MODELING THE TENSION OF THE PAPER WEB

by

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Abstract

The tension distribution of a paper web in a paper machine is typically uneven and the edges of the web are normally slacker than the middle areas. This contributes to many problems not only in the paper making process but also in the printing press. The formation mechanisms of the tension distribution are not well known.

The traditional approach in tension-related studies has been to handle paper as a one-dimensional string. However, this approach is not adequate to the study of three-dimensional moving webs. It is important for papermakers and printers to achieve good runnability and thus minimize the waste of paper. The improvement of runnability requires a better understanding of paper web dynamics and tension variations during the process in both the machine and cross directions. Stretching the paper web in the machine direction causes a non-homogeneous stress field in the web because the paper is subjected to mechanical shrinkage defined by the Poisson ratio of the paper. This typically causes a situation where the edges of the web are slacker than the middle areas. The cross directional tension is also an important factor that may have a crucial effect on the forming of wrinkles, for example. In this study factors affecting the machine directional tension were studied numerically and the known tension field theory distribution was examined.

Viscoelastic paper is a challenging material in terms of both modelling and web transport systems. In this study the finite element method (FEM) was applied to the modelling of the paper web. The models built were evaluated by tension measurements on a production scale. In the case of free open draw, the development of the tension field was studied.

The influence of mechanical conditions, such as guiding rolls, was modeled in press room conditions. Steady state analysis was performed for a moving paper web. The modelling results gave a better understanding of web transportation and FEM appears to be a promising tool for analyzing paper web behavior in different web handling systems.

1. Introduction

Production speeds and web widths are increasing in both paper machines and printing presses. This means that the control of the paper web is becoming more critical and that the paper maker and printer have to gain a deeper understanding of web dynamics to achieve better productivity.

It has been found in paper machine studies that the tension distribution across the paper web is normally uneven /1/. The edges of the paper web are normally slacker than the middle areas of the web. This can lead to runnability problems in paper machines and also in later stages of paper processing. It has also been found that the shape of the tension profile is passed on to the printing press /2/. This means that when the web is cut in the winder the typical crying shape of the tension profile normally turns into skew edge reel profiles and relatively even middle position profiles, Figure 1. This can lead to runnability problems in the press, where the typical tension related problems are register errors, web wandering, wrinkles and, in the worst case, web breaks. Also the press components such as nips may affect and sometimes dominate the shape of the tension profile /2/.

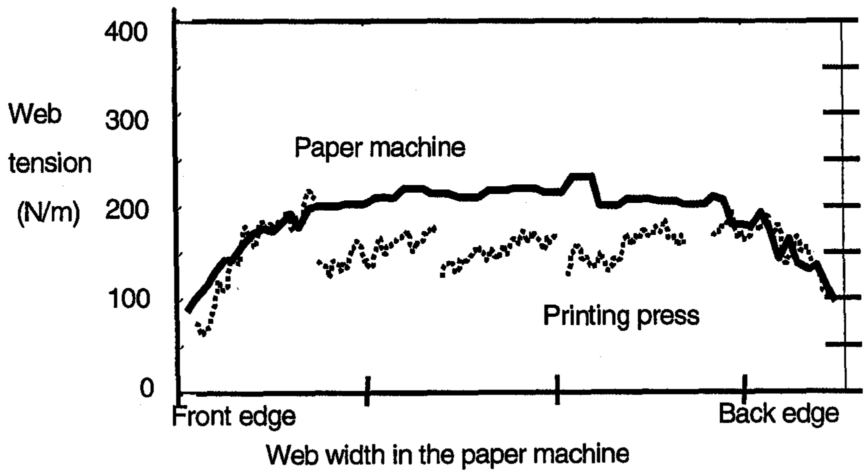

Figure 1. The web tension profile measured in a paper machine (solid line) and in a printing press (dashed line).

The different shapes of tension profiles cut from different parent reel positions can cause severe changes in tension field during a reel change in the printing press. Figure 2 presents the change in the tension profile during a reel change which took place at 200 s. The changing reels are cut from the front and back edge of a parent reel /2/.

