Preferred citation: M. Parola, S. Vuorinen, H. Linna, T. Kaljunen and N. Beletski. Modelling the Web Tension Profile in a Paper Machine. In **The science of papermaking**, *Trans. of the XIIth Fund. Res. Symp. Oxford, 2001*, (C.F. Baker, ed.), pp 759–781, FRC, Manchester, 2018. DOI: 10.15376/frc.2001.1.759.

MODELLING THE WEB TENSION PROFILE IN A PAPER MACHINE

Markku Parola, Samppa Vuorinen, Hannu Linna, Timo Kaljunen, Nikolai Beletski

VTT Information Technology, Espoo, Finland

ABSTRACT

Poor cross-directional (CD) tension profiles of paper webs cause runnability problems in paper mills as well as in printing presses. This study explored the formation of the cross-directional web tension profile in paper machines. The research programme was implemented in a period of four years. Tension measurements were made during the production in both paper machines and printing machines.

The finite element method (FEM) was applied to explore the build-up mechanisms of the web tension profile. In FEM modelling, the web was constructed from continuum elements and the physical interactions of the elements were defined, for example, by the Hookean law. The FEM analysis has numerous advantages and it is important to investigate the influences of the mechanical conditions and the material properties of the paper web. The simulations made by FEM could quantitatively predict the shape of the tension profile.

The paper web is stretched in many stages through the drying section. Stretching in the machine direction (MD) causes a non-homogeneous stress field in the web because the paper is subjected to mechanical shrinkage which is defined by the Poisson's ratio of the paper. This typically causes a situation where the edges of the web are slacker than the middle areas, the so-called crying shape. The uneven stress fields in the web also cause a lower MD and CD tensile stiffness because of lower frozen-in-stress in the

paper sheet. Further on, the slacker edge areas are affected by higher CD drying shrinkage which further diminishes the tensile stiffness and also leads to higher relaxation in the machine direction.

Several trials were made to control the web tension profile. These included moisture profiling, jet-wire speed, edge flow, strain rate and nip trials. The most effective control was by moisture profiling with the steam box in the press section. The drier sections of the web became tenser and vice versa. This was because the moisture content of the paper has a strong effect on the formation of the tensile stiffness of the paper. The principal shape of the tension profile is convex. According to this study it is impossible to reach an even tension profile with the existing dryer section configurations. However, the tension profile can be adjusted within certain limits by controlling, for example, the development of the moisture profile. These controls play an important role in improving the runnability of the paper machine, the winder and the printing press.

Two different instruments were used to measure web tension. IQTension measures the pressure within an air film that is formed between the paper web and the curved metallic deflection plate. The curved deflection plate is perforated at intervals, so that the pressure sensors connected to the orifices in the plate measure the cross directional (CD) profile of the air pressure, which correlates with the web tension profile. The web tension is measured at a high sampling rate in several parallel positions across the whole web width. In addition, the tensile stiffness profile can be defined by measuring the tension at different draws.

Scanning by Tenscan was used, when there was only a limited space for the measurement, or there was a need for measuring simultaneously with IQTension. Tenscan uses a laser beam to measure the passing time of a propagating membrane wave in the web. Other measurements included normal on-line measurements in the paper machines. The TSO and shrinkage profile measurements were made in the laboratory.

1 INTRODUCTION

Problems related to the web tension profile are common in paper manufacturing, as well as in printing. An uneven tension profile in the web can cause web breaks or wrinkles in the paper machine, in the winder or in the printing press. In this paper, web tension is defined as the stress applied to the paper web in the machine direction (MD). The web tension profile again is defined as the MD tension distribution across the whole width of the web. In this study, web tension is measured across the web from one edge to another and the results are often shown as cross direction (CD) profiles, according to, for example, basis weight or moisture profiles.

Normally, the web tension is convex, as can be seen in Figure 1 [1]. In most cases, the edges of the paper web are slack. This can result in poor runnability with edge reels, since the shape of the tension profile can still be seen in the press. Because of runnability problems, many printers avoid using edge reels in 4-colour printing. When passing through a nip, a slack area may create wrinkles. Slack areas also cause fluttering, which complicates web control.

The relevance of the web tension profile in predicting runnability in printing was determined in a long-term study [2]. Over 5000 reels were measured during one year on a rotogravure press. The main runnability problems were web breaks and register errors, which increased paper waste and decreased

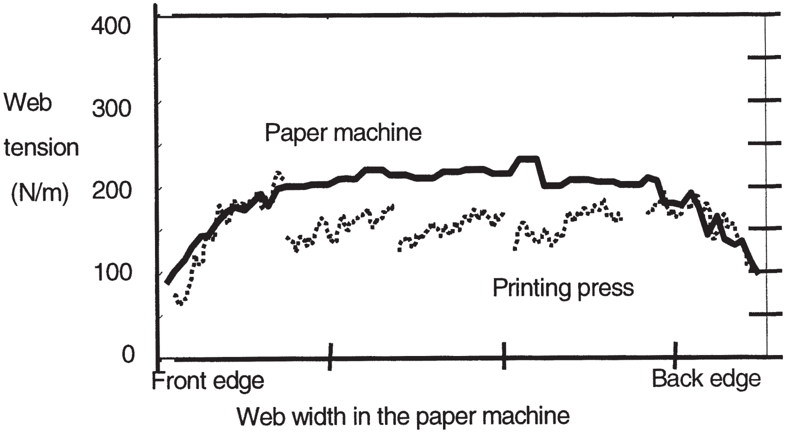

Figure 1 Web tension profile measured in a paper machine (solid line) and in a printing press (dashed line).

production efficiency. The connections between runnability and the tension profiles were examined statistically and different tension profile characteristics were studied on each reel.

The tense and slack areas, as well as the skew web tension profiles, cause runnability problems in the printing press, which is why the shape of the optimum tension profile is nearly even. Since the tension profile originates from the paper mill and can only be controlled locally in the press, correction of the profile has to be made at the paper mill. It was found that the paper grade with greater variation in tension profiles caused more web breaks and paper waste.

A paper web fails if the local strength is too low somewhere in the web or the momentary load is too high. Significant levels of breaks occur at web tensions that are an order of magnitude lower than the tensile strength of paper. It is important that the variations in strength and load remain sufficiently low and, at the same time, the tension distribution is low. Paper defects increase variation in paper strength and are, therefore, potential causes of breaks.

The results have clearly proven the importance of the web tension profile as an important property. An uneven tension profile contributes to the tendency to break, and further material waste – as well as losses in production time in both printing and at the paper mill.

