MODELING THE BEHAVIOR OF THE PAPER WEB IN PRINTING PRESSES

by

S. Vuorinen and M. Parola
VTT Information Technology Media
FINLAND

ABSTRACT

The production efficiency of printing presses is limited by runnability problems such as web breaks, register errors, wrinkling and lateral instability of the paper web. To explore these phenomena, one must study the interaction mechanisms between the paper web and the printing press. In offset printing damping water is applied to the web affecting the rheology of the running paper web. In numerous printing applications many webs are printed simultaneously, split and run together in the folder. Different webs should ideally be combined in certain tension steps. In practice this goal is difficult to achieve as paper properties may change from reel to reel and the press conditions may change temporally.

Finite element modeling (FEM) was applied to study the interactions between the paper web and printing press. The tension changes along the press line, the nip load and the dimensional changes of the paper were modeled by FEM. The paper was modeled as in a plane stress state using membrane elements. Measurements were carried out in laboratory, pilot and production scale. Measurements included nip load distribution, tension profile and web dimension measurements. Material parameters for modeling were measured and obtained from earlier work.

Nip load and its distribution affect the web's dimensional changes like dry widening and presumably the rate of moisture absorption to the paper web. The effect of printing nips on the pressure and nip length were modeled and the results were verified with the measurements. Results showed that the structure of the printing blanket has a considerable effect on nip pressure and nip length. Nip conditions may affect the magnitude of the web widening (fan-out) through the delayed time of the paper in a nip and through the magnitude of the nip pressure.

The formation of the paper web's tension profile in a newspaper offset press was studied. The effect of damping water to the tension was modeled and the results obtained by FEM correlated well with the measurements.

It was found that FEM can be successfully applied in order to model and simulate the interactions between the printing press and the paper web. The effects of printing nips were modeled as well as the changes in the web tension profile in the press. The modeling results correlated well with the measurements. The benefits of modeling are obvious as the productivity of printing presses is highly dependent on the tension behavior of the web and the actions taken in the press. This means that better productivity can be achieved by increasing the knowledge of the interaction mechanisms.

In this paper we will also discuss the requirements of FEM in the printing process. Future work should include more precise material models as various parameters, such as the creep / relaxation phenomena of the paper web, were not included in this work.

Steady state analysis was performed for a moving paper web. The modeling 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.

INTRODUCTION

Better efficiency of printing presses is one of the key issues when optimizing the printing process. Typical problems related to productivity that the printer has to face are web breaks, poor web stability and quality errors such as register errors.

There is still a lack of information about critical paper and press properties affecting the press runnability. This is partly due to the inadequate research methods and equipment but also to the stochastic nature of most runnability problems. Runnability problems are caused partly by the paper and partly by the printing press. To explore these phenomena one must study the interaction between the paper web and the printing press.

The focus of this work was on the newspaper web offset printing process. The paper is visco-elastic and anisotropic and its stress-strain behavior is affected by many properties such as moisture content, pulp composition and drying history.

In offset web printing damping water is applied to the printing plates from where it is transferred to the paper web. Normally there are several webs (multi web) printed simultaneously and folded together in the folder to form a newspaper. The added damping water along with the draws and the elements such as printing nips have an effect on the paper web's rheology. For example, the paper's moisture content affects the elastic modulus and creep-phenomenon of the paper. In multi web production different webs should be combined in certain tension steps to the folder. In practice this goal is hard to achieve as paper properties may change from reel to reel and the press conditions may change temporally. The paper also tends to widen in the printing press because it deforms in printing nips. This can cause color register errors mainly in a lateral direction. A register error of 0.1 mm can be seen as a quality error with the naked eye.

Measurements were carried out in one newspaper printing press equipped with several instruments. FE-modeling was applied to study the interactions of the paper and printing press. In earlier works [1,2] FEM has been successfully used to model the formation of paper webs tension profile in paper making.