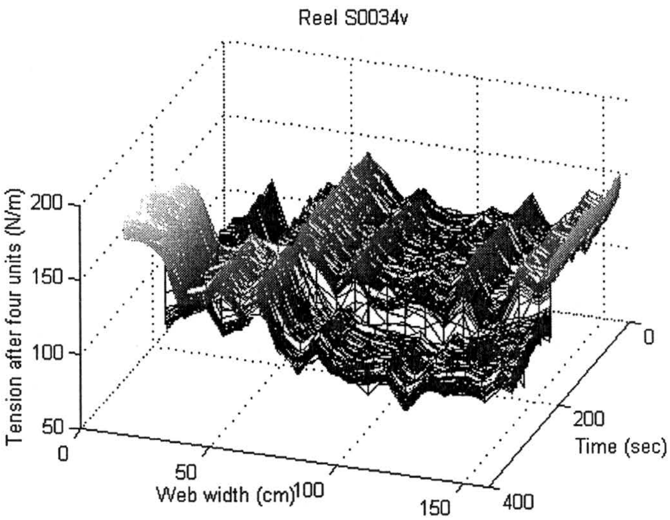

Figure 2. A change in the tension profile during a reel change measured after the printing units in an offset-coldset press. The front-edge roll is changed to a back-edge roll. The sampling frequency was 10 Hz. The reel change took place at 200 s.

The importance of tension profiles to the runnability of a printing press has been analyzed /3,4/ in long term studies. Studies have shown that customer reels with greater variation in cross directional tension have more web breaks and paper waste than other reels. Figure 3 presents the effect of tension profile range (maximum tension - minimum tension) on web break rate.

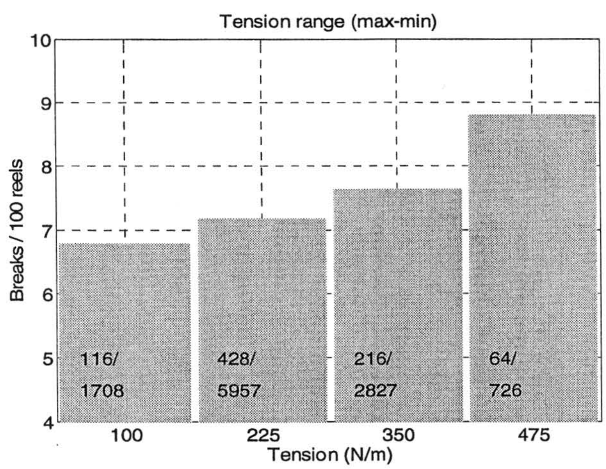

Figure 3. The effect of tension range on web break rate in a printing press. The tension range was calculated from 11200 reels. The total number of reels with a break and the number of reels in each category are shown in the columns.

The formation mechanisms of the cross directional (CD) tension profile have not been widely studied. VTT has carried out a large study on the build-up mechanisms of tension in paper machines, which will be published later. The traditional approach in tension related studies is to handle paper as a one dimensional string. This kind of premise is not adequate when studying three dimensional moving paper webs. Machine parts, such as nips and guiding rolls, and different means of control affect the formation of tension and these effects should also be studied. These are the main reasons why the finite element method (FEM) was applied to the modelling of the paper web. The models built were evaluated by tension measurements in paper machines and in printing presses.

2. Measuring method

The modelling of tension distribution in a web would be fruitless if tension profile (CD) could not be reliably measured. Several measuring instruments are available /3/ on market. In this study we used the IQTension measurement system developed by Metso (Figure 4) /4/.