2 MEASURING METHODS

Tension measurements were carried out in production with two types of devices: IQTension and Tenscan. IQTension is a cross-machine tension profile measurement device developed for permanent installations in the paper industry by Metso. IQTension Portable is a light and variable-width version of IQTension for trouble-shooting and research purposes. IQTension measures the pressure within the air film that is formed between the paper web and the curved metallic deflection plate. The curved deflection plate is perforated at intervals, so that the pressure sensors connected to the orifices in the plate produce the cross-directional (CD) profile of the air pressure p [3]

$$p = \frac{T}{R} \tag{1}$$

where T is the tension and R is the radius of the curved deflection plate.

When the measurement beam is pressed against the moving paper web, a layer of air is formed between the bar and the web because of air brought along the web. The measurement is performed continuously with a high sampling rate across the entire web width, making it possible to detect very rapid changes of tension in the paper web.

The pressure sensors of IQTension Portable are assembled inside the frame of the device. The frame, made of fibreglass, is light and firm enough to connect several frames together for variable web widths. According to our studies, the web starts to float at a speed of about 250 m/min. The deflection angle of the web is less than 10 degrees. This allows installation of the device in places with limited space – for example, between the printing units. Because the web does not touch the device, it is possible to measure the tension profile from the printed web without disturbing production.

Scanning by Tenscan was used when it was not possible to measure with IQTension or when there was a need for measuring simultaneously with IQTension. Tenscan uses a laser beam to measure the passing time of a propagating membrane wave in the web. The velocity v of the membrane wave is [4]

$$v = \sqrt{T/\sigma} \tag{2}$$

where T is the tension and σ is the basis weight of the paper.

The membrane wave is produced by a 1 kHz sound burst. The dependencies on the distance between the sensor and the paper web, and the velocity of the paper web, are corrected with experimentally-acquired conversion curves and look-up tables. Tenscan was made by ABB.

Other measurements included moisture profile measurements after the press section, normal on-line measurements at the dry end of the paper machines and laboratory measurements. The laboratory measurements of the paper samples included tensile stiffness and shrinkage profile measurements. The samples were taken across the test reels.

The moisture profile of the paper web was scanned with an IR-based MM55 from Infrared Engineering. The backscatter MM55 uses five narrow-band filters to measure selected infrared absorption bands. The sample and the reference wavelengths are derived from an infrared source housed in the sensor. The values detected from the backscattered energy are processed with algorithms devised for moisture.

The tensile stiffness was measured with Lorentzen & Wettre's TSO Tester. The velocity of an ultrasonic pulse propagated in the plane of a paper sheet corresponds with the elastic properties of the sheet. The Tensile Stiffness Index (TSI) is measured both in the machine and the cross-direction of the paper machine.

The shrinkage profiles of the paper samples were measured with a flatbed scanner and image analysis. The paper sample is scanned to consecutive images. The interval of wire lines are detected in the images with FFT-based analysis. The resuls are compared to the reference value measured in the middle of the web, which gives the shrinkage profile at intervals of 50 mm as a percentage of shrinkage.

3 MODELLING

3.1 Physical modelling

Modelling the tension of the paper web physically is challenging. Paper is an anisotropic and unhomogenous material composed of many material components. Therefore, the scientific laws of strength are usually difficult to apply. Studying stress components in three directions, the stiffness matrix [S] has nine components [5]; in equilibrium the volume element has three stress and six shear stress components. Stiffness matrix describes the state of stress

$$[E] = \begin{bmatrix} \sigma_x & \tau_{yx} & \tau_{zx} \\ \tau_{xy} & \sigma_y & \tau_{zy} \\ \tau_{xz} & \tau_{yz} & \sigma_z \end{bmatrix} \tag{3}$$

where the σ_i stress in i-direction and τ_{ij} is the shear stress in the j-direction face to the normal i.

The elasticity matrix $\{\sigma\}$ has 36 components for isotropic material and it is a generalized Hooke's law which defines stress-strain relation [5]. The strain matrix $\{\varepsilon\}$ defines the strain vector [5] for the elastic material. Normal stresses can be solved from the equation

$$\{\sigma\} = [\mathrm{E}]\ \{\varepsilon\}. \tag{4}$$

Normal stress for the isotropic and elastic material can be defined as [5]

$$\sigma_i = \frac{E}{(1+v)}\left[\varepsilon_i + \frac{v}{(1-2v)}(\varepsilon_x + \varepsilon_y + \varepsilon_z)\right],\ \ \mathrm{i = x,y,z} \tag{5}$$

where the E is the elastic modulus of the material, v is the Poisson's ratio, and ε represents the strain. Shear stresses can also be defined by the shear modulus G and by the shear strain γ.

$$\tau_{ij} = G\gamma_{ij}, \qquad \text{ij} = \text{xy,yz,zx}. \tag{6}$$

The stress state is known for the object if we know all nine stress components for the stiffness matrix [E]. If we look at the composition of the paper, it is obvious that the stiffness matrix [E] can only be defined for an infinitesimal volume and unhomogenously. Now one needs some kind of finite approximation for the problem. In this study the tension was approximated and modelled by the scientific laws of strength of materials like the tension field theory, Hooke's law, etc.

3.1.1 String models and 2D-connection model

Web tension is usually only modelled in one dimension. These string models can tell how the MD tension develops, for example, in open draws, winding and web transporting. In this study, tension of the open draw and multi-draw was studied.

Under a load, paper has elastic, viscoelastic and plastic behaviour, depending on the strain rate. Stress relaxation and creep are also characteristic properties in a paper and these properties can be modelled with mechanical string models. One well-known model is Maxwell model, where the linear spring characterizes the elastic and the dashpot the linear viscoelastic behaviour of the web in machine-direction.

Figure 2 Maxwell viscoelastic material model [6].

The strain-stress relation can be solved if the initial stress state σ_0 is known [6]

$$\sigma(t) = \sigma_0 e^{-\kappa t/\eta} = k\varepsilon_0 e^{-\kappa t/\eta} \tag{7}$$

where the κ is a string constant, the η is a damping constant, t is time and the ε_0 is the strain. The time-stress curve can be fitted to a point system and the k and the η can be defined. The model can also be useful in a study of the influence of time-dependent excitation of the model – for example, when studying the tension variation of a non-round roll in unwinding. Maxwell's model is mechanical and does not explain the material properties of paper.

Otherwise, this model gives the relaxation time constant and if there are more components in the model, the number of fitted parameters also increases.

The extended one-dimensional string model is called the two-dimensional connection model. In the plane stress state, the generalized Hooke's law can be written for orthotropic material as [7]

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = \frac{E_y}{E_y - v^2 E_x} \begin{bmatrix} E_x & E_x \cdot v & 0 \\ E_y \cdot v & E_y & 0 \\ 0 & 0 & \frac{1-v}{2} \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} \tag{8}$$

where σ_i is the stress in i-direction, τ_{xy} is the shear stress in the plane, E_i is the elastic modulus in i direction, v is the Poisson's constant and the γ_{xy} is the shear strain. From Equation 8 comes

$$\sigma_x = \frac{E_x E_y}{E_y - v^2 E_x} [\varepsilon_x + v\varepsilon_y] \tag{9}$$

and

$$\sigma_y = \frac{E_x E_y}{E_y - v^2 E_x} [\varepsilon_y + v\varepsilon_x]. \tag{10}$$

These are the main stresses in the plane stress state. Poisson's constant could be given also in two directions in this model (v_{xy} and v_{yx}). The effect of drying shrinkage can be applied to the model.