In this study the Finite Element Method (FEM) was used to simulate the printing process numerically. FEM is a widely used numerical method for analyzing structures and solids. The method provides an approximate solution to the discretized problem. Material models, boundary conditions and loads define a mathematical model of a physical problem in the FE-method. The model consists of elements and nodes that represents the discretization of the physical model. The shape functions of the elements, and sets of kinetics and kinematic relations together with constitutive relations defines the fundamental equations of elasticity to be solved. A numerical solution of the simulation results in a convergenced solution of the numerical calculation. The commercial FE-package ABAQUS/Standard was used in this study.

MEASURING METHODS

Measurements were carried out in a coldset-offset newspaper printing press during normal production. Some tests were carried out in pilot and in laboratory scale.
The IQ-Tension measurement system developed by Metso was used to measure the tension profile of the paper web. Measurements can be performed continuously across the entire web width making it possible to detect rapid tension changes. The device has been introduced in an earlier paper [1]. The measuring positions of the on-line measurements can be seen in Figure 1.

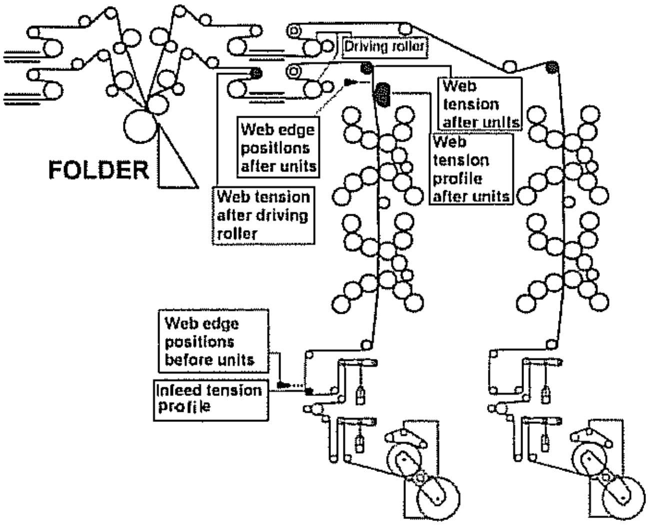


Figure 1 – The web tension measurements and web edge measurement positions in a 4-high printing tower.

The web width and lateral movements were measured by line scan cameras. Cameras were positioned on the web edges before and after the printing unit (Figures 1 and 2).

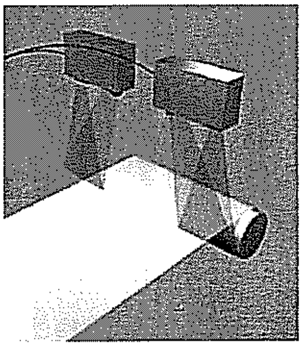
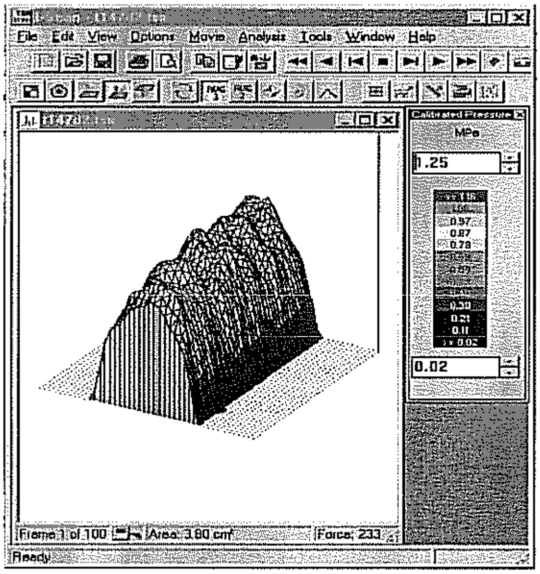


Figure 2 – The method for measuring the positions of web edges by line scan cameras (Visi 10).

A Tekscan pressure measuring device was used to measure nip loads and it's distribution in static state. Tekscan can be used to measure pressure distributions up to 3.5 MPa for an area of 29 x 29 mm, using 1936 point resolution. The thickness of the sensor is 0.1 mm. Figure 3 represents an example result of nip load measurement.



1.25

0.02

Frame 1 of 100

Area: 3.80 cm²

Force: 233

Ready

Figure 3 – Example result of printing nip load measurement by Teskscan.