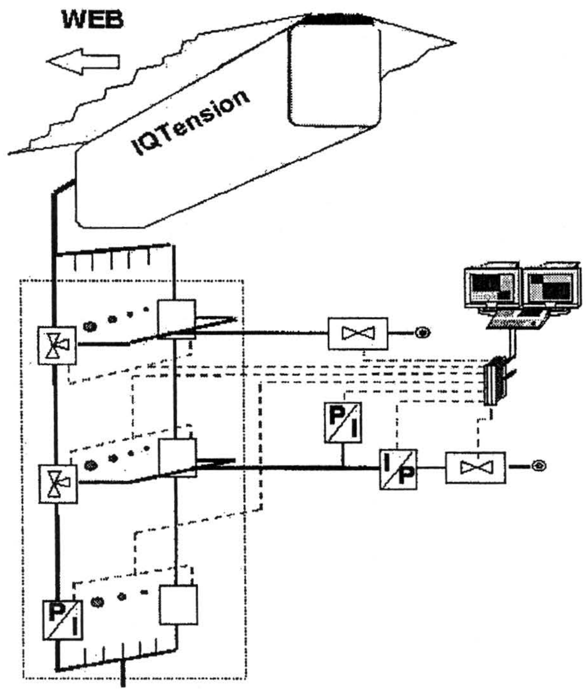

Figure 4. IQTension measuring apparatus.

The measurement is performed continuously across the entire web width making it possible to detect rapid tension changes. IQTension was developed for permanent installations in the paper industry.

IQTension is based on a curved measuring beam, where the measuring orifices are crosswise to the paper web. When the measuring beam is pressed against the moving paper web, an air layer is formed between the beam and the web because of the air brought along with the web. The air pressure correlates with the web tension. The air film pressure is measured by pressure sensors through orifices in the beam surface and the signals are converted to a tension profile /4/.

The sampling rate of the tension profile depends on the performance of an AD converter and on the number of the pressure sensors connected to the measuring beam. VTT has used a sampling frequency of 100 Hz with an average of 10 samples, which gives a tension profile ten times per second. The distance between the measuring orifices (of the pressure sensors) is 25 mm.

According to our studies, the web begins to float at a speed of 250 to 500 m/min depending on the paper grade and tension level. The wrap angle of the web is very small, only about 10 degrees. This allows the device to be installed in places with very little space, for example, between the printing units. Since the web does not touch the device, it is possible to measure the tension profile of the printed web without disturbing production. The results have shown that the surface characteristics of different paper grades have no effect on the pressure /5/.

3. Finite Element Method (FEM)

The Finite Element Method is a general numerical tool for physical problems. FEM is a method for solving partial differential equations (PDE) with complicated boundaries /6/. Multiple loading conditions may be applied to a system. The loading may be in the form of a point load, a pressure or a displacement. The method requires the definition of elementary volumes, for each of which the integral can be approximated as a function of the node values of the unknown functions.

Mathematically, the structure to be analyzed is subdivided into a mesh of finite sized elements of simple shape. Within each element, the variation of displacement is assumed to be determined by simple polynomial shape functions and nodal displacements. Equations for the strains and stresses are developed in terms of the unknown nodal displacements. From this, the equations of equilibrium are assembled in a matrix form which can be programmed and solved on a computer. After applying the appropriate boundary conditions, the nodal displacements are found by solving the matrix stiffness equation. Once the nodal displacements are known, element stresses and strains can be calculated. 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.

The FEM session consists of three main stages, the pre-processing stage, the solution stage and the post-process stage /7/. In the pre-processing stage the analyst selects the type of analysis to be used, e.g. structural, fluid, thermal or electromagnetic. Element types, material properties, model dimensions and the element mesh are also defined in this first stage of analysis. Material properties define the physical laws acting between the elements. In the second stage the loads and boundary conditions are applied to the model and the solution of the problem is solved automatically by the software. The third and the last stage is postprocessing, in which the results of the analysis are presented in the form of tables, contour plotting, deformation shapes, etc. Usually stresses and strains are plotted, or, if required the yield stresses and strains according to the main theories of failure (von Mises, St. Venant, Tresca etc.). Other information such as the strain energy, plastic strain and creep strain may also be obtained.