Hygro-expansion of the paper can be defined [8]

$$\Delta L = L\beta\Delta H \Rightarrow \frac{\Delta \mathrm{L}}{\mathrm{L}} = \beta\Delta H = \varepsilon \tag{11}$$

where L is length, ΔL is change of length, β is moisture expansion coefficient for the drying shrinkage [1/% RH] and ΔH is moisture change (negative for drying) [RH%]. Now Equation 11 can be added to the model [8]

$$\sigma_x = \frac{E_x E_y}{E_y - v^2 E_x} [\varepsilon_x + v\varepsilon_y - \Delta H(\beta_x + \beta_y)] \tag{12}$$

and

$$\sigma_y = \frac{E_x E_y}{E_y - v^2 E_x}\,[v\varepsilon_x + \varepsilon_y - \Delta H(\beta_x + \beta_y)]. \tag{13}$$

This is the linear elastic model and it can be useful when modelling the cross-directional tension. Note that the hygro-expansion coefficient has to be defined in every moisture content separately. Poisson's ratio has a big effect on the profile in these equations.

3.1.2 Finite Element Method (FEM)

The finite element method is a general numerical tool for physical problems. In the field of engineering design one may come across many complex problems, where mathematical formulations are tedious and usually not possible by analytical methods. In such situations one can resort to the use of numerical techniques. The finite element solver is an extensive partial differential equation solver. In FEM the problem is split into small pieces (elements), which can then be modelled and approximated with differential equations. These elements connect at a finite number of joints called "Nodes". The equations of equilibrium for the entire structure or body are then obtained by combining the equilibrium equation of each element, so that continuity is ensured at each node. The necessary boundary conditions are then imposed and the equations of equilibrium are solved to obtain the required variables – such as stress, strain, temperature distribution or velocity flow – depending on the application. The result will always be an approximation and not analytically exact. Errors are decreased by processing more equations and results accurate enough for engineering purposes are available at reasonable cost. Accuracy improves as more elements are used [7].

The finite element method comprises of three major phases: (1) preprocessing, in which the analyst develops a finite element mesh to divide the subject geometry into subdomains for mathematical analysis and applies material properties and boundary conditions; (2) solution, during which the program derives the governing matrix equations from the model and calculates the primary quantities; (3) post-processing, in which the analyst checks the validity of the solution, examines the values of the primary quantities (such as displacements and stresses) and derives and examines additional quantities (such as specialized stresses and error indicators) [9].

FEM ANALYSIS OF THE PAPER WEB

If paper is considered as a continuous material, the continuum mechanics models are applicable. The tension profile studies can be done by two-dimensional stress field analysis; one-dimensional string models do not take account of cross-directional interactions.

In FEM analysis the structure of the geometry can be divided into finite elements and all the material properties of the finite elements can be defined separately. The paper web models can be very detailed if a large number of elements are used. If the z-directional properties are modelled, the number of elements becomes very large.

In this study paper was considered a continous two-dimensional solid material obeying the tension field theory. The forming of principal stresses in open draws of the paper machine were examined. Several material properties were used to study the tension profiles. In this case, two-dimensional plane-stress elements (CPS4) were used [9].

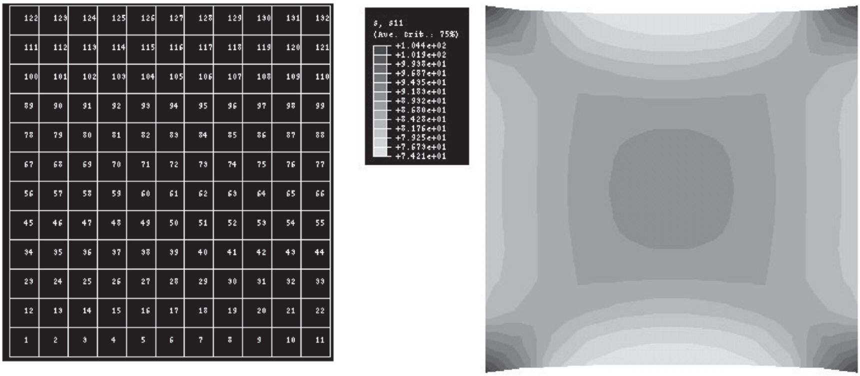

Figure 3 Simulation of the paper web by FE modelling. The paper web is constructed from homogeneous elements (the figure on the left) which conform to physical laws. The element network is fixed on both edges and the simulated web is stretched to the right. The figure on the right side represents the tensions (MD) induced in the web. The darker areas are more tense.

4 RESULTS

Modelling results

4.1.1 Measurements and data gathering in paper machines

Studies, including several test runs, were carried out on four paper machines producing newsprint (2 machines), catalogue and SC base paper. Measurements included tension profile, moisture profile and reel hardness measurements. Tension measurements were carried out at the dry end as moisture measurements were done before the dryer units. Tensile stiffness (TSO) and drying shrinkage measurements were performed in the laboratory.

Data gathering was performed normally from the paper mills' databases. This information included setting values of slice, steam box, velocities of different groups, remoisturizing and nip loads in various places. Dry end profiles, such as dry weight, moisture content and bulk, were also collected. All data collected was processed with a created software.

An extensive study was carried out on one particular paper machine, which has an on-line tension profile measurement system installed. With this system, on-line MD tensile stiffness profile can be defined. This is possible simply by doing several different draws in the space where the measurement takes place. In this way, the stress-strain test can be carried out on-line. Figure 4 illustrates the principle of defining the on-line tensile stiffness.

