DEVELOPMENT OF WEB TENSION IN A WINDING NIP

by

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ABSTRACT

Today practically all winding devices apply a nip to the wound roll. In this winding method, radial pressure is applied by a winding drum to the wound roll at the point where the web enters the roll. This reduces the air entrainment into the roll and increases the tension of the web entering the roll. The wound roll internal stress profile is determined by this Wound-On-Tension (WOT). If the WOT along with the elastic moduli of the web are known, the internal stresses of the wound roll can be calculated. A winding simulation model predicting the internal stresses of a wound roll would provide a valuable tool for the optimal selection of the winding control parameters. When the incoming web enters the nip area its state of stress and strain changes significantly. An evaluation of these changes without any presumptions necessarily calls for a rigorous contact mechanical solution. The aim of the present paper is to calculate the surface tractions and the WOT due to the winding nip and, hence, provide means to predict the wound roll stresses as a function of the winding parameters.

The contact mechanical model is based on the plane strain elastic solutions of the wound roll, winding drum and the wrapping and intervening web, combined with the indentation, stick and slip equations. A homogeneous elastic orthotropic material law for the roll, drum and web is used. The incoming web may slip with respect to the roll and drum, whereas slippage of the layers in the roll is not allowed (solid roll model). The stick-slip pattern within the contact zone is iterated using a variant of the Panagiotopoulos Process. Numerical calculations revealed a typical mechanism for the development of the nip-induced tension when the winding drum is hard and the coefficient of friction between the drum and web is larger than that between the web and roll. Due to the appearance of a double-sided slip zone in the vicinity of the trailing edge of the nip, the web moves faster than the wound roll and winding drum and, hence, the web tension increases. It is also shown that for a winding drum covered with a thin rubber cover, most of the web tension increase occurs at the winding drum wrap. In addition, the dependence of the nip-induced tension on the winding force, layer-to-layer friction, wound

roll and winding drum radii, drum cover compliancy and the elastic constants of the web was studied numerically. The calculated results were in good qualitative agreement with the experimental ones.

NOMENCLATURE

a	nip half width
s	tangential coordinate of the web
$A_{rr}, A_{r\theta}, A_{\theta\theta}, G_{r\theta}$	elastic constants of the cylinder and web
M_1, M_2	driving torques of the roll and drum
R_1, R_2	roll and drum radii
P	vertical compressive load on the cylinders
$p^\pm, q^\pm$	normal and tangential surface tractions at the web-roll (+) and web-drum(-) contacts
T_0	initial web tension
F	winding force
$\varepsilon_r, \varepsilon_\theta, \gamma_{r\theta}$	radial, tangential and shear strains
$\sigma_r, \sigma_\theta, \tau_{r\theta}$	radial, tangential and shear stresses
WOT	Wound-On-Tension
WOC	Wound-On-Condition

INTRODUCTION

The paper sheet is wound and unwound several times during the paper manufacturing process. The winding or reeling should be done in a manner that minimizes the amount of reject. Hence, the winders and reelers should strain the paper as little as possible during the winding process and produce rolls or reels that are not susceptible to defects during transportation or any other further processing. Due to the tendency of increasing the reel diameters and roll widths, these demands are not always easy to fulfill. In addition, development in the paper making process and paper grades can be unfavorable to winding and wound roll quality.

Accordingly, the tendency among the winder and reeler suppliers during the last decade has been to reduce the stress on the paper during winding and to improve the cross-machine direction uniformity of the reel or rolls [1]. This has been achieved by reducing the nip-induced stresses on the wound rolls with compliant winding drum covers and belt-supports, and partial elimination of the non-uniform nip loads due to reel or roll deflection. However, without solid contact mechanical theory of the winding nip it is not possible to reliably evaluate the strain on the paper or wound roll in the vicinity of the nip. Also, proper evaluation of the *Wound-On-Tension* (WOT) requires a contact mechanical solution of the rolling contact problem of winding. If the WOT along with the elastic moduli of the paper are known, the internal stresses of the wound roll can be calculated accurately [2]. In this paper, the goal is to develop a simple but rigorous contact mechanical model of the winding nip, which is based on the first principles.