Nip pressure distributions were measured in the printing press as well as in the laboratory. In the laboratory the nip loads were measured by using a pilot nip testing device (NTD) which is shown in Figure 4.

Figure 4 shows the NTD without printing blankets. The pressure between rollers can be controlled. Also the contact point between rollers can be controlled, which makes it possible to study asymmetric nip compressions.

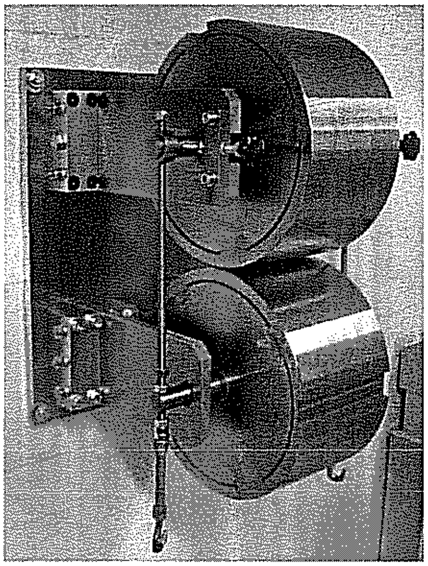


Figure 4 – Nip testing device (NTD).

Laboratory measurements

Tensile stiffness and orientation profiles of the paper webs were measured with Lorenzen & Wettre's TSO-tester.

Dynamic tensile tests and relaxation tests were carried out using an Impact tensile tester for paper samples. With Impact it is possible to test paper samples at a velocity of 1 m/s. Tests were performed in machine direction (MD) and cross direction (CD).

RESULTS

The web tension profile, web widening, web movements and the effect of printing nips were measured and modeled.

Web tension profile

In order to avoid runnability problems in a printing press it is important to know how the tension changes during the process. Magnitude and the rate of moisture expansion are essential values when examining stresses in offset printing presses. The paper's moisture content influences the web tension variation in lateral and longitudinal directions and also affects print quality.

It is very difficult to measure the web tension profile and web expansion between the printing units. Therefore the initial tension profile at infeed and tension after the printing units have been modeled and measured, see Figure 1.

The web tension profile after the printing units was modeled by FEM. Paper is highly anisotropic material but can be assumed ortotropic because of thin structure of the paper web. For this reason, an orthotropic material model for the paper was used and the web was constructed from membrane elements [3]. These elements can carry in-plane loads only. The stress-strain relationship for linear orthotropic material when hygroexpansive strain is added to the elastic strain can be written in form [4,5]:

$$\begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \tau_{12} \end{Bmatrix} = \begin{bmatrix} C_{11} & C_{12} & 0 \\ C_{21} & C_{22} & 0 \\ 0 & 0 & C_{44} \end{bmatrix} \begin{Bmatrix} \varepsilon_{11}^{TOT} - \varepsilon_{11}^{H} \\ \varepsilon_{22}^{TOT} - \varepsilon_{22}^{H} \\ \gamma_{12} \end{Bmatrix}, \tag{1}$$

where C_{ij} are orthotropic stiffness parameters. The total strain can be estimated from the equation

$$\varepsilon^{TOT} = \varepsilon^{E} + \varepsilon^{H}, \tag{2}$$

where the total stain is a sum of elastic strain and hygroexpansive strain. Both strains are dependent on moisture content and were defined as linear functions of moisture content [6]. Hygroexpansivity was defined as [6]:

$$\beta = \frac{\varepsilon^{H}}{\Delta mc}, \tag{3}$$

where Δmc is a moisture change .

Water application was assumed to be $0.5\,g/m^2$ [6] in each printing nip and it was imported to the model using a time aplitude curve. Hygroexpansivity, $\beta=0.0002$, was used in MD according to literature [6,7]. The elastic modulus profile was calculated from stress-strain tests carried out at the infeed unit in the printing press. The effect of the moisture on the elastic modulus was estimated from literature [8]. The measured tension profile at the infeed was used as initial tension in the model. The draw between printing units was assumed to be zero as printing units are run at the same speed by the main shaft.