Apart from on-line tensile stiffness, an interesting feature of this kind of

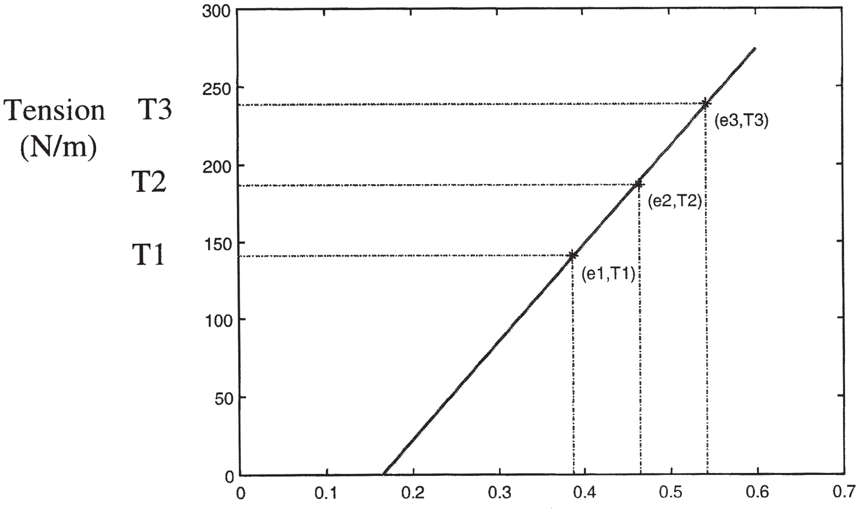

Figure 4 Defining the on-line tensile stiffness. Strains e1–e3 are calculated from draws. The on-line tensile stiffness can be defined as the slope of the stress-strain curve. Tension in Y-axis is measured on-line in several spots across the web.

definition is the point of intersection in the X-axis. At first glance it was figured that the intersection represents the built-up frozen-in strain in paper, which takes place in the drying section. However, it is impossible to find out if the stress-strain curve is linear to the point of intersection with this method of measurement. Also, the relaxation and creep phenomena occurring in the paper in the drying section are not included in this kind of examination. Because of these problems, the frozen-in strain was left out of further analyses.

4.1.2 FEM modelling results

The paper web was modelled by FEM. The web was constructed from plane stress elements. The build-up of the tension profile was modelled from the wet end to the dry end. The number and lengths of open draws, and the strains, were measured in the paper machine as well as the tension profile at the dry end. The web was only modelled in open draws – the possible changes in the web while under drying fabrics were neglected. The physical law applied to all elements was Hookean while no information about relaxation phenomena was available. The growth in elastic modulus of paper in the drying section was estimated from literature [10]. The values of the different parameters are presented in Table 1.

Table 1 Table of the parameters used in modelling.

Span	Solids content [%]	Draw length [m]	MD Elastic modulus [kN/m]	Strain [%]
1	45	2	75	3.6
2	50	1	150	0.17
3	60	1	200	0.12
4	70	1	280	0.09
5	90	1	410	0.09
6	95	4.6	460	0.035
7	95	4.4	460	0.078
8	95	9.2	460	0.5

The elastic modulus (= tensile stiffness * grammage) in MD and CD were profiled from the third drying group. The elastic modulus values were fixed, so that in MD the web edges had 10% lower modulus values than in the middle and in CD the values were 40% lower than the middle. This profiling corresponded to laboratory measurements.

The measured drying shrinkage profile was added to the model in the last two open draws in the drying section. Shrinkage was added to the modelling as a change in the draw because it was concluded that the web edges with greater CD-shrinkage move towards the centre and thus travel a longer distance in MD than in other areas of the web. The drying of the web also leads to shrinkage in the machine direction, which was considered by using higher draws in the last two open draws in the dryer section. The tension profile modelled in the first open draw was passed as initial tension to the next draw. The web was fixed from the other end so that it was able to shrink mechanically in the open draw.

Figure 5 represents the modelling results and the measured tension in the paper machine.

It can be seen that the shape of the modelled final tension profile correlates quite well with the measured one. The model used is quite simple as many, presumably important, variables – for example, relaxation, adhesion,

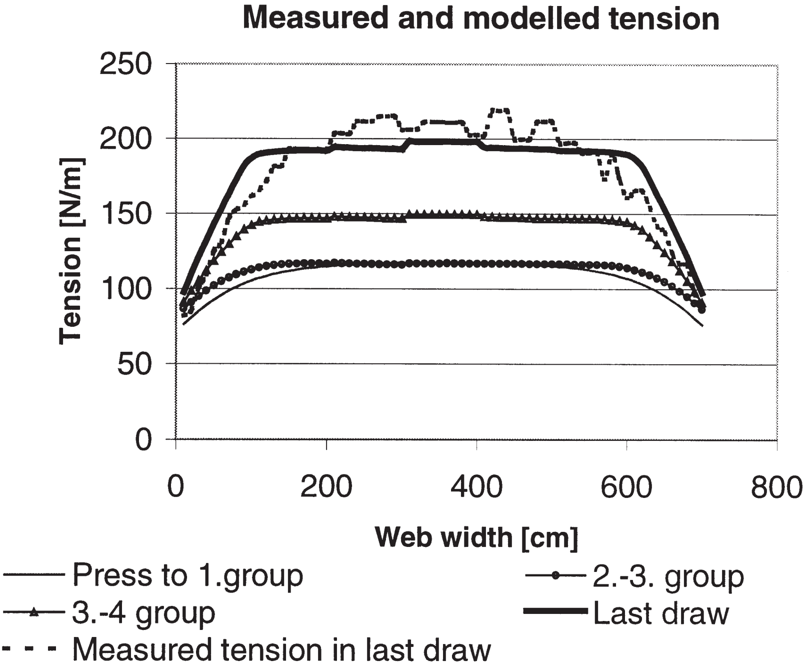

Figure 5 Modelled tension profiles in different open draws and the measured tension profile in the dry end.

gravitation and centrifugal forces – are neglected. This can, in part, explain the difference between the modelled and measured tensions.

Even by presuming the paper web as a homogenic material, one gets a final tension profile in which the edges of the web are slacker than the middle areas (Figure 6). This is because the web shrinks mechanically in open draws. This effect is defined by the Poisson value.

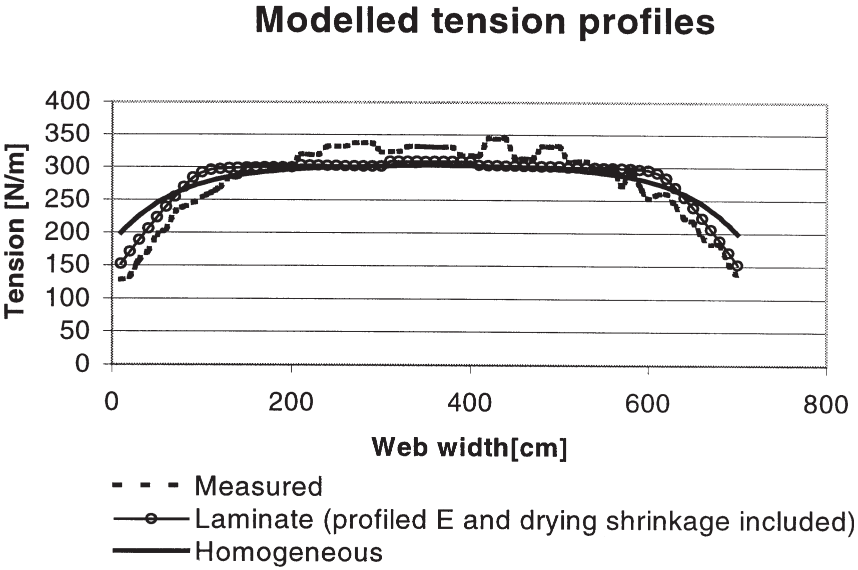

Figure 6 The modelled and measured final (dry end) tension profiles. Tension modelled for homogeneous material, an anisotropic material (laminate) with drying shrinkage and the measured tension profile.