Despite the vast amount of literature that exists on the rolling contact of two parallel cylinders, rolling contact theory is not yet widely applied to the winding. Bentall &

Johnson [3] have studied the rolling contact of two cylinders with and without an elastic strip going through the nip. They restricted their treatment to isotropic materials, identical cylinders and essentially free rolling conditions. In addition, a half-space approximation for the cylinders was used and, hence, the theory is not suitable for a drum with a thin elastic cover. Tervonen [4] has extended the treatment to linear, viscoelastic cylinders and tractive rolling. His model includes covered cylinders and a sheet in the nip but is also restricted to isotropic materials. Soong & Li [5,6] have considered the rolling contact of two cylinders with linear, elastic and isotropic layers bonded to a hard core and driving an elastic thin sheet with extensional stiffness. The rolling contact articles referred above provide a close analysis of the present problem. The only missing feature is that the paper web is not wound on one of the cylinders.

J. D. Pfeiffer [7] reported in 1968 on extensive winding simulation tests done by rolling a drum on a flat horizontal bed with several paper layers clamped rigidly from the other end. This simulates the surface winding of an infinite radius wound roll. He observed that the sheets nearest the nip would displace in the direction of the moving nip while sheets further off the nip would travel in the opposite direction. He concluded that somewhere under the contact interface there must be an instant center of rotation. The tension increase was explained to be due to the velocity gradient between a point in the high-pressure area and another point in the direction of the outgoing nip having zero velocity. A corollary is that WOT is due to the interlayer slippage.

Jalkanen presented in 1968 [8] a theoretical model for calculating the Nip-Induced Tension. His derivation was based on the assumption that the speed of the incoming sheet is equal to the speed of the winding drum from the leading edge to the center of the contact and equal to the speed of the wound roll thereafter. He arrived at the following expression for the nip-induced tension (NIT):

$$\mathrm{NIT} = E_t t \frac{\delta}{R_1} , \tag{1}$$

where E_t is the tangential modulus of the sheet, t the thickness of the sheet, δ the indentation depth in the middle of the nip and R_1 the radius of the wound roll. Despite Pfeiffer's and Jalkanen's credit as forerunners in this field, their trains of thoughts were mainly kinematical and thus they could not give a comprehensive or general explanation for the NIT mechanism.

In 1993, J. K. Good and Z. Wu wrote an article entitled "The Mechanism of Nip-Induced Tension in Wound Rolls" [9] where they proposed a new explanation for the nip-induced tension. Their theory was based on similar phenomena as seen when rolling dough with a rolling pin: dough is extruding away from the nip under the rolling pin. The nip-induced tension was concluded to be caused by Poisson's effect, i.e., elongation of the sheet due to the compressive radial stress. Although Good & Wu seem to be the first to account for the stress state of the sheet, the shortcomings of their model include fairly strong initial assumptions on the internal nip mechanics and the lack of proper force equilibrium considerations.

Perhaps the first paper, where an attempt to apply the well-developed machinery of contact mechanics to the winding problem was made, is due to E. G. Welp and B. Guldenburg in 1997 [10]. The force equilibrium equations were correctly formed but their model did not properly describe the conditions of the sheet entering the wound roll after the nip, which is a distinctive feature of winding compared to calendering. Their model was also restricted to an isotropic material model of the paper web, which is actually known to be strongly anisotropic. Although their approach was a contact mechanical one, the solution methods used were not correct, since the stick and slip behavior

was assumed and the iterative schemes for calculating the contact tractions were not carried out in full. The main deficiency in all previously mentioned studies is the lack of a proper *Wound-On-Condition* (WOC) for the web wound onto the roll. The WOC would provide an additional equation to the contact formulation describing mathematically the fact that the paper sheet fed into the winding nip will later become part of the wound roll.