Figure 5 presents measured tensions before the printing units (infeed) and after the printing units and the obtained FEM result. It can be seen that the modeling result correlates well with the measuring result.

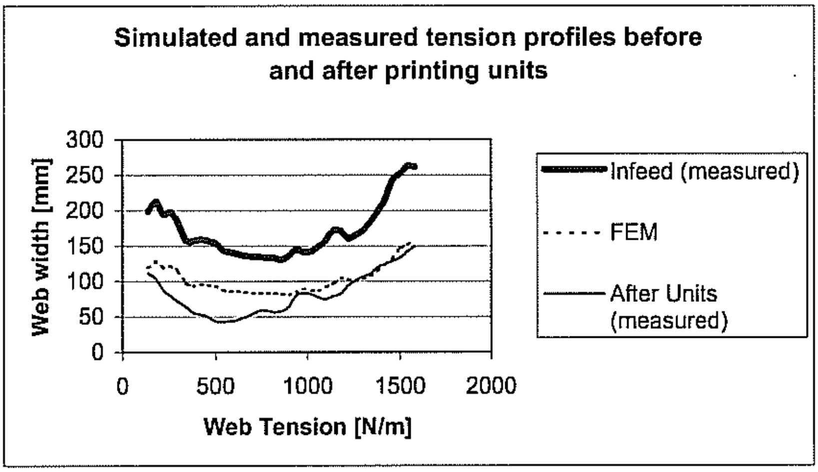


Figure 5 – Modeled and measured tension profiles in a printing press.

Web widening

Web widening was determined as the difference of the web width between the two measuring points located before and after the printing units (as shown in Figure 1). Web widening was measured for over 800 customer reels. Measured reels were 1600mm wide. The paper web normally widens as it travels through the printing units. Web widening between the units causes register errors which is called fan-out. This phenomenon is problematic because the amount of widening tends to change from reel to reel so that the compensation of the widening becomes difficult. In other words, the total amount of widening is not relevant to the printer but the variation of the widening from reel to reel is [9]. Widening is partly caused by mechanical deformation (dry-widening) of paper in the printing nips, ε_{cd}^{M}, and partly by the hydroexpansion of paper, ε_{cd}^{H}. Also, web tension affects the widening of the web through Poisson-effect and mechanosorption. Figure 6 presents the average dry and total widenings of 367 start-up reels [9]. Interestingly the dry widening of the different papers is of the same amount although the total widenings are not [9]. This suggests that the difference in water absorption causes the differences in web widening.

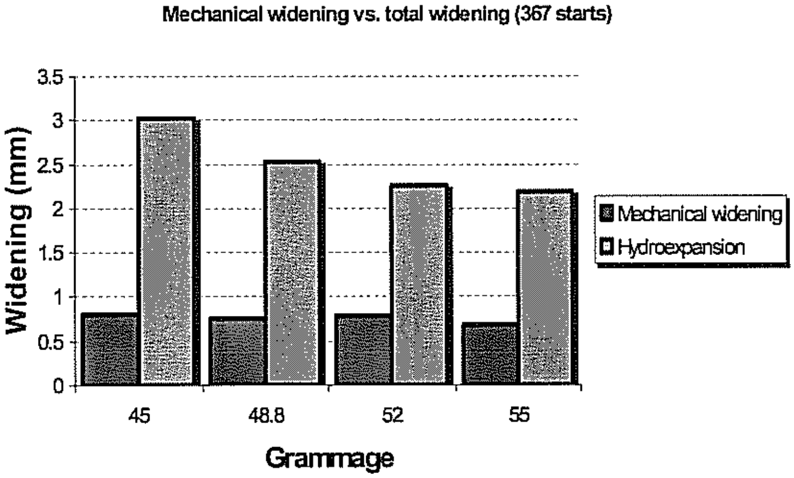


Figure 6 – Mechanical widening and total widening calculated from 367 press starts.

Web widening was studied using the FE-method and equation 1. Based on literature, the hygroexpansivity $\beta=0.0005$ was estimated [6,10] in CD and used in all elements. Web widening results across the web before the printing unit, between the printing nips and after the printing unit can be seen in Figure 7.