4. Modelling the web tension in the paper machine

The web tension profile in the paper machine was modelled by the FEM. The web was constructed from plane stress elements which can be used when the thickness of a body or domain is relatively small in relation to its lateral (in-plane) dimensions /2/. The stresses are functions of the planar coordinates alone, and the out-of-plane normal and shear stresses are equal to zero. Simulations were performed using a linear elastic Hookean material model and an ortotropic material model was used. In addition to the simulations the web tension profile was measured in the paper machine before the reeler. The lenght of this open draw was 9.2 meters and the tension profile was measured about 2 meters away from the soft calander nip. As the web width was 7 meters, the modelled mesh was a rectangle 9.2 meters long and 7 meters wide. The lay-out of the paper machine's dry end can be seen in Figure 5.

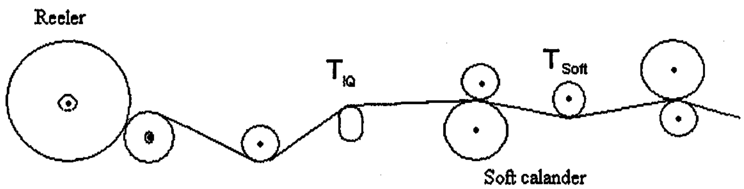

Figure 5. The open draw in the paper machine's dry end and the measuring device location IQT.

The strains measured in the different draws were used in the model. The initial tension profile was measured and used in the model as the pre-tension in the machine direction (MD). The tensile stiffness profile was calculated from the stress-strain curve and was used in the models. The stress-strain trials were carried out in the paper machine's last draw by measuring the tension profile in three different strain levels. The tensile stiffness (on-line) was defined as the slope of the stress-strain curve.

The modelled MD tension fields induced in the web can be seen in Figure 6. The MD tension fields continually change along the draw, although the relaxation is not considered in the model. This is due to the boundary conditions, as the web is fixed from the other side and allowed to shrink in the draw. The material model used was homogenous and isotropic, which means that the tensile stiffness was the same in the MD and CD.

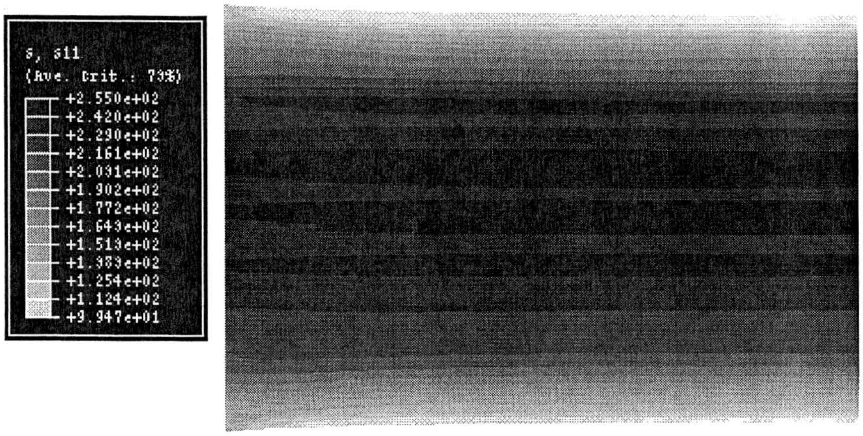

Figure 6. Modelled machine directional stresses induced in the web in an open draw (Deformation scale factor = 500). A monochrome spectrum symbolizes the different tension levels. The darker areas are more tense than the lighter areas. The left side of the simulated web is fixed and the web is stretched to the right.

The modelling results at the two different tension levels are shown in Figure 7.