A rigorous contact mechanical model of the winding nip was first presented by Jorkama and von Hertzen 1999 [11]. A model consisting of the wound roll, winding drum and the intervening sheet was presented. The roll and drum were modeled as linear, orthotropic, homogeneous cylinders with a rigid core and the sheet was modeled as an orthotropic material as well. An iterative scheme (Panagiotopoulos process) was proposed for the solution method of the stick and slip zones. However, no numerical simulations were carried out and, hence, the present paper will continue the treatment by presenting some numerical results. Also, the theory is extended to include a contact mechanical treatment of the web wrapping the winding drum and the wound roll behind the nip. Although the approach has been to model the rolling contact problem of winding based on first principles, some more or less *ad hoc* assumptions have been made:

a) The cylinder geometry is used for the wound roll, although it resembles rather the Archimedean spiral wrapped around the core. This brings about a problem how the web is to be attached to the cylinder behind the nip. In this paper, this problem is resolved by setting an additional requirement (the WOC) that the tangential velocities of the web and wound roll surface are equal at a given location behind the nip. It should also be acknowledged that the solid elastic cylinder model, used for the wound roll, cannot account for commonly observed internal slippage of the paper layers.

b) It is well known that the relation between pressure and strain is nonlinear in the compression tests of paper stacks and thus the elastic moduli become state dependent [12]. Paper stacks display hysteresis when loaded and unloaded repeatedly [13]. Accounting for the nonlinear material behavior and hysteresis is beyond the scope of this work. As the goal here is to obtain a phenomenological description of the winding nip behavior, suitable "average" constant elastic moduli will be used.

c) In high speed winding the entrained air affects to the stick and slip behavior of the web in the nip and winding drum and wound roll wraps. This phenomenon is not accounted for in the present paper.

THEORY

The winding configuration to be studied is shown in Figure 1a. The wound roll is depicted as the upper circle and the winding drum as the lower circle. The paper web wraps the winding drum (wrap angle θ_d), enters the nip from the left and finally the wound roll behind the nip. The wound roll and winding drum are pressed against each other with a uniform line load P [N/m] and driven by torques M_1 and M_2 [Nm/m], respectively. The tension of the web, prior to the winding drum wrap, is T_0 [N/m]. The problem statement is to find the surface stresses of the web, wound roll and winding drum and the WOT, i.e., the tension of the topmost paper layer of the wound roll at a location on the wound roll surface which is "far away" from the nip, so that the nip induced strains on the roll surface are negligible and the web does not slip (anymore).

Following the contact mechanical approach of refs [11,14], the elastic solutions of the contacting bodies – web, wound roll and winding drum – are utilized when forming the matching equations of contact mechanics: indentation and either slip or stick equa-

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tions. The unknowns of the problem are the surface tractions, i.e., the contact pressures and shear stresses, and the WOT.

The wound roll and winding drum are modeled as linear, orthotropic, homogeneous cylinders with a rigid core. Hence, for example, this model can handle a winding drum covered with some elastic material, such as rubber. For the wound roll this is an approximative model since firstly, the adjacent paper layers might slip inside the roll and secondly, because the wound roll geometry is rather an archimedean spiral than a cylinder. The cylinder model will induce the problem how to describe the topmost paper layer becoming later part of the roll. Also, the linear, elastic model is not capable to represent some features of the actual roll behavior, such as nonlinear radial modulus and hysteresis [12,13].

The paper web is modeled as a linear, orthotropic, homogeneous sheet in polar coordinates. The equilibrium and constitutive equations are satisfied to first order with respect to the thickness of the web.

The problem of describing the winding nature of the rolling contact problem is solved by forcing the web and the wound roll surface to move at equal tangential velocities at a certain location behind the nip (Fig. 1b). The location of this point is left as a parameter of the model. However, the validity of this approximation can be checked from the solution. If the web and wound roll tangential speeds become equal already before that point then this WOC appears to reflect the true nature of the web and wound roll interaction. At this WOC location the web tension is the WOT.

The matching equation for the radial compression within the nip is obtained by requiring that the resulting deformations of the web, winding drum and wound roll comply with the original undeformed geometry. Solving the nip pressures from this *indentation equation* constitutes the *normal problem* of the system. The matching equations in the tangential direction of the web-winding drum and web-wound roll contact are either the *stick equation* (tangential speeds are equal) or *slip equation*. For sake of simplicity the choice for the slip equation is the *Amonton's* friction law. Because it is not known beforehand whether the contacting bodies at a point under inspection are slipping or sticking, the solution process starts by assuming that every point is sticking. From the calculated solution, the points where the tangential traction exceeds the friction limit are moved to the set where the slip equation is applied. This is continued until none of the points are changed from stick to slip. Finally, the directions of the tangential tractions are checked with respect to the slipping velocities. This procedure constitutes the *tangential problem* of the system. The normal and tangential problems are solved separately. The contact pressures obtained from the normal problem are taken as inputs to the tangential problem and the tangential tractions obtained from the tangential problem as inputs to the normal problem. This method of solving rolling contact problems is known as the *Panagiotopoulos Process* [15].

