- Drying stress: internal forces and stresses in a paper caused by shrinkage of the fibers during drying.
- Drying load: the external force that strains or restrains the web during drying.
- Potential shrinkage (free shrinkage): the total shrinkage occurring during drying if shrinkage is not prevented.
- Drying shrinkage or allowed shrinkage: the total shrinkage in a paper web during drying (negative shrinkage equals strain in drying).
- Dried-in-strain: the difference between potential shrinkage and drying shrinkage [3].
- Frozen-in-stress: status where the paper is under stress during its passage through paper machine [1]
- Final drying tension: in this study, the final drying tension is defined as the tension level at the end of drying.

If the drying stress exceeds the drying load, the web shrinks. If the drying load exceeds the drying stress, the web is strained [3]. Additionally, Htun stated that yield stress is the limit reached by drying stress. There is strong evidence to suggest that in paper subjected to restrained drying, the final stress, internal stress and yield stress are identical [17], although this interpretation has been criticized by Skowronski [18].
Wet straining can be used to influence paper properties by varying free drying, restrained drying (0%) and a degree of wet strain at initial dryness, and can be tested using uni-axial

and bi-axial testers [19–20]. The tensile strength and tensile stiffness of dry paper can be improved by straining at below 60% dryness [6–7]. On the other hand, free drying to 60% dryness gives the highest increase in strain at break [21]. Tensile stiffness and strain at break can be improved by combining free drying and restrained drying (including wet straining) at 40–55% dryness. This dryness range gives maximum loss factor values in dynamic mechanical testing [7, 22]. The effects of wet straining may differ depending on the dryness of the straining, although the total degree of wet straining is the same [6–7]. Lätti et al. developed an optimal straining strategy for fixed drying tensions which minimizes tension variations in dry paper by means of factorial methods [16].

The objective of the present study was to investigate the effects of multi-stage straining during drying on the tensile properties of dried paper. We studied the effects of straining during wet pressing at around 50–60% dryness on a pilot paper machine, and straining during drying at 60–80% dryness on a laboratory tester. The effects in the dry paper were measured by means of breaking tensile testing. The results were analyzed using statistical multivariate methods.

EXPERIMENTAL

Test Rig and Drying Unit

A C-Impact tensile tester with drying unit was used for the laboratory trials [23]. Use of a drying unit is introduced for the first time in this paper. Air at a temperature of 95 °C was blown onto one side of each paper strip using the drying unit attached to the tester. The length of the paper sample was 180 mm and width 20 mm. The frequency of data recording was 1 kHz. The main components of the C-Impact tester used for the measurements are shown in Figure 1.

1) Force sensor,
2) Dryer unit,
3) IR temperature sensors (2 pc.),
4) PIRMA moisture sensor (Near InfraRed -technique),
5) Actuator,
6) Strain sensor,
t Control unit,
t Control unit for drying air temperature and flow rate,
t Data logging (8 channels),

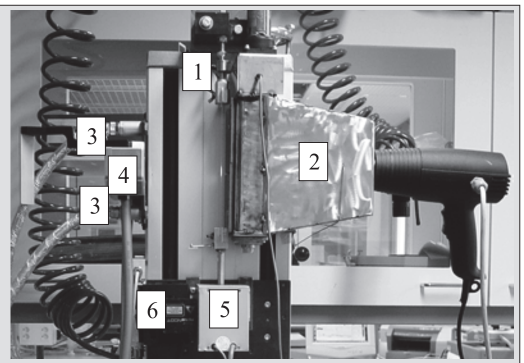

Figure 1 – Main components of the C-Impact tester.

Materials

The paper samples were never-dried SC paper samples at 58% dryness. All samples were prepared on a pilot paper machine and all tests were performed in the machine direction (MD). The dry grammage of the samples was 54 g/m^2 and the filler content 25–26%. The jet/wire-ratio was 1.08 for all samples.

Experimental

The paper samples were strained at two locations in the press section of the pilot paper machine, as presented in Figure 2 and Table 1. The draw at the 1st location during wet pressing was 1.2%, 2.0% and 5.0% and the draw at the 2nd location was constantly 0.2%. In the other test case, the draw at the 2nd location was 0.2%, 1.0% and 2.0% and the draw at the 1st location was constantly 2.0%.

	Draw at 1st location, %	Draw at 2nd location, %	Subgroups for 1st draw analysis	Subgroups for 2nd draw analysis
Subgroup 1	1.2	0.2	x	
Subgroup 2	2.0	0.2	x	x
Subgroup 3	2.0	1.0		x
Subgroup 4	2.0	2.0		x
Subgroup 5	5.0	0.2	x	

Table 1 – Draw combinations at the pilot paper machine press section.

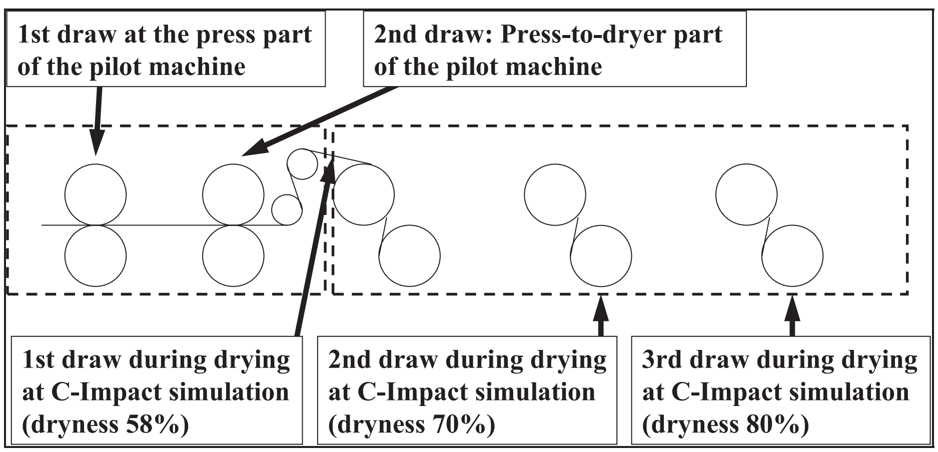

Figure 2 – Schematic illustration of the draws performed at the press section of the pilot paper machine and the dryer section draws simulated by the laboratory tensile tester.