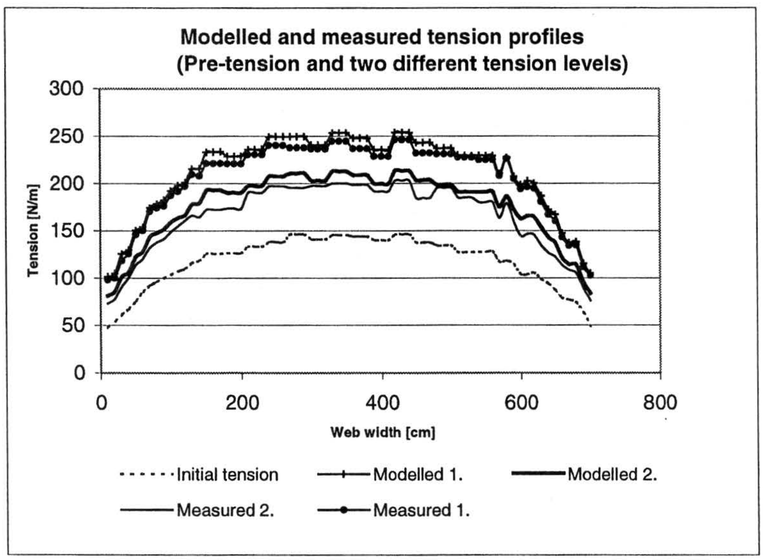

Figure 7. The measured and modelled tension profiles in the last draw before the reeler.

It can be seen that the simulated tension profiles are quite similar to the measured tension profiles. In these two tension levels the total strain was in the first case 0.54 % and in the second case 0.61 %. The shape of the profile is convex; the edges of the web are much slacker than the middle area. There are many factors in the paper machine which influence the tension profile, such as edge flows, steam box control, uniformity of cylinder drying, roll alignment, drying shrinkage, nip load distribution, moisture changes in paper, the relaxation and creep in the paper sheet, etc /8/. The above-mentioned effects are in this case included in the initial tension profile used. It is known that the paper material is ortotropic. In this simulation it was found that both the isotropic and orthotropic material models gave the same results using an initial tension profile, which shows that the initial tension profile had a big effect in these simulations.

It was also found that the defined tensile stiffness (on-line) differed remarkably from the laboratory measurements, as can be seen in Figure 8. The laboratory measurements were carried out by ultrasonic TSO tester.

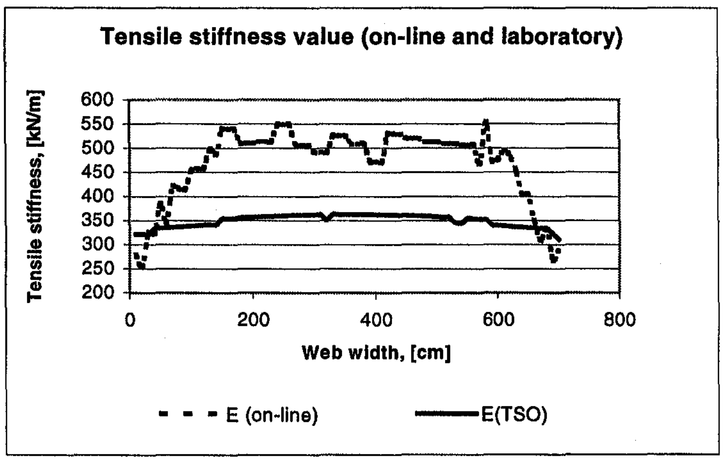

Figure 8. Tensile stiffness measured in the paper machine (E on-line) and in the laboratory (E (TSO)).

The variation across the tensile stiffness profile in dynamic conditions is remarkably bigger than in the laboratory measurements. There are several factors which may cause the difference - for example, the relaxation phenomenon is included in the on-line measurements, as is the effect of mechanical shrinkage, the possible effect of different initial loads across the web and gravitational and centrifugal forces acting on the web. This result also means that one cannot predict the shape of a tension profile by using the tensile stiffness of the paper sheet measured in the laboratory by traditional means.

5. Modelling the effect of a skew roller in a press

Normally, the web tension is convex /4/, as can be seen in Figure 1 (chapter 1). In most cases, the edges of the paper web are slack. This results in poor runnability with edge reels, since the shape of the tension profile can normally still be seen in the press.

In this study it was found that the press may also have a big effect on the shape of the tension profile. In one press line it was found that the shape of the tension profile was dominated by the press. The moving paper web was displaced in the lateral direction by a skew roller. The tension profile was measured by IQ-tension™ before the infeed unit. The press components are shown in Figure 9.