The orthotropic elastic constants A_{rr}, $A_{r\theta}$, $A_{\theta\theta}$ and $G_{r\theta}$ of the wound roll and paper web are defined by the *plane strain* constitutive equation

$$\sigma_r = A_{rr}\varepsilon_r + A_{r\theta}\varepsilon_\theta \ ,$$
$$\sigma_\theta = A_{r\theta}\varepsilon_r + A_{\theta\theta}\varepsilon_\theta \ , \tag{2}$$
$$\tau_{r\theta} = G_{r\theta}\gamma_{r\theta} \ ,$$

where σ_r, σ_θ and $\tau_{r\theta}$ are the radial, tangential and shear stresses, respectively, and ε_r, ε_θ and $\gamma_{r\theta}$ the radial, tangential and shear strains, respectively. The winding drum cover is assumed to be isotropic with modulus of elasticity E and Poisson's ratio v. The layer-to-layer friction coefficient of paper is μ^+ and paper to winding drum friction coefficient

μ^-. In addition to the initial web tension T_0 and nip load P, a third winding parameter, the *winding force F* is defined by

$$F = \frac{M_1}{R_1} \qquad (3)$$

RESULTS

Perhaps the most interesting issue is how the web tension of the topmost paper layer develops from the initial value T_0 to WOT. Numerical simulations revealed that when the winding drum is hard (e.g. steel) and the friction coefficient between paper layers is smaller than between paper and the winding drum, certain general stick-slip pattern does occur. The basic features of this solution for a hard winding drum are shown in Fig. 2. The winding force was chosen to match surface winding ($F = 0$) although the basic behavior is quite general and thus applicable to all values of F. The parameter values used in the calculations are shown in Table 1. When μ^- was larger than μ^+, the web did not slip in the winding drum wrap according to the numerical simulations. Hence, when the web enters the nip the slip speed between web and drum is zero (Fig. 2b dash-dotted line). The web-roll contact is slipping at the nip entry so that the web moves slower than the roll (Fig. 2b dashed line). This is due to the larger tangential strain of the wound roll induced by the WOT mechanism previously. Hence, the surface shear stress q^+ (Fig.2a, solid line) is negative at the nip entry. As the tangential strain of the wound roll further decreases towards the nip center the web-wound roll slip velocity decreases and finally becomes zero (at about –0.8). Since the web-drum contact is still sticking, the wound roll tangential strain is constant. However, due to the nip compression, there is still tendency for the wound roll tangential strain to decrease. In order to accommodate these two effects the surface shear stress q^+ starts to increase (from –0.8 to –0.5). When q^+ reaches the friction limit it can't anymore keep the wound roll tangential strain constant and, hence, the web-wound roll contact starts slipping at – 0.5. Within the web-winding drum stick zone it must be $q^+ = -q^-$ since the tangential strain of the web cannot increase. At the end of the nip zone the web-winding drum contact starts to slip so that the web moves faster than the winding drum. From this point at 0.75 till the end of the nip zone both sides of the web are slipping with web moving faster than the wound roll and winding drum. It is at this region where most of the WOT develops. The slippage between web and wound roll still continues for a short distance behind the nip (~1-3 times nip width). In all numerical calculations the web remained in stick from now on till the WOC point. The conclusion is that the WOC is accurate enough to reflect the winding nature of the problem. The further increase of the web tension behind the nip is generally small – only a few per cents from the total tension.