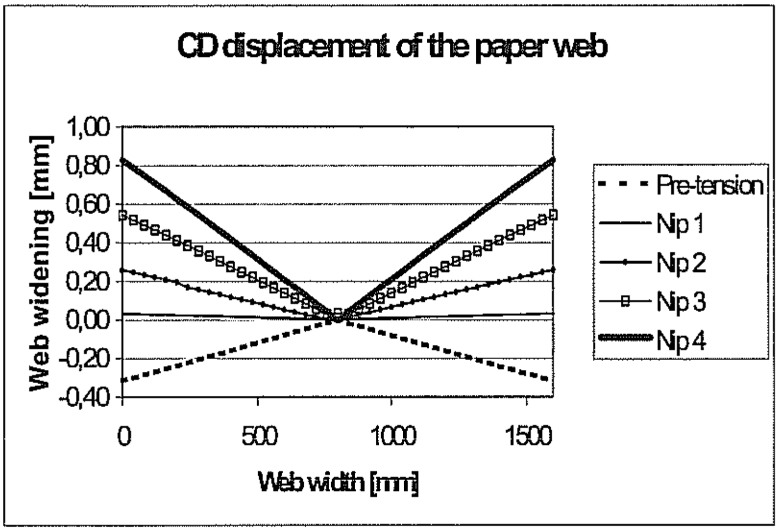


Figure 7 – The FE-result of web widening across the paper web due to water and ink intake before and after each sequential printing nip.

As can be seen from Figure 7 the total widening was 1.6 mm. This is lower than the measured values (2-3 mm), which is probably due to an absence of mechanical widening in the model. When the mechanical widening (Figure 6) is added to the modeling result the total widening is about 2.4 mm, which is inside the measured range of widening.

Web movements

Lateral movements were measured with same cameras as the web widening (Figures 1 and 2). Lateral movement of the web causes register errors and when severe - web breaks. It was found that the tensile stiffness orientation angle (TSO angle) had an effect on the web's lateral movements [9]. In Figure 8 the lateral movement is plotted against the TSO angle value. The web tended to move in the opposite direction to that pointed by the TSO angle.

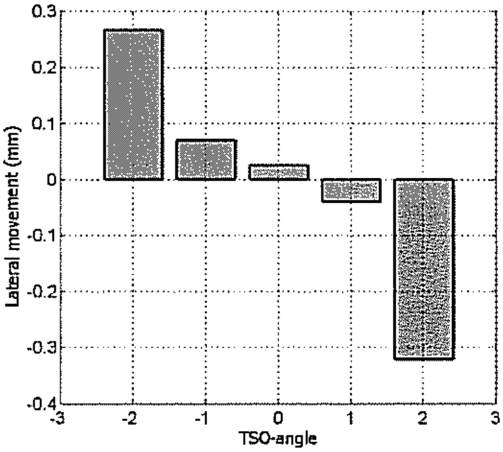


Figure 8 – The effect of the TSO angle on lateral movement of the paper web, 256 measured reels. The negative and positive values in lateral movement represent different lateral directions.

Web movement was modeled by FEM. Elastic moduli for the orthotropic material model were measured using a dynamic tensile tester. Shear modulus values were calculated using the following relations [11,12,13]:

$$G_{12} = 0.387\sqrt{E_1 E_2}\,, \tag{4}$$

$$G_{13} = \frac{E_1}{55}, \tag{5}$$

$$G_{23} = \frac{E_2}{35}, \tag{6}$$

where E_1 and E_2 are representing elastic moduli for machine direction and cross machine direction of paper respectively.

Plane-stress analysis for 11m long web (the distance between cameras) was performed using an orientation angle of 2°. Figure 9 shows the displacement field in the web using a typical stress level (220 N/m) used in the infeed unit.