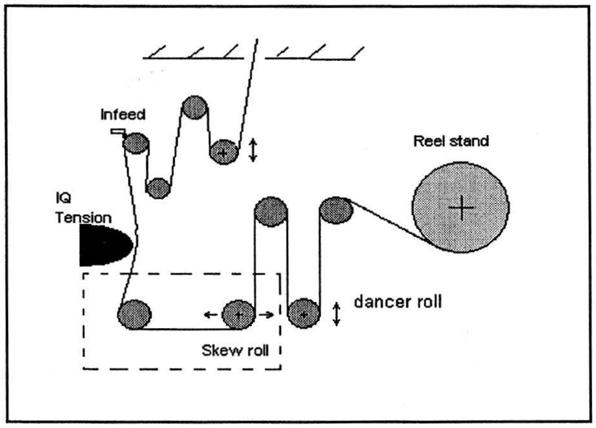

Figure 9. Press components in the reel stand of a printing press. The dashed line represents the simulated area.

The measured tension profiles of three reels are shown in Figure 10. It can be seen that all three profiles are skew and slightly U-shaped, altough the original shape of the tension profile was convex in the paper machine.

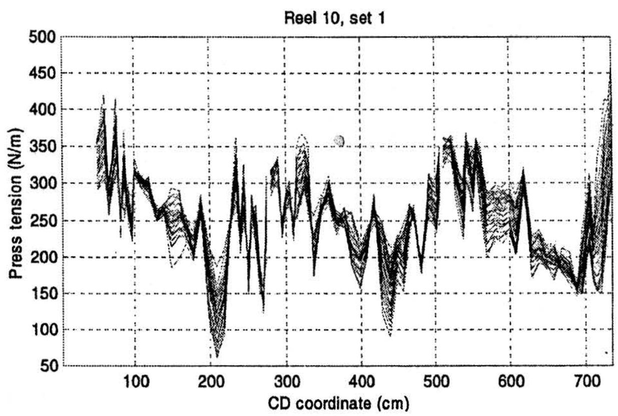

Figure 10. Tension profiles of three rolls in a printing press. The x-axis represents the web width in the paper machine.

The FE method was applied to model the behaviour of paper web in the press. The paper web was modelled as a linear elastic isotropic web, built of 3D continuum stress elements. The geometry of the model is shown in Figure 11.

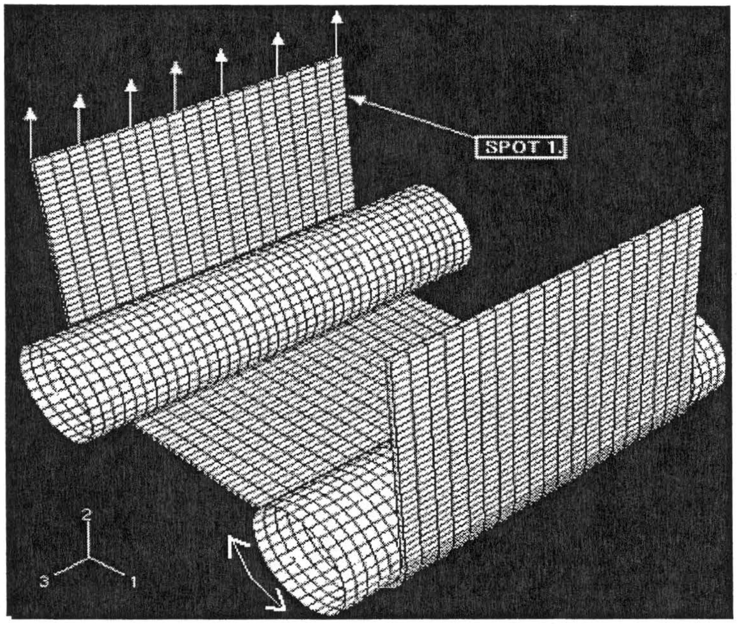

Figure 11. Model mesh of the guiding rolls and the paper web. The skew roll is on the right and the web tension measuring point is in spot 1.