It was demonstrated above that with a hard winding drum most of the WOT developed at the nip zone, none at the winding drum wrap and just a small portion at the wound roll wrap. With a compliant winding drum the behavior with respect to the winding drum wrap is different. Numerical calculations have showed that the web slips for considerable portions at the winding drum wrap before the web enters the nip. Depending on the wrap angle, most of the WOT can develop at the winding drum wrap. Fig. 3 shows the development of the web tension for a steel core winding drum with 8mm thick rubber cover ($E = 5.37$ MPa, $v = 0.43$). The winding wrap angle is 56 degrees. At the winding drum wrap region, the web is slip starts 35° before the nip and, hence, the tension increases in this slip region according to the capstan equation to 512

N/m [14]. At the leading edge of the nip the web sticks to the winding drum cover. As the tangential strain of the compliant cover decreases toward the center of the nip, the web tension drops to 450 N/m. From the center of the nip to the trailing edge the tangential strain of the cover increases and, hence, the web tension increases to 715 N/m. A permanent WOT 600 N/m is developed as the web enters the wound roll wrap. Comparison of the developed WOT between the hard and rubber covered winding drums show that they are about the same order. A benefit of the rubber covered winding drum is due to the reduced surface stresses (extended nip width). Hence, the internal, nip induced, wound roll stresses are smaller and the J-lines are shorter.

At the previous stage of the development of the model [14], WOC was applied at the trailing edge of the nip. Hence, the mathematical formulation simplified greatly, as the treatment could be confined in the nip region. Simulations with the current model revealed that the earlier model oveshooted the WOT estimate. However, most of the qualitative predicting with these two versions of the winding nip model agree. Sublinear behavior of WOT vs. P relation, WOT increasing with winding force F, increase in the nip induced tension when $A_{r\theta}$, $A_{\theta\theta}$ and $G_{r\theta}$ are increased and increase in the nip induced tension when A_{rr} is decreased are some of the phenomena which the model predicts. All these comply with experimental observations.

CONCLUSIONS

A rolling contact mechanical theory of winding, based on the first principles, is presented. With the model, the basic mechanism of the development of the WOT could be explained. Also, it was shown that with a compliant winding drum, most of the WOT is produced at the winding drum wrap. Further, the model can explain qualitatively a major part of experimentally observed phenomena of the winding nip behavior.

The further development of the model consist of taking into account the nonlinear material behavior of the wound media, further development of the web model and study of the possibly of replacing Amonton's friction law with a some more advanced one. Also, an interesting issue to study is developing an approximative and simpler way to calculate WOT. In that work the results of the model, presented in this paper, could be utilized.

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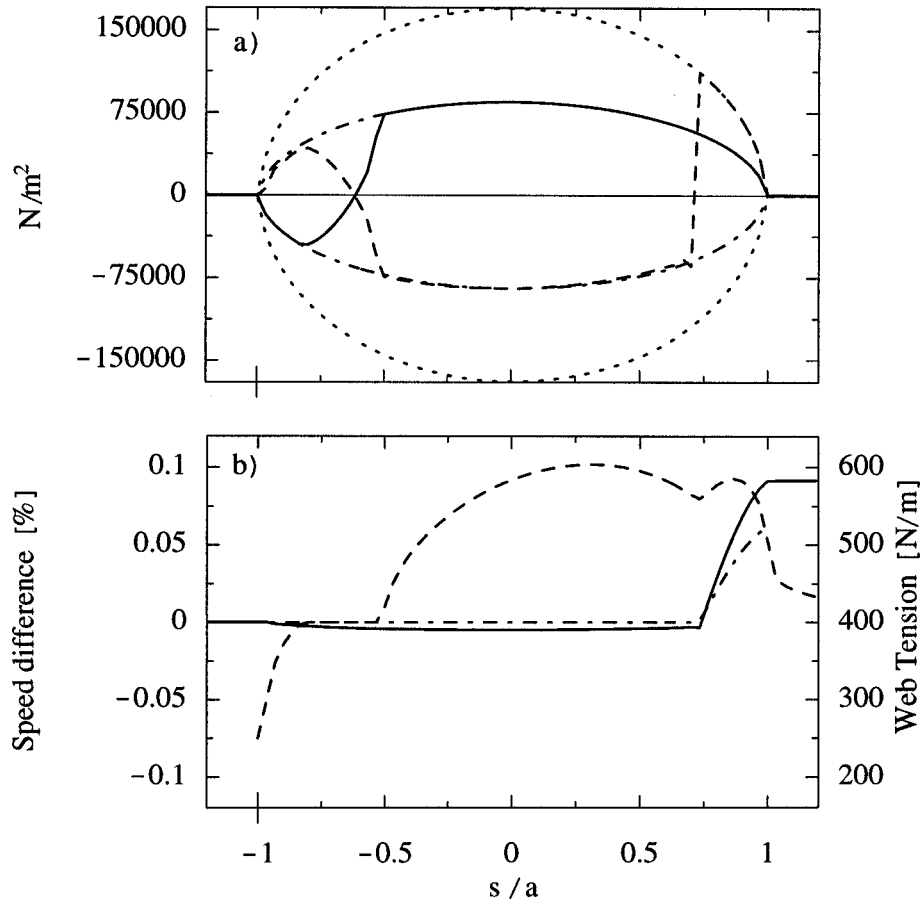
Figure 1. Winding configuration (a) and the model (b)