The paper samples were dried using the C-IMPACT tensile tester. The drying time of all samples was 53 s and the dryness at the end of drying was 95–96%. The drying rate was around 2.5 $kg/m^2/h$. The draws were performed at three different dryness levels, as shown in Table 2. The 1st draw during drying simulates the typical wet paper web status upon transfer to the dryer section. The timing and extent of the 2nd and 3rd draws were obtained by averaging the typical tension and strain levels of an actual SC paper machine. In this study, paper tension is measured instead of stress as the thickness of wet paper is difficult to measure and paper drying also results in non-uniform thickness.

	Draw level 1	Draw level 2	Draw level 3
1st draw at dryness 58–60%, factor B	0.6%	0.9%	1.2%
2nd draw at dryness 69–71%, factor C	0.1%	0.2%	0.3%
3rd draw at dryness 82–85%, factor D	-0.05%	0%	0.05%

Table 2 – Draws during drying, as measured with a C-Impact tensile tester (strain rate 5.56 %/s).

All combinations were measured, giving a 3^3 factor series [24, 25]. The first draw was at an initial dryness of around 60%, the second at a dryness of around 70%, and the third at around 80% dryness. By repeating the draws on five separate paper samples (Table 1, giving factor A), two separate 3^4 full factor series could be formed (the statistical analysis method is given in the Appendices). Five repeats were performed for each trial point. A breaking tensile test was performed immediately after the drying test for four of the repeats using the C-Impact tensile tester. The temperature of the paper samples during the breaking tensile test was approximately 65 °C.

RESULTS AND DISCUSSION

The controlled variables of the laboratory test included the draw levels and the blown air temperature. Figure 3 shows example tension, temperature, dryness and strain data for a paper sample dried using a laboratory tensile tester. The three peaks in the tension data are the direct result of the draw steps. A breaking tensile test was performed after drying (the final tension peak). The breaking tensile test yields several interesting results which can be compared to the known strain history. The paper temperature follows the three drying phases (as explained in the introduction). A constant temperature range at times 5–20 s is an indication of water saturation of the paper and a high evaporation rate.

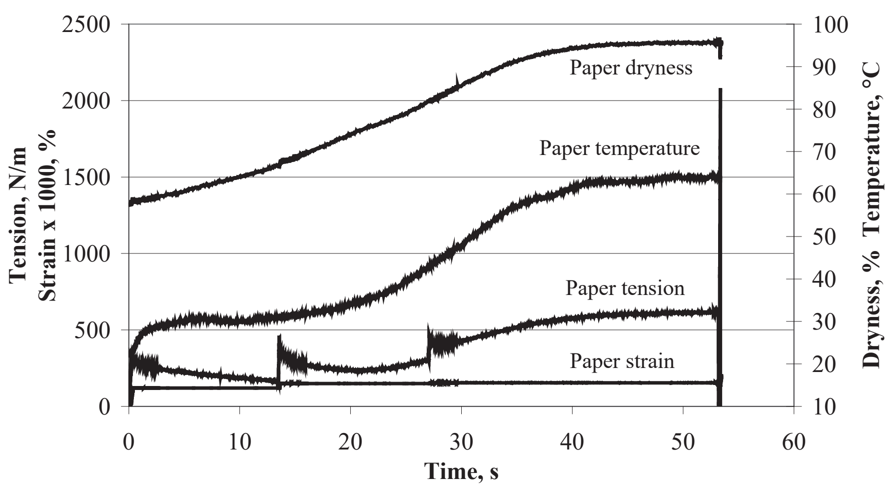

Figure 3 – Example of drying test data with three steps of draw.

Figure 4 shows three drying loads (1–3) from subgroup 3 (shown in Table 1) and the drying stress (4) without straining. The figure shows the tensions with maximum, median and minimum strains according Table 2.

The final tension at the end of drying was generated primarily by shrinkage, with the draws increasing the final drying tension by 10–40%. Due to the viscoelasticity of paper, tension relaxation, in the form of a rapid decrease in tension, always occurs after each draw. In Figure 4, tension curve #3 shows 'tension recovery' after de-straining at 27 seconds, which is also due to the viscoelasticity of the paper. Draws at 50–70% dryness play a vital role in maintaining tension and thereby ensuring paper machine runnability at the start of the dryer section.

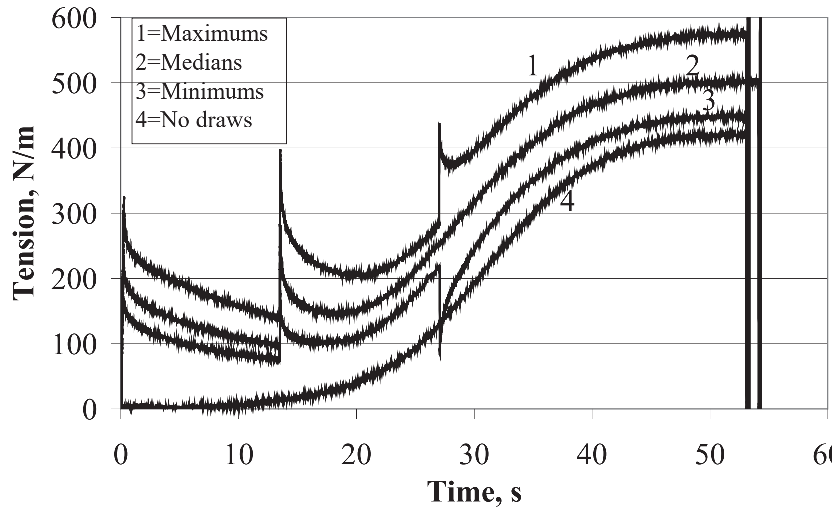

Figure 4 – Drying loads (1–3) and drying stress (4) per category - The different combinations of draws according to Table 2 are #1 'maximums', #2 'medians', #3 'minimums'.

Figures 5–7 show the strain at break, tensile strength and tensile stiffness of dry paper plotted as a function of the sum of all draws (both pilot paper machine and laboratory tensile tester). The circled subgroups 1–5 represent the combinations of draws performed on the pilot paper machine (shown in Table 1). The data points inside the circles represent the different combinations of draws performed by the laboratory tensile tester (shown in Table 2). The data points for the drying stress tests (no draws case) are also given as a reference.