The effect of the Poisson value on the modelled tension profile is presented in Figure 7. The Poisson value varies between different papers and is typically between 0.1 and 0.5 – depending, for example, on the type of pulp, degree of beating and orientation [11].

The effect of anisotrophy, which was defined as the tensile stiffness ratio (MD/CD), on the shape of the modelled profile was also studied (Figure 8). It can be seen that the more oriented sheet gives a flatter shape to the tension profile. This can be understood by accepting that if the ratio approaches infinity, the web can be assumed to be constructed merely from machine directional strings.

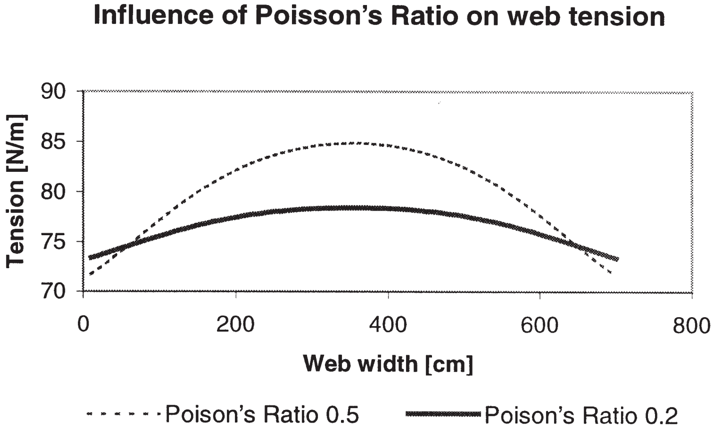

Figure 7 The effect of the Poisson value on the shape of the modelled tension profile with one draw.

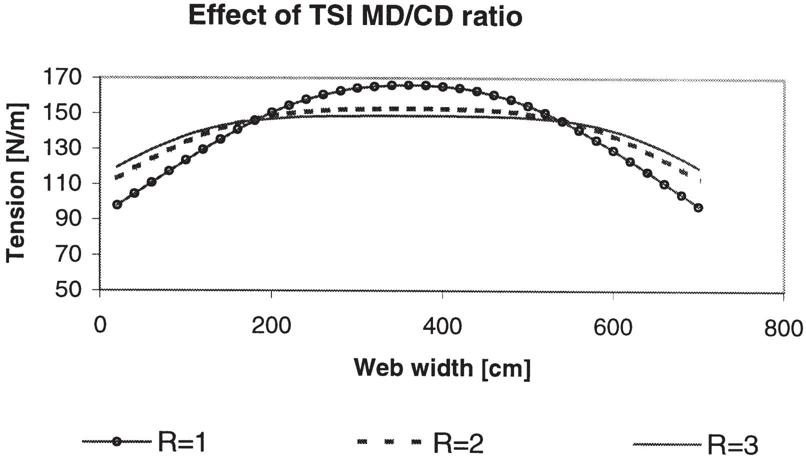

Figure 8 The effect of the tensile stiffness (MD/CD) ratio on the shape of the modelled tension profile with one draw. R = MD tensile stiffness/CD tensile stiffness.

Wahlström [12] has studied the formation of the CD drying shrinkage profile by FEM. The modelled shrinkage profiles had good correlation with the measured shrinkage profiles. Wahlström studied the effect of the free draw length in the drying section on the shrinkage profile and found that the draw length has an effect on the shrinkage profile.

The possible effect of draw length on the tension was studied and modelling gave the same kind of results on tension as Wahlström has reported in the shrinkage studies (Figure 9).

The MD tension fields induced in the web can be seen in Figure 10. The MD tension fields continually change in the draw, although the relaxation is not considered in the model. This is due to boundary conditions as the web is fixed from the other side and allowed to shrink in the draw.

It can be seen that the pattern of MD tension fields changes with different draw lengths, which can explain the difference in the modelled profiles with different draw lengths.

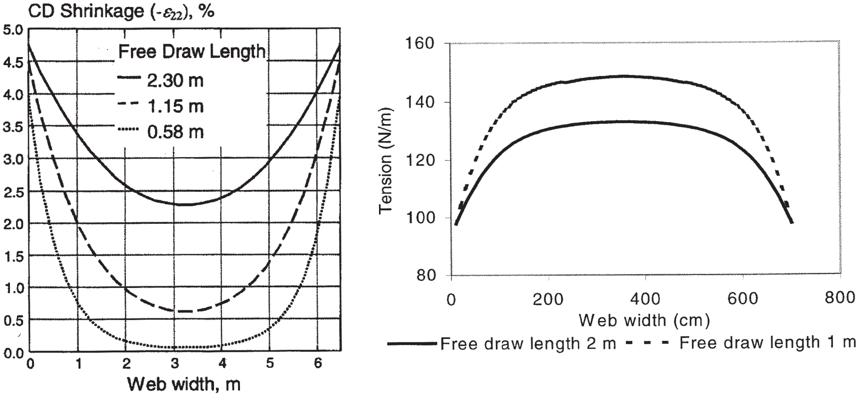

Figure 9 The effect of free draw length on the modelled tension profile (right) and the modelled shrinkage profile with one draw. The figure on the left-hand side is from [12].

Tension was also modelled and measured in the last draw before the reeler with different strain levels. The tensile stiffness (MD) in the model was calculated from tension measurements as explained in Chapter 4.1.1. The measured strain was used in the model. The initial tension profile was measured before the strain trials and was used in the model. Figure 11 represents the

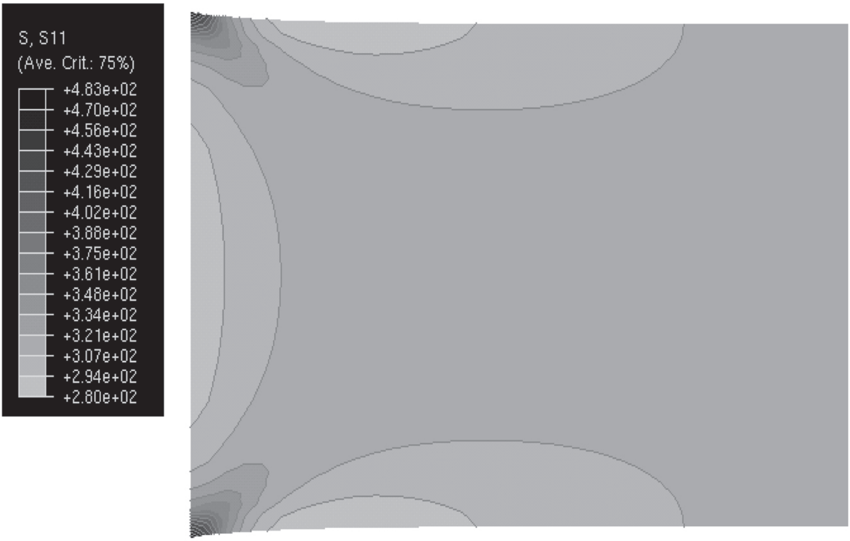

Figure 10 Modelled machine directional stresses induced in the web in an open draw. A monochrome spectrum symbolizes different tension levels. The darker areas are more tense than lighter areas. The left side of the simulated web is fixed and the web is stretched to the right.