This simulated web was deflected to the same degree as on the press. The web was fixed from the one side (the right side in Figure 11) and was stretched to the left (see arrows in Figure 11). The contacts between the paper and the rollers were assumed to be frictionless as the rollers revolve along with the moving web. The results correlated well with the measured tension profile on the press (Figure 12).

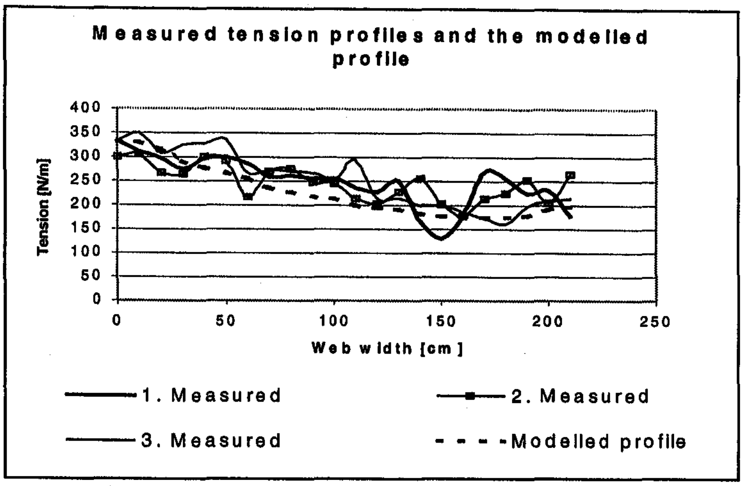

Figure 12. Measured tension profiles (averaged from Figure 10.) and the modelled profile.

In Figure 12. it can be seen that all three measured profiles are quite similar and that they follow the modelled curve. The correlation coefficients calculated between the modelled and measured profiles in order from measure profiles 1-3 are 0.77, 0.75 and 0.91.

The modelled tension profiles were found to be dependent on the strain level (Figure 13). When the tension level is increased, the profile tends to lose its U-shape and change to a skew form.

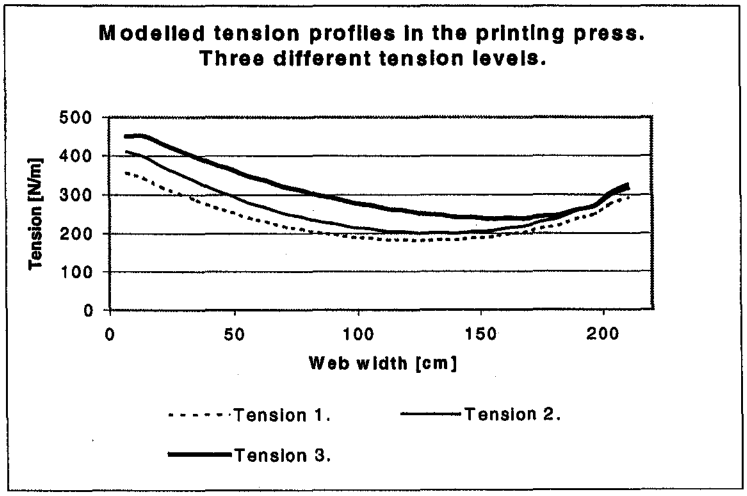

Figure 13. Modelled tension profiles in the printing press.

6. Conclusions

Production speeds and web widths are increasing in both paper making and printing presses. The web tension and its distribution in the web plays an important role in web handling at every process stage. The formation mechanisms of the tension fields in the web have not yet been adequately explored. One of the main reasons for this is that suitable measuring methods have not been available for very long.

In this study the formation of the cross-directional web tension profile was studied in a paper machine and in a printing press. The paper web was modelled by the finite element method. The modelling results were evaluated by tension profile measurements made by the IQTension system.