The 'big picture' of the strain history is clearly evident in Figures 5 and 6. Strain at break decreases in an almost linear manner as the sum of the draws increases, whereas maximum tensile strength seems to be a function of the sum of draws. Strain at break values vary between and within subgroups 1–5, and sum of draws values vary by up to 0.3%, which indicates the importance of the straining strategy. Strain at break is clearly affected by the dryness of the draws. Similar observations can be made for the other properties. More detailed analysis of single draws were performed using the statistical method (ANOVA) described in Appendix 1.

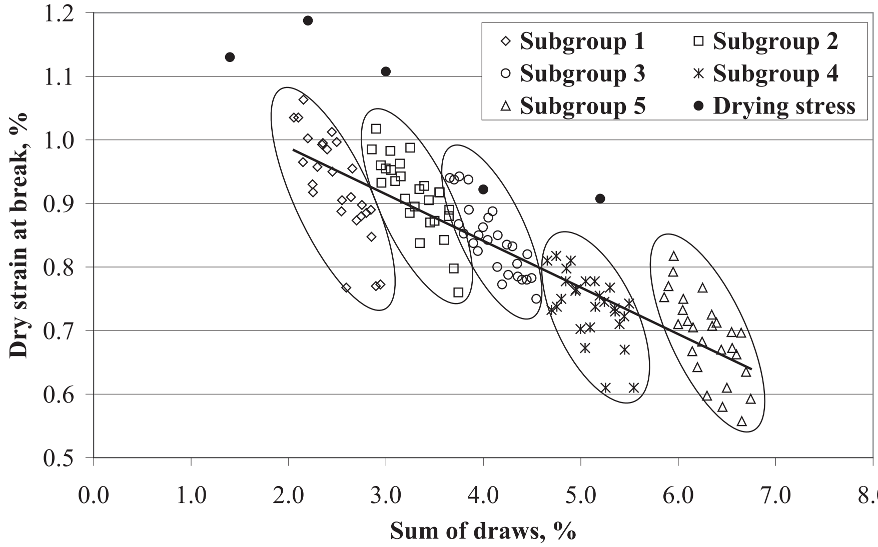

Figure 5 – Average dry paper strain at break of all observations - The sum of draws comprises the draws shown in Tables 1 and 2.

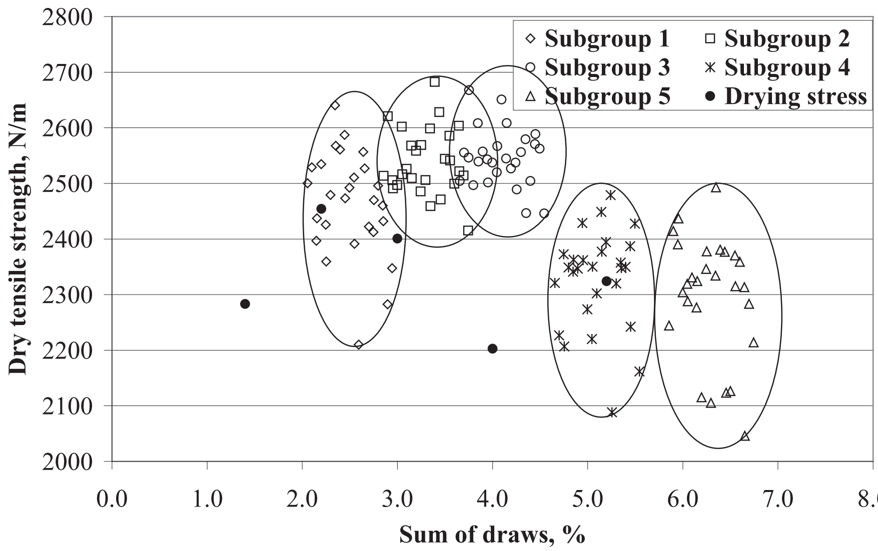

Figure 6 – Average dry paper tensile strength of all observations - The sum of draws comprises the draws shown in Tables 1 and 2.

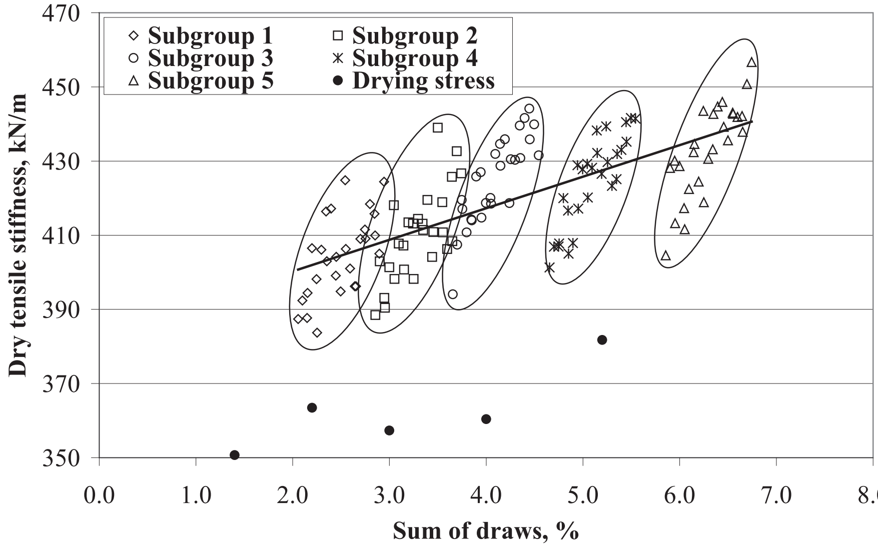

Figure 7 – Average dry paper tensile stiffness of all observations - The sum of draws comprises the draws shown in Tables 1 and 2.

The P-values of the factors are given in Tables 6 and 7 in the appendices. The press draws were significant in all cases at a confidence level of at least 95%. The 1st draw during drying was significant at a level of 99% in all cases excluding the tensile strength of the 2nd press draw series. In the case of elastic strain and drying tension in both series and tensile stiffness in the 2nd press draw series, all main factors were significant at a confidence level of 95%.

Although in the majority of cases the main factors were significant with a confidence level of at least 95%, the contribution ratio may still be too low to explain the data statistically. The contribution ratios of the main factors are shown in Tables 3 and 4. In some of the cases unexplained variance (error) is relatively high, up to 50%. Tables 8 and 9 in the appendices show the contribution ratios by using a fractional design L(0,0) according Montgomery [25]. The contribution ratios are highly similar in both designs. A fractional design gives a lower error term, while the most powerful term seem to increase. A full factorial design seems to give more accurate and more balanced average plots for all main factors.