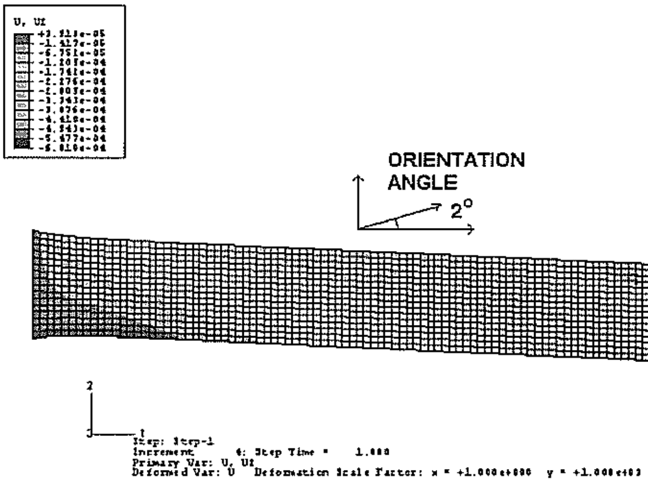


Figure 9 – Displacement field in orientated paper web under tension (220 N/m).

The modeling gave lateral movement of 0.5 mm using an orientation angle of 2° and 0.25 mm using an orientation angle of 1°. The direction of the modeled movement was the same as measured. These results correlate satisfactorily with the measured results of 0.3 mm and 0.06 mm respectively. The model produced greater movement probably due to the absence of tension drop in the model.

Printing nip

An offset printing nip consists of two printing blanket cylinders that are pressed against each other. A typical blanket is a laminate structure composed of three or more material layers. Figure 10 shows one configuration of one 3-layered blanket type.

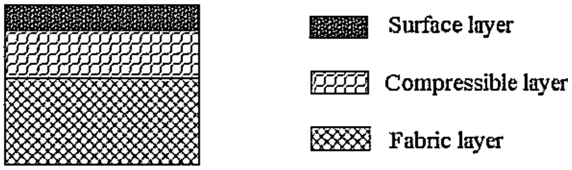


Figure 10 – 3-layered blanket configuration.

The purpose of the surface layer is to transfer the image to paper. The surface layer can be considered as an isotropic and incompressible rubber material. The compressible layer is composed of rubber material that contains pores. Compressibility of the blanket is an important property as it eliminates variation of blanket thickness and reduces bulge at the printing nip. The anisotropic fabric layer forms a base for the blanket providing in-plane strength.

An offset printing nip model was constructed using 2D plane-strain elements. A printing blanket was modeled using hyperelastic and orthotropic linear elastic (fabric layer) material models for a three-layered structure [14]. Material parameters were obtained from literature [14]. Figure 11 shows the stress contours obtained with the FE-model.

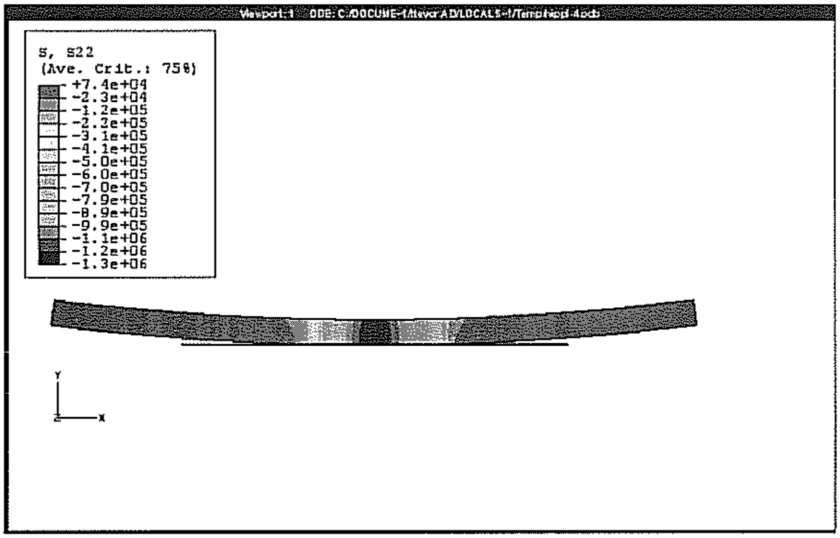


Figure 11 – Radial directional stresses in a symmetric printing nip.