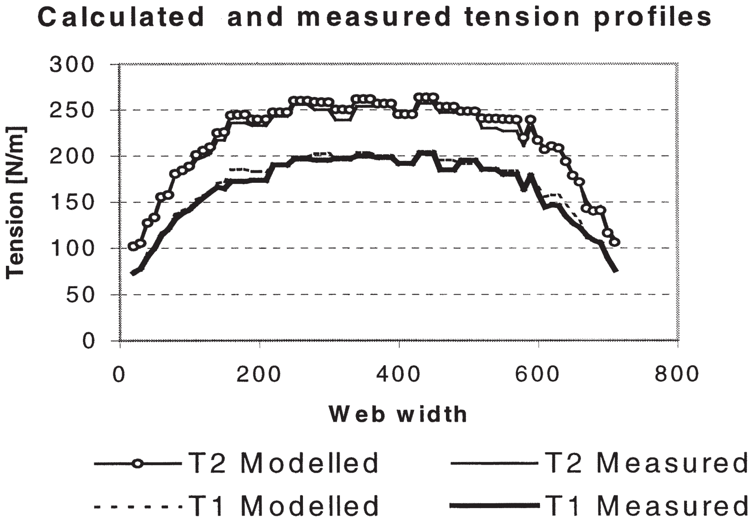

Figure 11 The measured and modelled tension profiles in the last draw before the reeler.

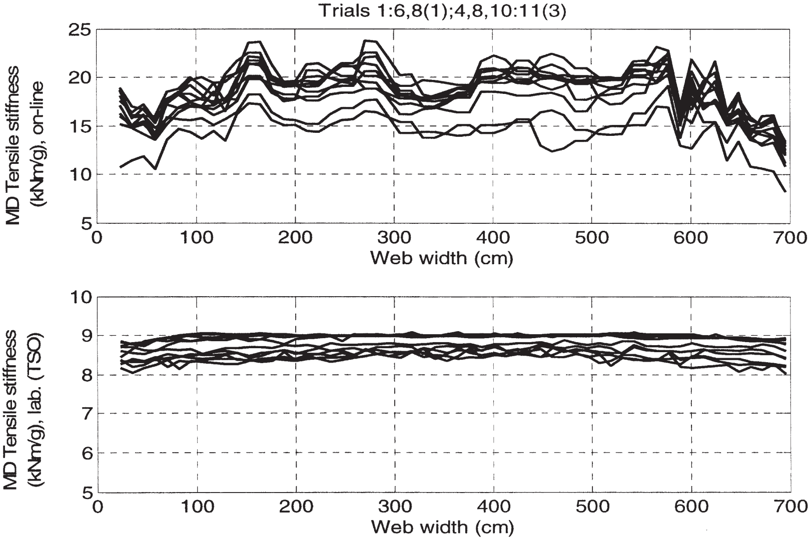

Figure 12 Tensile stiffness obtained from on-line tension measurements and laboratory.

results of the modelled and measured tensions. T1 and T2 represents different tension levels in the last open draw.

It can be seen that the modelled and measured tension profiles are quite similar. It must be noted that the on-line MD tensile stiffness differs a lot from the laboratory measurements, and this was the case in all trials. Figure 12 represents the MD tensile stiffness obtained from the tension measurements and in the laboratory (TSO-tester).

It can be seen that the tensile stiffness measured in dynamic conditions clearly differs from the laboratory measurements. The variation across the profile in dynamic conditions is much bigger than in the laboratory measurements. There are several factors which may cause the difference – for example, the relaxation phenomenom is included in on-line measurements, the effect of the mechanical shrinkage, the possible effect of the different initial loads across the web and gravitational and centrifugal forces acting on the web.

The models used in this study do not include all of these factors and in future they should be included in the modelling in order to get a clearer picture of the formation of the tension profile. This would benefit not only the paper maker but also all parties dealing with paper web handling.

4.1.3 The formation of the cross-machine tension profile based on modelling

The formation of web tension profile was studied with FEM modelling. The paper web is strained in several open draws along the paper machine. Stretching in open draws causes a non-homogeneous stress field in the fixed web because the paper is subjected to mechanical shrinkage, as defined by its Poisson ratio. This leads to a situation where the edges of the web become slacker, both in MD and CD, than the middle areas. As drying stresses have a remarkable effect on the tensile stiffness of paper, the slacker edges become less stiff than the middle areas of the web, which also amplifies the slackness of the edge areas. Further on, the slacker edge areas are affected by higher CD drying shrinkage which also diminishes the tension. According to present knowledge this is due to reduction in tensile stiffness [13] and increasing MD relaxation due to the physical movement towards the center of the web [14].

The CD tension profile and CD drying shrinkage profiles were measured in three paper machines and in every case the negative correlation between these two properties was high; the correlation coefficient varied between –0.8 and –0.95. It is proposed that these two properties are in close interaction, because in the slacker areas the force resisting the shrinkage is lower and because the higher shrinkage leads to decrease in tensile stiffness and increase in MD relaxation. Further studies are needed to define the interactions between the drying shrinkage and web tension profile.

The FEM models used in examinations lacked many important factors affecting the formation of the tension profile. However, the basic shape of the profile could be explained by using simple models.

4.2 Control possibilities of the tension profile in paper machines

The experiments carried out on the paper machines included trials with: slice control, jet-wire speed, edge flow, control of moisture profile, control of draws, breaker stack and calendering trials.