	A	B	C	D	cross factors	error
Tensile strength	26	2.3	0.6	0.8	19.7	50.5
Strain at break	54.9	10.1	2.8	0.6	7.7	23.9
Tensile stiffness	50.8	19.6	5.7	2.3	9.1	12.5
Elastic strain	0.6	85	8.4	0.2	3.9	1.9
Final drying tension	23.1	18.5	6	40.2	5.8	6.5

Table 3 – Contribution ratios of main factors, sum of cross factors and error in the case of 1st draw at pressing.

	A	B	C	D	cross factors	error
Tensile strength	36.8	0.8	0.8	0.7	13.5	47.4
Strain at break	42.3	11.8	1.3	0.5	10.6	33.6
Tensile stiffness	17.9	34.8	6.7	6.6	13.4	20.6
Elastic strain	0	85.3	8.6	0.1	4.1	1.9
Final drying tension	2.9	22.6	8.3	47.7	8	10.5

Table 4 – Contribution ratios of main factors, sum of cross factors and error in the case of 2nd draw at pressing.

The last step of the data analysis was to plot the averages in order to illustrate the directions and average magnitudes of the effects, which provides valuable information for determining optimal conditions. Despite the high error, for example in the case of tensile strength, some guideline values were obtained.

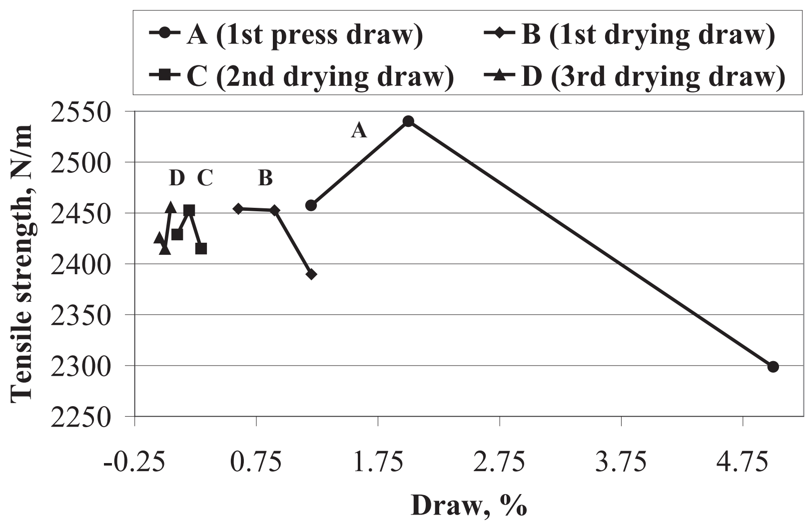

Figure 8 – Average tensile strength as a function of draw strain (main factors) - Draw after 2nd press constantly at 0.2 %.

The draws performed at the press section of the pilot paper machine (factor A) were found to contribute 26% and 37% of tensile strength variation after drying. The effects of the 1st and 2nd draw at the press section on tensile strength were not linear, and the maximum tensile strengths were observed at 2.0% and 1.0% strain, respectively. The effect of the 1st draw in the press section on the tensile strength is shown in Figure 8, and the 2nd draw goes equally. The non-linear behavior of the press section draws and the effect of the drying draws in terms of improved tensile strength in comparison to the drying load and drying stress cases are seen in Figure 6. Despite the high error terms, it seems that high straining leads to lower tensile strength. The effects of factors B, C and D (draws performed using the laboratory tensile tester) were not significant with respect to tensile strength.

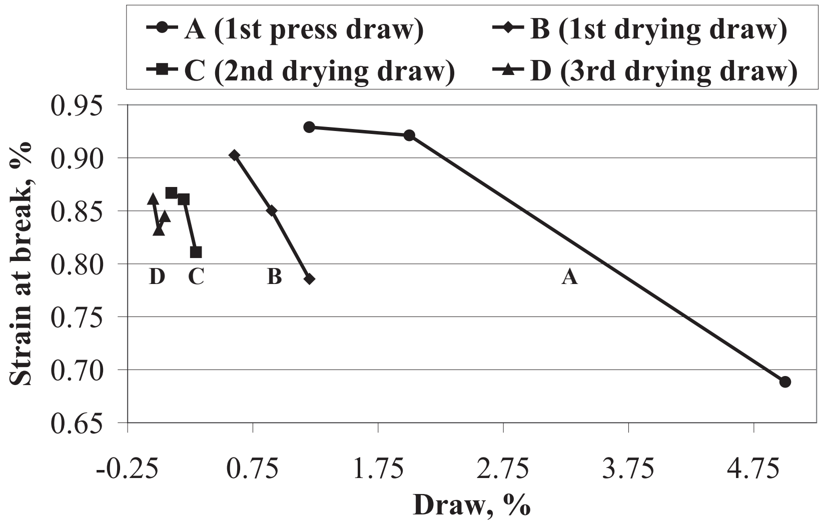

Figure 9 – Average strain at break as a function of draw strain (main factors) - Draw after 2nd press constantly at 0.2 %.

Factors A and B together explained 68% and 54% of the strain at break variance in the case of the 1st and 2nd draws at the press section (Figure 9 shows the case of the 1st draw). Unexplained variance was 18% and 34%, respectively. Increased draw during wet pressing and drying produced an almost linear reduction in strain at break. Although the paper samples were stored in a cold room between wet pressing and drying, the effect of wet straining remained. The negative effect of press section draws on strain at break is also seen in Figure 5.

In the case of tensile stiffness, factors A and B together explained about 70 and 50% of the variance. Unexplained variance was around 13% and 21%. An increase in any of the strains A, B, C or D led to increased tensile stiffness in Figure 10 (showing the case of the 1st draw). The positive effect of press section draws on tensile stiffness is also seen in Figure 7.

The effects of straining during drying on tensile stiffness were not linear, which has also been reported in literature [2, 19]. According to Haslach, repeated loading often affects the apparent elastic modulus of pulp fibers with elastic modulus values approaching that of perfectly oriented crystalline cellulose [26]. According to Jentzen, cycling to higher and higher strains does not effect the elastic modulus if the fiber is dried under load, but if the fiber is dried under zero load, the elastic modulus increases under repeated loadings to higher strains [8].