Printing nip pressures were measured with the pilot scale testing device and in a printing press. Figure 12 shows the measured and modeled nip pressures. The nip pressure derived by Herz for two frictionless symmetric elastic spheres is [15]:

$$p(x) = p_0\sqrt{1-\frac{x^2}{a^2}}, \tag{7}$$

where p_0 is maximum pressure peak, x is position along the nip and a is half of the nip length.

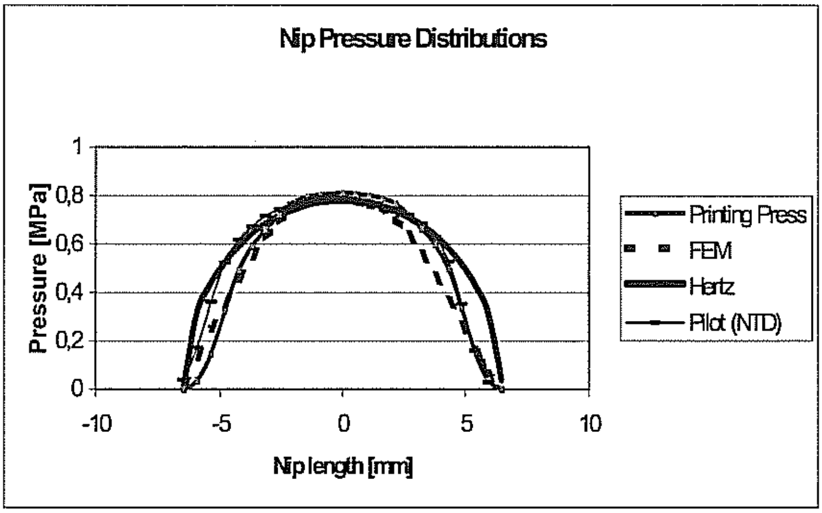


Figure 12 – Nip pressure distributions measured and modeled by different methods.

It can be seen that the Hertz solution differs from the measured nip load distributions. The measured and FE-modeled load profiles are beneath the Hertz solution. It can be seen from figure 12 that the FE-modeled nip pressure correlates well with the measured load in the printing press. The measured nip pressure by the pilot device (NTD) correlated also quite well with the pressure measured in the printing press.

REQUIREMENTS FOR THE FE-METHOD IN THE PRINTING PROCESS

FE-modeling has proven to be suitable for analyzing the interactions between the paper web and the printing press. Nevertheless many questions still need to be answered before simulations for the whole printing process can be made.

More knowledge is needed of the dynamics in the printing nips, as so far only static nips have been studied. It is highly presumable that the nip conditions differ in dynamic situation. The effect of web transport elements such as turner bars on web tension have not yet been studied. As the folding of different webs at the folder is a crucial stage in terms of runnability, the effect of folding elements such as turner bars on web tension should be studied in detail.

The effect of moisture on the paper web's rheology needs further study. For example, the moisture dependent creep properties for the paper under a short time span are not yet included on the current model. The strain of the paper web can be divided into separate components:

$$\varepsilon_{\text{tot}} = \varepsilon_{elastic} + \varepsilon_{\text{hygroexpansive}} + \varepsilon_{\text{creep}} \qquad (8)$$

It is also possible that the paper undergoes plastic strain in the nips. The effect of moisture and possible drying on the elastic modulus also needs further investigation. The web length and web width in different draws also has an effect on the web's elastic modulus which needs to be considered in further work.

Wrinkling in a paper web before the nips can cause creasing. In this study only in-plane deformations of paper were considered. It was assumed that the paper web had no significant shear behavior in the printing unit that would dramatically change the stress state due to possible wrinkling behavior. Even so, wrinkling of the web can happen for example when rollers are misaligned and/or the web tension profile is skew. Modeling of out-of-plane deformations requires proper material parameters for transverse shear moduli.

CONCLUSIONS

The higher productivity of printing presses is a goal for every printer. In practice the runnability problems such as web breaks, poor web stability and register errors makes it difficult to reach this goal. Both the printer and the paper maker need more knowledge about interactions between the paper web and the printing press.