The most effective experiments were the moisture control trials. The effect of the moisture profile control could be clearly seen in the tension profile. As moisture increased in a certain area, the tension dropped. The best actuator found to control the moisture profile was the steam box in the press section. The changes made by the steam box could be later corrected with remoisturizer. The final tension profile could be manipulated in this way without ruining the final moisture profile. The effect of moisture content on tension is based on the changes in tensile stiffness. The effect is two-fold. First, the moisture content has a straight effect on tension – as moisture content

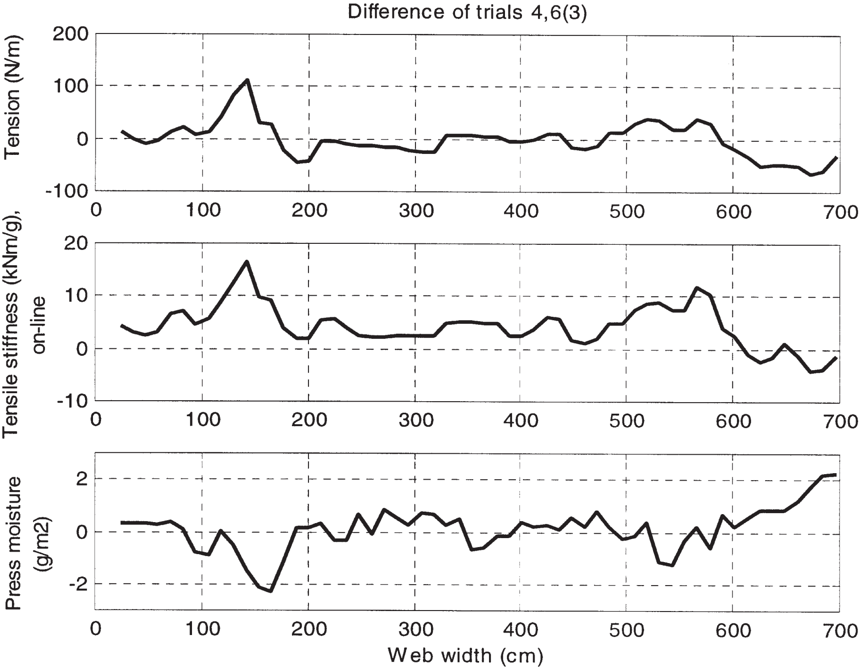

Figure 13 The effect of moisture change on tension and tensile stiffness defined on-line. Profiles are response profiles (trial – reference point). Average values were: tension 250 N/m, on-line tensile stiffness 20 kNm/g and press section moisture 41 g/m^2.

increases, the tensile stiffness of paper decreases. Second, the moist slack areas of the web have a lower drying stress than other areas, which also diminishes the tensile stiffness. This fact makes it possible to control the tension profile by profiling the moisture in different parts of the machine. The effect of steam box control on web tension, tensile stiffness (on-line) and moisture in the press section can be seen in Figure 13. Control of the steam box led to changes in the moisture profile, and the effects on on-line tensile stiffness and web tension were clear.

It can be seen that the moisture changes made in the press section had a clear effect on the dry end tension profile. The response in tensile stiffness is almost identical to the tension change.

Jet-wire speed and edge flow trials caused changes in the orientation profile, which led to changes in the tensile stiffness and tension profile. Figure 14

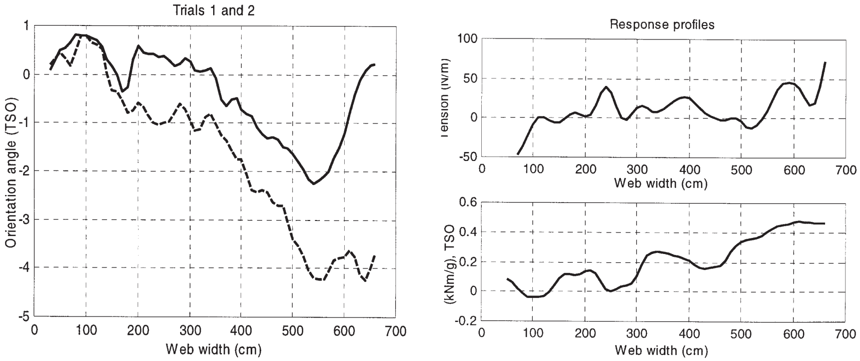

Figure 14 The effect of the edge flow trial in the tension, MD tensile stiffness and orientation angle (TSO) profiles. Edge flow was controlled in the back edge of the paper machine, which evened out the orientation angle (TSO), left figure. The tension and MD tensile stiffness profiles are response profiles (trials 1–2). The solid line on the left-hand side represents trial 1. The average tension was 400 N/m and the average tensile stiffness was 8.5 kNm/g.

represents the effect of edge flow control on the tension profile and the tensile stiffness (TSO-tester).

The other experiments mentioned above often generated changes in the moisture profile, and changes in the tension could often be explained by moisture.

According to the results of the modelling and tests, it is impossible to get an even tension profile with existing dryer section configurations. In any case, the tension profile can be adjusted between certain limits by, for example, controlling the evolution of the moisture profile. New constructions on impingement drying with superheated steam, with the capability of moisture profiling, may help to even out the tension profiles in paper making.

5 CONCLUSIONS

Production speeds and web widths are increasing in paper machines. This means that the control of the paper web is becoming more critical and that the paper maker has to gain a deeper understanding of web dynamics in order to achieve better productivity. The web tension profile in the paper machine is normally convex in shape, which means that the edges of the web are slacker than in the middle. As the shape of the tension profile is normally passed to the printing press, the edge reels tend to have very skew tension profiles and many printers find these reels troublesome – at least in offset four-colour printing where water is added to paper in every printing unit.

The formation mechanisms of the tension profile were studied by finite element modelling and in paper machine trials. Models were verified by measurements in a paper machine. Although a relatively simple material models were used, the simulations could quantitatively predict the shape of the tension profile.

It is suggested, based on modelling work, that the basic mechanism behind the convex shape of the tension profile is largely due to the drying process. The web is stretched in the machine direction in several open draws from the wet end to the dry end. Stretching in the machine direction causes a non-homogeneous stress field in the web because the paper is subjected to a mechanical shrinkage defined by its Poisson ratio. This leads to a situation where the edges of the web become slacker than the middle areas. The uneven stress fields in the web through the drying section lead to lower tensile stiffness values on the edge areas because the drying stresses have a remarkable effect on the tensile stiffness. The slacker edge areas had higher CD drying shrinkage which, based on present knowledge, diminishes the tensile stiffness and also leads to higher MD relaxation. These effects amplify the slackness of the edge areas. Further studies are needed to define the interactions between the drying shrinkage and web tension profile.

Several trials were carried out to control the web tension profile. These included moisture content profiling, jet-wire speed, edge flow, strain rate and nip trials. The most effective control was moisture profiling with the steam box in the press section. The more dried sections of the web became more tense and vice versa. This was because the moisture content of the paper has a strong effect on the formation of the tensile stiffness. The major shape of the tension profile is convex. According to this study, it is impossible to get an even tension profile with existing dryer section configurations. New constructions of impingement drying with superheated steam, with the capability of moisture profiling, may help to even out the tension profiles in paper making. In any case, the tension profile can be adjusted between certain limits by, for example, controlling the evolution of the moisture profile. These controls play an important role when improving the runnability of the paper machine, winder and printing press.