The relative elastic strain in Figure 11 is the value of recovered strain compared to the strain level preceding de-loading. Relative elastic strain is clearly explained by the 1st and 2nd draw during drying, the sum of contribution ratios being over 93%. Relative elastic strain was decreased by an increase in factors B and C. The effects of the press draws (factor A) were lost due to viscoelastic recovery, probably during sample storage. Major changes due to viscous behavior are very rapid (a few seconds), and avoiding this effect was therefore not possible. The strains induced by the press draws are dried in the structure in a different way on paper machines were the tension during drying is continuous.

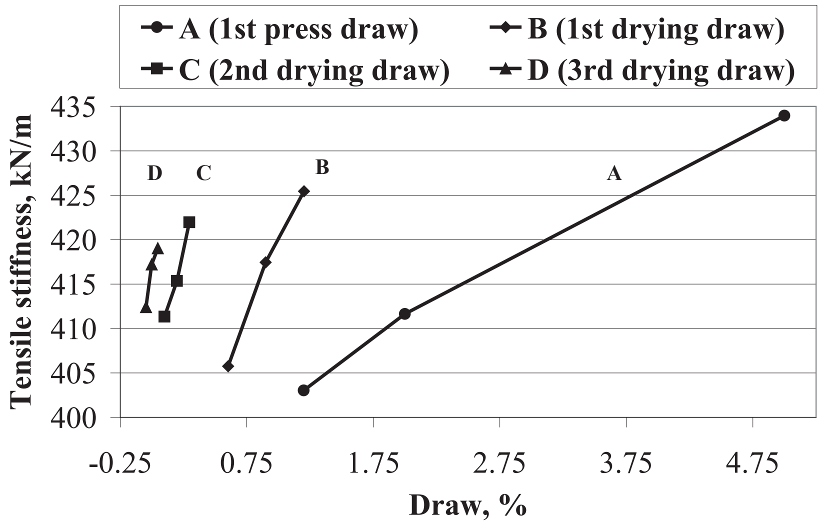

Figure 10 – Average tensile stiffness as a function of draw strain (main factors) - Draw after 2nd press constantly at 0.2 %

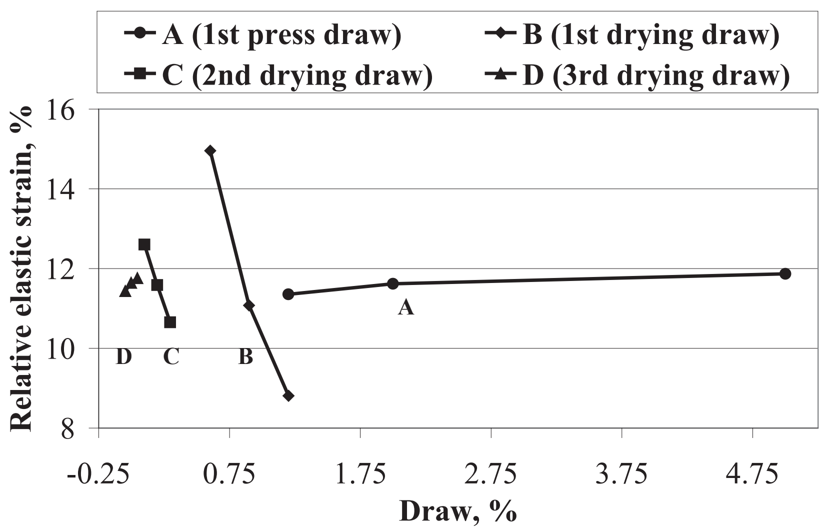

Figure 11 – Average relative elastic strain as a function of draw strain (main factors) - Draw after 2nd press constantly at 0.2 %.

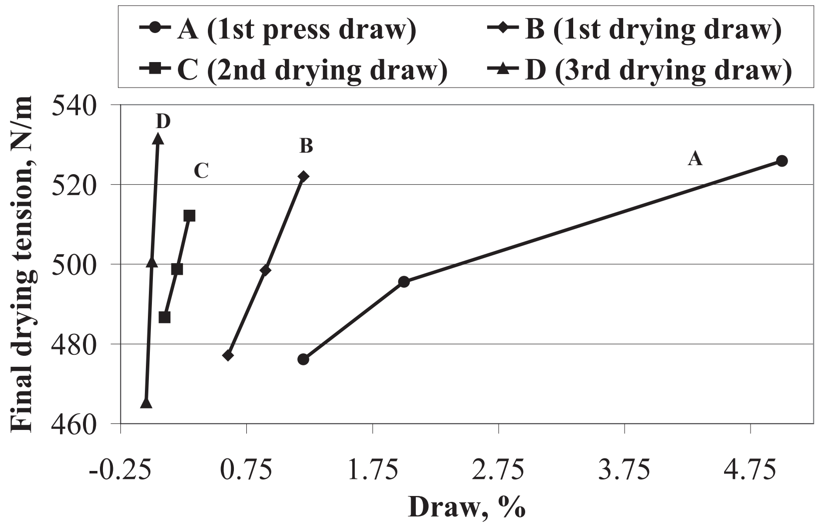

Figure 12 – Average final drying tension as a function of draw strain (main factors) - Draw after 2nd press constantly at 0.2 %.

Final drying tension was the only studied property in which all main factors had a higher contribution than the sum of the cross factors or error. The 3rd draw during drying at around 80% dryness had the greatest effect on final drying tension, although its contribution to the overall strain history was minor. Secondly, the 2nd draw during drying at 70% dryness had a minor effect on final drying tension. This result indicates the importance of the straining strategy. The effects of final drying tension in Figure 12 follow the behavior of tensile stiffness.

CONCLUSIONS

The drying and multi-stage straining conditions of a paper machine can be closely reproduced using a C-Impact tensile tester with drying unit. The effects of draws performed at the press section of a pilot machine were revealed by laboratory drying and breaking tensile testing. The tension levels, drying time, and temperature of the paper samples were realistic compared to an industrial paper machine.

A typical value for the 1st draw at the press section, which is needed to counteract the adhesion between the wet web and the press roll surface, is around 3.5%. The limits in the study were 1.2–5%. A typical value for the 2nd draw at the press section, needed for smoothing the paper surface, is around 1%. The limits in the study were 0.2–2.0%. The effect of the 1st and 2nd press section draws on the results varied, but were similar to each other in all test cases.