The FE method gave good correlation with measurements in both the paper machine and printing press studies. Results suggest that the FE -method is suitable for analyzing the tension formation in a paper web in different process stages. The shape of the final tension profile in the paper machine was found to be mainly dependent on the initial tension profile and tensile stiffness profile. The tensile stiffness used in modelling was defined in the stress-strain trials performed on-line in the paper machine. It was found that this on-line tensile stiffness differed remarkably from laboratory measurements. It is suggested that this difference is due to the effect of mechanical shrinkage of the web, the effect of the different initial loads across the web and gravitational and centrifugal forces acting on the web. This result means that the shape of the tension profile cannot be predicted by using traditional laboratory scale tensile stiffness measurements.

Normally, web tension profiles in the paper machine are convex, and in most cases the edges of the paper web are slack. This results in poor runnability with reels cut from paper web edges, since the shape of the tension profile can normally still be seen in the press. In this study it was also found that printing press elements may cause severe disturbances to the web tension profile. It was found that a skew roller in the press lead to this kind of phenomenon. This was discovered by modelling the guidance of the paper web passing the rollers by the FE method. The modelling results were verified by tension measurements in the press.

The interactions of the paper web and the printing press require further studies. These studies may produce significant information for the paper maker and for the printer concerning the essential parameters affecting the performance of the paper web on the press.

Literature

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Name & Affiliation	**Question**
D. Hristopulos – Paprican	What was the physical model that you solved with the finite element method (what type of equations did you actually simulate? The second question has to do with the study of defect of the CD tension variation and the web breaks, is the result based on the statistical analysis or is there also a physical model motivating the dependence of web breaks on the CD variation?
Name & Affiliation	**Answer**
S. Vuorinen – VTT Information Technology	The paper web was modeled as linear elastic material, so the type of equation was Hooke's law. The web breaks in the press was studied statistically based on a variation of a MD tension, but profiled as a function of CD location.
Name & Affiliation	**Question**
Curt Bronkhorst – Weyerneauser	Figure 7 suggests that the difference between the initial and the measured and modeled profiles is that occurs through one draw, is that correct?
Name & Affiliation	**Answer**
S. Vuorinen – VTT Information Technology	Yes, only one draw was modeled. First, the initial tension profile was measured and it was used in the model.
Name & Affiliation	**Question**
Curt Bronkhorst – Weyerneauser	Between two dryer cams?
Name & Affiliation	**Answer**
S. Vuorinen – VTT Information Technology	No, between the reeler and the soft calendar.
Name & Affiliation	**Question**
Curt Bronkhorst – Weyerneauser	Would this change in the tension profile be the result of change in moisture content?
Name & Affiliation	**Answer**
S. Vuorinen – VTT Information Technology	The convex tension profile was explained by the uniformity of cylinder drying and drying shrinkage.
Name & Affiliation	**Question**
K. Good – OSU	Is this tension variation as a function of moisture profile or is it tension variation as a variation of web length across the width? We saw in the last paper that the tension variation was due to a change in elongation across the width, so maybe that paper across the width is of equal moisture content but perhaps the edges are longer than the center?

Name & Affiliation	Answer
S. Vuorinen – VTT Information Technology	In this simulation, the initial tension included all these terms and results from the simulation showed the initial tension is responsible for the tension profile. The best correlation was between the tension profile and drying shrinkage. When the web edges are under more shrinkage that could affect the elongation profile.
Name & Affiliation	**Question**
K. Good – OSU	When the producers of paper in large rolls measure tension profiles like this across the web width, do they then try to reintroduce moisture to attempt to even out these profiles at later points in the machine?
Name & Affiliation	**Answer**
S. Vuorinen – VTT Information Technology	Usually these non-uniform tension profiles occur in the paper machine's dry end and there is not much you can do about it. Remoisturing is not an answer.
Name & Affiliation	**Question**
K. Tanimoto – Mitusbishi	How do you measure the underlying stiffness variation?
Name & Affiliation	**Answer**
S. Vuorinen – VTT Information Technology	It is calculated from the sequential tension profiles and from the speed differences of rollers based on a Hooke's law.