The modelling of the tension in different production stages requires further studies. Time-dependent phenomena and, for example, gravitational, adhesion, frictional and centrifugal forces should also be added to the material descriptions. In this way, the increased knowledge of the dynamic stress-strain behaviour of the paper web would lead to better web handling and controlling.

REFERENCES

1. Parola, M. and Beletski, N., “Tension across the paper web – a new important property”, Proceedings of the 27th EUCEPA Conference, 11–14 October, Grenoble, France (1999).
2. Kaljunen, T., Parola, M. and Linna, H., “CD Profile Measurements and Paper runnability”, XIV IMEKO World Congress, CD Symposium 97, Volume XB, 4–5 June, Tampere, Finland, pp 8–13 (1997).
3. Åkerlund, K., Happonen, E., Mustonen, H., “Web tension profile measurement: a tool for runnability control, Automation days *95*” (3–5. May 1995), Finnish Society of Automation, Helsinki, Finland, p. 329–333 (1995).
4. Marttinen, T., “A contactless tension profile meter”, Doctor’s Dissertation, Acta Polytechnica Scandinavica, Applied Physics Series No. 192, Finnish Academy of Technology, Helsinki, Finland, 80 p. 000 (1994).
5. Alexander, J.M., *Strength of materials, 1, Fundamentals*, Publisher: Ellis Horwood, Chichester, ISBN 0–470–27119–1 (1981).
6. Findley, W.N., Lai, J.S., Onaran K., *Creep and relaxation of nonlinear viscoelastic materials*, ISBN 0–7204–2369–4 (1989).
7. Cook, R.D, Malkus, D.S, Plesha, M.E., *Concepts and applications of finite element analysis*, 3rd Edition, ISBN 0–471–84788–7 (1989).
8. Kurki, M, Pakarinen, P, Juppi, K, and Martikainen, P. (Markku Karlsson, *Papermaking Science and Technology, Papermaking, Part 2*), Drying, Chapter 11, Web handling. ISBN 952–5216–09–8, TAPPI (2000).
9. *ABAQUS User’s Manual*, Version 6.1, Hibbitt Karlsson & Sorensen, Inc, Pawtucket (RI) (2000).
10. Kuhasalo, A, Niskanen, J, Paltakari, J, and Karlsson, M. (Markku Karlson, *Papermaking Science and Technology, Papermaking, Part 2*), Drying, Chapter 1, Introduction to paper drying and principles and structure of dryer section. ISBN 952–5216–09–8, TAPPI (2000).
11. Niskanen, K, and Kärenlampi, P. (Kaarlo Niskanen, *Papermaking Science and Technology, Paper Physics*), Chapter 5, In plane tensile properties, ISBN 952–5216–09–8. TAPPI (1998).
12. Wahlström, T, Adolfsson, K, Östlund, S, Fellers, C., “Numerical modelling of the cross direction shrinkage in a dryer section, a first approach”, TAPPI International Paper Physics Conference, San Diego, CA. (1999).
13. Htun, M., The influence of drying strategies on mechanical properties of paper. Dissertation, The Royal Institute of Technology, Stockholm, Sweden (1980).
14. Koskimies, J., Linna, H., Moilanen, P. and Yli-Kauppila, J., “Control of the web tension profile improves runnability and product quality in paper mills”, Proceedings EUCEPA Symposium, 5–8 October, Budapest, Hungary (1992).

Transcription of Discussion

MODELLING THE WEB TENSION PROFILE IN A PAPER MACHINE

Markku Parola, Samppa Vuorinen, Hannu Linna, Timo Kaljunen and Nikolai Beletski

VTT Information Technology

Derek Page Institute of Paper Science & Technology

When I first joined the industry 50 years ago the major problem in papermaking was identified as the problem of cross-directional control. The problem was, of course, the difference in properties between paper at the edge and paper at the centre. 50 years later, its delightful to see somebody, tackling, with modern techniques, this problem and apparently getting somewhere. That said, do I understand correctly that according to you the major reason for the difference between the edge and the centre in the MD tension is associated with Poisson's ratio? If you set Poisson's ratio to zero, do you get a completely uniform tension?

Samppa Vuorinen

Yes, if Poisson's ratio is zero, you will get an even tension, but if you take account of drying, you will not get an even tension profile.

Derek Page

Is that because at the edge the sheet can contract laterally in the CD easily, whereas in the centre it can't because it's held by the rest of the sheet?

Samppa Vuorinen

Yes, that is true.

Discussion

Tetsu Uesaka Paprican

My question is on the same issue of modeling. The mechanical strain is coupled in the MD and CD, through the Poisson ratios, and this mechanical strain is basically the total strain minus, so-called thermal or hygro strain, as you indicated in the proceedings. According to your conclusions, if you have a fixed dryer configuration, this means that you always see convex tension profile. However, in our experience, we actually solved some tension profile issues at a given dryer configuration. So this means that probably something different is going on such as indicated by the previous speaker. Is the Poisson's effect taken properly into account in your calculations? Also you indicated in the proceedings, only one Poisson's ratios, but obviously we have two Poisson's ratio in the case of orthotropic materials. So depending on which value you use, the result would be quite different.

Samppa Vuorinen

I don't know if I have followed the question, but I think that if you have two Poisson's ratios in two directions, you profiled that, these are minor effects in this simulation; whether this drying shrinkage was added to the change in draw, and it is so major that we didn't take these actions into account. I mean we did not profile the Poissons ratio across the ucb, and the effect of drying shrinkage had major effect.

Bryan Phillips Consultant

We've been working on CD shrinkage profiles. You claim that you can get a flat MD tension profile – get the edges the same as the centre of the web – by steam box adjustment. What happens to the CD shrinkage profile?

Samppa Vuorinen

It was flat in the beginning but it inherited to the next draw, but MD profile not so even, but the CD profile was even because it had also a minor effect. By steam box control you can control the tension profile in certain limits, yes.

Bryan Phillips

But the curves you presented, always showed that the MD tension profile is lowest at the edges, but you say that you can adjust that by using the steam box. If we end up with a flat tension profile at the reel, the CD shrinkage profile still remains the same – we've seen that CD shrinkage at the edges is 8%. Can you really get a flat MD tension profile with a shrinkage profile of 8% at the edges and maybe 1 or 2 % at the centre?

Samppa Vuorinen

I have to say that I can't really answer that question, my colleague should have been here to answer these questions but he is ill. I'm considering this FEM section more. As is shown in the paper, you can control the moisture profile by the steam box in the press section. The changes made by the steam box could later be corrected with a re-moisturiser. This makes it possible to control the tension profile in different parts of the machine.