The design of the trials was full factorial (multivariate), which enabled the use of statistical methods in the data analysis. The analysis methods were customized to the needs of the studies. In some cases, the effects of the draws were minimal and statistical correlation was low. The low correlation was partly due to the normal statistical variation of paper. It was concluded that the use of a fractional factorial design instead of a full factorial design would lead to equally statistically good results, but would also be biased towards the most powerful factor term.

Straining and stresses during drying had a significant influence on the elastic properties of paper. Increasing the draws after the press cylinders and during drying led in an almost linear fashion to decreased strain at break of the dried paper. The maximum tensile strength value was found to correspond to a press draw of between 2–4%. Tensile stiffness was increased by straining at the press cylinders and during drying. The time dependence of paper straining was evident in a number of ways, such as in elastic strain, where the effect of the press draw was diminished by viscous recovery. Conversely, some tensile properties, such as tensile strength, are insensitive to viscous recovery. Draws and draw dryness therefore affect different paper properties in different ways.

REFERENCES

1. Htun, M., "The Influence of Drying Strategies on the Mechanical Properties of Paper," PhD Thesis, KTH Paper Technology, 1980.
2. Silvy, J., "Effects of Drying on Web Characteristics," Paper Technology, Vol. 12, No. 5, 1971, pp. 377–387.
3. Kiiskinen, H., Paltakari, J., and Pakarinen, P., "Drying and Paper Quality," Paper Making Part 2, Drying, FAPET, Helsinki, Finland, 2000.
4. Parsons, S.R., "Effect of Drying Restraint on Handsheet Properties," Tappi, Vol. 55, No. 10, 1972, pp. 1516–1522.
5. Henderson, J.T., Barton, J.S., and Erfurt, H., "Effects of High Consistency Refining on the Properties of the Consolidated Web," Consolidation of the Paper Web, Transactions of IIIrd Fundamental Research Symposium Cambridge, 1965, pp. 875–895.
6. Hansson, T., Fellers, C., Htun, M., "Drying Strategies and a New Restraint Technique to Improve Cross-Directional Properties of Paper," Fundamentals of Papermaking, Transactions of IXth Fundamental Research Symposium Cambridge, 1989, pp. 743–781.
7. Htun, M., "The Control of Mechanical Properties by Drying Restraints," Structure and Properties, Marcel Dekker, New York, 1986, pp. 311–326.
8. Jentzen, C.A., "The Effect of Stress Applied during Drying on Some of the Properties of Individual Pulp Fibers," Tappi, Vol. 47, No. 7, 1964, pp. 412–418.
9. Pye, I.T. , Washburn, O.V., and Buchanan, J.G., "Structural Changes in Paper on Pressing and Drying," Consolidation of the Paper Web, Transactions of IIIrd Fundamental Research Symposium Cambridge, 1965, pp. 353–367.
10. Page, D.H. and Tydeman, P.A., "Physical Processes Occurring during the Drying Phase," Consolidation of the Paper Web, Transactions of IIIrd Fundamental Research Symposium Cambridge, 1965, pp. 371–392.
11. Van den Akker, J.A., Jentzen, C.A., and Spiegelberg, H.L., "Effects on Individual Fibres of Drying under Tension," Consolidation of the Paper Web, Transactions of IIIrd Fundamental Research Symposium Cambridge, 1965, pp. 477–506.
12. Duncker, B., Hartler, N., and Samuelsson, L.G., "Effect of Drying on the Mechanical Properties of Pulp Fibres," Consolidation of the Paper Web, Transactions of IIIrd Fundamental Research Symposium Cambridge, 1965, pp. 529–537.
13. Schniewind, A.P., Ifju, G., and Brink, D.L., "Effect of Drying on the Flexural Rigidity of Single Fibres," Consolidation of the Paper Web, Transactions of IIIrd Fundamental Research Symposium Cambridge, 1965, pp. 538–543.
14. Salmen, L., Fellers, C., and Htun, M., "The Development and Release of Dried-in Stresses," Nordic Pulp And Paper Research Journal, Vol. 2, No. 2, 1987, pp. 44–48.

15. Arlov, A.P. and Ivarsson, B., “Effects of Draws and Felt Tension on Mechanical Properties of Paper,” Svensk Papperstidning, Vol. 54, No. 21, 1951, pp. 729–738.
16. Lätti, H., Heikkinen, A., and Kettunen, H., “Drying Induced Tension Variation in Paper Web,” The Science of Papermaking, Transactions of XIIth Fundamental Research Symposium Oxford, 2001, pp. 737–758.
17. Htun, M. and de Ruvo, A., “Relation between Drying Stresses and Internal Stresses and the Mechanical Properties of Paper,” Fibre–Water Interactions in Paper-Making, Transactions of VIth Fundamental Research Symposium Oxford, 1977, pp. 477–487.
18. Skowronski, J.W., “Testing of In-Plane Internal Stresses in Paper Part 1. Review and Discussion of Prior Published Work,” Prazeglad Papierniczy, Vol. 64, No. 3, 2008, pp. 153–156.
19. Zhang, G., Laine, J.E., and Paulapuro, H., “Characteristics of the Strength Properties of a Mixture Sheet under Wet Straining Drying,” Paperi ja Puu, Vol. 84, No. 3, 2002, pp. 169–173.
20. Wahlström, T., “Influence of Shrinkage and Stretch during Drying on Paper Properties,” Paper Technology, Vol. 41, No. 6, 2000, pp. 39–46.
21. Htun, M. and de Ruvo, A., “The Influence of Drying Strategies on the Relationship between Drying Shrinkage and Strain to Failure of Paper,” The Role of Fundamental Research in Paper Making, Transactions of VIIth Fundamental Research Symposium Cambridge, 1981, pp. 385–398.
22. Htun, M., de Ruvo, A., and Fellers, C., “The Dynamic Mechanical Behaviour of Paper During Drying,” Journal of Applied Polymer Science, Vol. 30, 1985, pp. 1597–1604.
23. Kouko, J., Kekko, P., and Kurki, M., “Effect of Strain Rate on Strength Properties of Paper,” Proceedings of the 2006 Progress in Paper Physics – A Seminar, Miami University, Oxford, Ohio, 2006.
24. Frigon, N.L. and Mathews, D., Practical Guide to Experimental Design, John Wiley & Sons, Inc., 1997.
25. Montgomery, D.C., ‘Design and Analysis of Experiments’, Fourth edition, John Wiley & Sons, Inc., 1997.
26. Haslach, H.W., “The Moisture and Rate-Dependent Mechanical Properties of Paper: A Review,” Mechanics of Time-Dependent Materials, Vol. 4, No. 3, 2000, pp. 169–210.