In this work the interactions of the paper web and the printing press were modeled using the FE method. The model results were verified with measurements in a printing press. The forming of web tension, web width, web movements and nip loads were studied. It was found that the modeling results correlated well with the measurements. Web tension measurements and simulations based on FE models through the whole press line helped the printer to find new and better ways of web handling which led to increased productivity.

Based on this study the FE-method can be applied when studying the interactions between the paper web and the printing press. Nonetheless, many press and paper parameters need to be studied in more detail. For example the moisture effect on paper's rheological properties such as creep and elastic modulus needs to be examined in detail. The effect of nip dynamics and web transport elements such as turner bars on web tension should also be further studied.

The ultimate goal of further work is to find the key paper and press parameters affecting the printing press runnability. This would enable advanced control methods to be built into printing presses, which would lead to higher productivity.

REFERENCES

1. Vuorinen, S. and Parola, M., "Modeling the tension of the paper web," 6th International Web Handling Conference, 10-13 June 2001, Oklahoma State University, Oklahoma, USA.
2. Parola, M, Vuorinen, S., Linna, H., Kaljunen, T., and Beletski, N., "Modelling the web tension profile in a paper machine," The Science of Papermaking, Transactions of the 12th Fundamental Research Symposium. Oxford, GB, 17-21 Sept. 2001, Baker, C. (ed.)., Vol. 1. Pulp and Paper Fundamental Research Society, Lancashire, pp. 759–781.
3. Hibbitt, Karlsson & Sorensen, ABAQUS User's Manual, Version 6.1, Inc, Pawtucket (RI), 2000.
4. Walhström, *et.al.*, "Numerical modeling of the cross direction shrinkage profile in a dryer section, a first approach," TAPPI, International Paper Physics Conference, San Diego, 1999, USA.
5. Cook, R. D., Malkus, D. S., and Plesha, M. E., Concepts and Applications of Finite Element Analysis, 3rd Edition, Wiley, New York, 1989, ISBN 0-471-84788-7.
6. Niskanen, K., Paper Physics, Papermaking Science and Technology, ISBN 952-5216-16-0, Fapet 1998.

7. Niskanen, K., Mäkinen , J., Ketoja, J., Kananen, J., and Wathen, R., "Paper industry invests in better web runnability," Paperi ja Puu - Paper and Timber, Vol.85/No.5/2003.
8. Salmen, L., "Temperature and water induced softening behaviour of wood fibre," Dr. Thesis, KTH, Stockholm, 1982, Sweden.
9. Paukku, J., Parola, M., and Vuorinen, S., "Web Widening and Lateral Movements of Paper Web in a Printing Press," International Printing and Graphic Arts Conference, 4-6 October 2004, Vancouver, British Columbia, Canada. IPGAC (2004). IPGAC preprints, pp. 245 – 249.
10. Gomer M., Lindholm G., "Hygroexpansion of newsprint as a result of water absorption in a printing press," 43rd Annual TAGA Conference, Rochester, New York, May 5-8, 1991.TAGA, Rochester, pp. 268-282.
11. Mann, R. W., Baum G. A., and Habeger, C. C., "Determination of all nine orthotropic elastic constants for machine-made paper," Tappi Journal, Vol 63, No 2, 1980, pp. 163-166.
12. Baum, G.A.; Brennan, D.C.; and Habeger, C.C., "Orthotropic elastic constants of paper," Tappi Journal, Vol 64, No. 8, 1981, pp. 97-101.
13. Persson, K., "Material Model for Paper: Experimental and Theoretical Aspects," Master Thesis, Lund Institute of Technology, Sweden, 1991.
14. Torbjörn, L., "Materialkarakterisering av gummiduk för offsettryckning. Examensarbete i hållfasthetslärä utfört vid English title: Constitutive modeling of rubber blankets for offset printing," Master Thesis, Royal Institute of Technology, Stockholm, Sweden, 1998.
15. Wiberg, A., "Rolling contact of a paper web between layered cylinders with implications to offset printing," Licentiate Thesis, Department of Solid Mechanics. Royal Institute of Technology, Stockholm, 1999.