APPENDICES

Statistical Analysis Methods

The experiment design was full factorial (multivariant), which enabled the use of statistical ANOVA (Analysis of Variance) methods in the analysis of the data. In this study, two separate 3^4 full factorial designs (3x3x3x3) were created, giving four factors (independent variables) with three distinct values. The factors were fixed as follows: three draws during drying on a laboratory tensile tester, and one draw during sample forming on a pilot paper machine. The effects of the factors (independent variables) on the dependent variables (e.g. tensile stiffness) were tested by four or five repeats (observations).

The evaluation of the data included seven steps: 1) Sum of squares, 2) Degrees of freedom, 3) Mean squares, 4) F-ratio, 5) Looking up the critical value of F (P-value), 6) Contribution ratio and 7) Plots of averages.

Calculation of steps 1–4 was performed according to Montgomery [25]. The P-value of step 5 was obtained using the FDIST function of MS Excel, and the Contribution ratio CR_i of step 6 was obtained as in equation {6} in accordance with Frigon [24].

Example equations for the sum of squares are given in {1–3} below.

Total sum of squares:

$$SS_T = \sum_{i=1}^{a}\sum_{j=1}^{b}\sum_{k=1}^{c}\sum_{l=1}^{d}\sum_{m=1}^{n} y_{ijklm}^2 - \frac{y_{.....}^2}{abcdn} \qquad \{1\}$$

Total sum of squares for main factor A:

$$SS_A = \frac{1}{bcdn}\sum_{i=1}^{a} y_{i....}^2 - \frac{y_{.....}^2}{abcdn} \qquad \{2\}$$

Error sum of squares:

$$SS_E = SS_T - \left(\frac{1}{n}\sum_{i=1}^{a}\sum_{j=1}^{b}\sum_{k=1}^{c}\sum_{l=1}^{d} y_{ijkl.}^2 - \frac{y_{.....}^2}{abcdn} \right) \qquad \{3\}$$

A high SS_{Factor} value reflects a large difference in the factor means, and a low value likely indicates no differences in the treatment means. The degrees of freedom of the 3^4 full factorial design in the cases of four and five repeats are tabulated in Table 5.

Mean squares MS_i is a quotient of the sum of squares SS_i and degrees of freedom DF_i, for example for main factor A.

The mean square for main factor A:

$$MS_A = \frac{SS_A}{DF_A} \qquad \{4\}$$

The P-value approach was used for rejecting the hypothesis of no differences in factor means (null hypothesis). F-statistics were used to specify P-values for the factorials of the data sets (reference distributions shown in Figure 13). The F-statistic is the mean square for the factor (MS_A, MS_{AB}, MS_{ABC}, etc.) divided by the mean square for the error (MS_E) [25]. This statistic follows an F distribution with (k-1) and (N-k) degrees of freedom, where k is the number of levels for the given factor.

Calculation of F-statistics:

$$F_0 = \frac{SS_{Factor}/(k-1)}{SS_E/(N-k)} = \frac{MS_{Factor}}{MS_E} \qquad \{5\}$$

	Degree of freedom (4 repeats)	Degree of freedom (5 repeats)
Main factors (A, B, C, D)	2	2
Two-factor interactions (AB, AC, AD, BC, BD, CD)	4	4
Three-factor interactions (ABC, ABD, ACD, BCD)	8	8
Four-factor interaction (ABCD)	16	16
Error	243	324
Total	323	404

Table 5 – Degree of freedom for sources of variation in cases of four and five repeats.

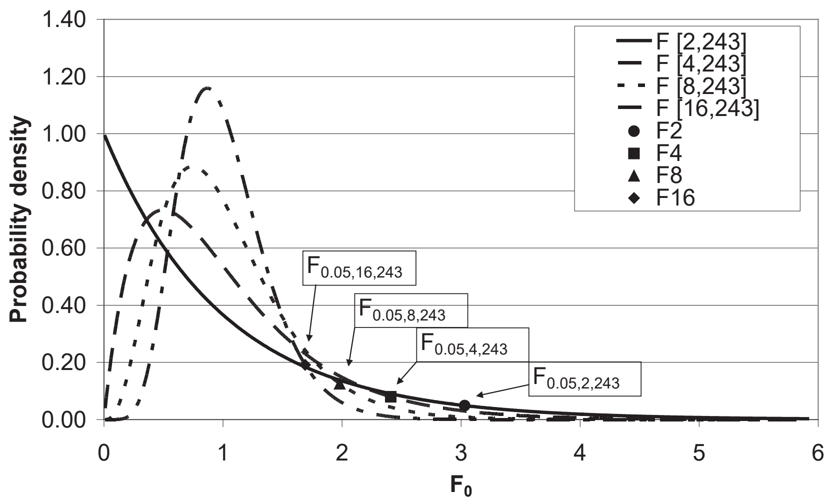

Figure 13 – Reference distributions (main factors and interactions) for the test statistic F_0 of drying tests with four observations.

The P-value is the probability obtained from the F-distribution, with a value ranging from zero to one. If the P-value is smaller than or equal to the significance level, the null hypothesis is rejected. The higher the P-value, the less the observed relation can be believed to be a reliable indicator of the relation between the variables in the population. The P-values of the two full factorial groups are shown in Tables 6 and 7, in which P-values lower than 0.05 and 0.01 are categorized.

The final step of data evaluation was the percentage of contribution ratio CR_i (also known as R^2), which is a quotient of the sum of squares of the factors and the total sum of squares.

Contribution ratio of factors:

$$CR_{Factor} = \frac{SS_{Factor}}{SS_T} \quad \{6\}$$

The contribution ratio of error measures the unexplained or residual variability of the data. The contribution ratios of the factors, interactions and error with respect to the results are shown in Tables 6 and 7.

	Tensile strength	Strain at break	Tensile stiffness	Elastic strain	Drying tension
A	<0.01	<0.01	<0.01	<0.01	<0.01
B	0.22	<0.01	<0.01	<0.01	<0.01
C	0.16	<0.05	<0.01	<0.01	<0.01
D	<0.01	<0.01	<0.01	<0.01	<0.01
AB	0.14	0.38	<0.01	<0.01	<0.01
AC	0.27	0.27	0.19	<0.01	<0.05
AD	0.60	0.89	<0.01	<0.01	<0.01
BC	0.87	0.59	0.10	0.42	<0.01
BD	0.63	0.29	<0.01	<0.05	<0.01
CD	0.51	0.91	<0.01	0.26	<0.01
ABC	0.27	0.36	<0.05	<0.01	<0.01
ABD	0.06	0.33	<0.05	0.23	0.45
ACD	<0.05	0.22	<0.05	<0.01	0.23
BCD	<0.05	0.09	0.07	<0.01	<0.01
ABCD	0.80	0.41	<0.05	<0.01	0.53

Table 6 – P-values of the main factors and all interactions, where the main factors are the 1^{st} draw at the press section and 3 draws during drying on a laboratory tensile tester.

	Tensile strength	Strain at break	Tensile stiffness	Elastic strain	Drying tension
A	0.14	<0.01	<0.01	<0.01	<0.01
B	0.15	<0.05	<0.01	<0.01	<0.01
C	0.17	0.19	<0.01	<0.01	<0.01
D	<0.01	<0.01	<0.01	<0.05	<0.01
AB	0.31	0.43	0.73	<0.01	0.076
AC	0.59	0.67	0.38	<0.01	<0.01
AD	0.93	0.71	<0.01	0.06	<0.05
BC	0.18	0.26	0.21	<0.01	<0.01
BD	0.43	0.33	0.19	0.09	<0.01
CD	0.67	0.61	0.07	<0.01	<0.01
ABC	0.11	<0.05	<0.01	<0.01	0.09
ABD	0.67	0.62	<0.01	<0.05	<0.01
ACD	0.59	0.27	0.08	<0.05	<0.01
BCD	0.84	0.76	<0.01	<0.01	<0.01
ABCD	0.31	0.40	0.09	<0.05	<0.05

Table 7 – P-values of the main factors and all interactions, where the main factors are the 2nd draw at the press section and 3 draws during drying on a laboratory tensile tester.

Tables 8 and 9 show the contribution ratios by using a fractional design L(0,0) according Montgomery [25]. A fractional design gives information of cross factors only and no information of cross factors.

	A	B	C	D	error
Tensile strength	56.0	1.4	2.1	4.9	35.7
Strain at break	69.9	7.1	3.2	0.7	19.1
Tensile stiffness	51.5	23.9	11.4	2.4	10.9
Elastic strain	1.4	88.4	8.0	1.1	1.2
Final drying tension	19.8	24.0	10.1	41.7	4.4

Table 8 – Contribution ratios of the main factors and error in the case of the 1st draw during pressing, using a fractional design L(0,0).

	A	B	C	D	error
Tensile strength	53.0	0.4	0.3	1.6	44.8
Strain at break	46.8	11.8	1.4	3.3	36.7
Tensile stiffness	23.0	35.7	2.8	9.8	28.8
Elastic strain	1.2	86.3	10.2	1.0	1.3
Final drying tension	4.8	26.7	6.7	54.7	7.1

Table 9 – Contribution ratios of the main factors and error in the case of the 2nd draw during pressing, using a fractional design L(0,0).

Multi-stage Tensile Straining during Drying of SC Paper

J. Kouko[(1)] & P. Kekko[(2)],
[(1)]VTT Technical Research Centre, [(2)]Metso, FINLAND

Name & Affiliation	**Question**
Günther Oedl , Brueckner Machinery	Were you able to measure the dryness during the process of drying? Your charts displayed dryness.
Name & Affiliation	**Answer**
Jarmo Kouko, VTT Technical Research Centre	Yes we used an infrared sensor that was attached to the tester.
Name & Affiliation	**Question**
Günther Brandenburg, Technische Universität München	How did you measure the strain in the web?
Name & Affiliation	**Answer**
Jarmo Kouko, VTT Technical Research Centre	We measured the strain and tension in the tensile tester by strain and force sensors which are in the tester.
Name & Affiliation	**Question**
Günther Brandenburg, Technische Universität München	Then you measured the force directly and not the strain, because the strain requires the elongation?
Name & Affiliation	**Answer**
Jarmo Kouko, VTT Technical Research Centre	We measured stress or force depending on how you scale it. We measured the strain with a sensor and the strain actuator made the draws.
Name & Affiliation	**Question**
Günther Brandenburg, Technische Universität München	This you could do online when the paper was transported through your setup?
Name & Affiliation	**Answer**
Jarmo Kouko, VTT Technical Research Centre	The web tension was not measured in a pilot paper machine. Samples of the paper from the pilot machine were taken and stored in cold storage. Drying tests were performed off-line on these samples in the laboratory. Strain and tension were measured during these tests. It is difficult to measure tension in a paper machine.
Name & Affiliation	**Question**
Tim Walker, TJWalker & Associates	In figure 10, the relative elastic strain – I missed what that was. I think you had a nice diagram on the side of the graph. Explain those. What is the relative elastic strain?
Name & Affiliation	**Answer**
Jarmo Kouko, VTT Technical Research Centre	There were both tensile stiffness and the relative elastic strain figures in the proceedings. The relative elastic strain is the strain measured when you release the tension in a sample from a higher level to zero level. You measure an immediate strain that is negative.

Name & Affiliation	Question
Tim Walker, TJWalker & Associates	Regarding the different properties in your charts: Can you comment on what the desirable values are? Is a higher number good? What levels of these properties are optimal?
Name & Affiliation	**Answer**
Jarmo Kouko, VTT Technical Research Centre	The optimal values vary depend on the paper grade. In the case of relative strain, I wanted to show that this press effect was lost and what the typical values are. It depends on dryness.
Name & Affiliation	**Question**
Tim Walker, TJWalker & Associates	For potential strength I assume you would prefer a paper that is stronger. Or are you striving for a product that strains a lot before it breaks?
Name & Affiliation	**Answer**
Jarmo Kouko, VTT Technical Research Centre	Overall the paper properties change quite a bit due to the strain level and rate and on dryness. That is important when the paper goes to the printing houses. Also for wide webs there is a CMD profile of tension, strain, etc. At various CMD locations the web has different tensile and straining histories. As a result edge cut rolls have different properties than center rolls. These different analyses help to understand what properties exist inside a given roll.