Figure 2. Hard winding drum: (a) Tangential tractions of the wound roll (solid line) and winding drum (dashed line) contacts and the friction limits $\mu^- p$ (dotted line) and $\mu^+ p$ (dash-dotted line) and (b) the relative tangential speed differences in the web-roll contact (dashed line) and web-drum contact (dash-dotted line) and the web tension (solid line).
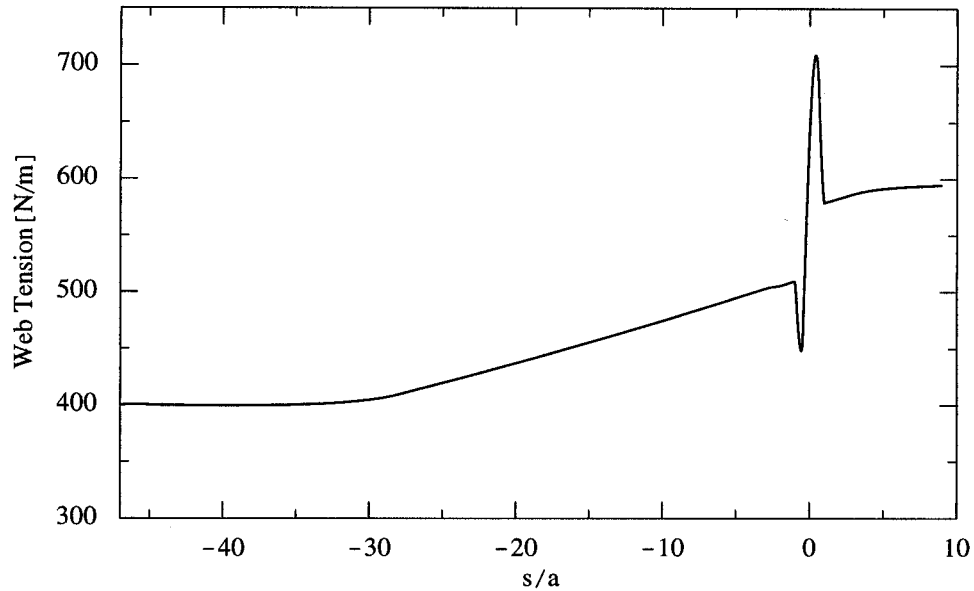
Figure 3. Compliant winding drum: Development of the web tension, (-47,-1) winding drum wrap, (-1,1) nip and (1,10) wound roll wrap.

Table 1.

Parameter values used in the calculations

Parameter	Notation	Value
Paper to roll friction coefficient	μ^+	0.2
Paper to drum friction coefficient	μ^-	0.4
Wound roll radius	R_1	0.3 m
Winding drum radius	R_2	0.5 m
Radial elastic constant	A_{rr}	20 MPa
Tangential elastic constant	$A_{\theta\theta}$	3 GPa
Cross elastic constant	$A_{r\theta}$	5 MPa
Shear modulus	$G_{r\theta}$	10 MPa
Radial nip load	P	4 kN/m
Winding force	F	0 N/m

Development of Web Tension in a Winding Nip   **M. Jorkama**[1] **and R. von Hertzen**[2] – Metso Paper, Inc.[1] and Helsinki University of Technology[2], Finland

Name & Affiliation	Question
Curt Bronkhorst – Weyerhaeuser	Can you give me a sense of how the nip induced tension mechanics will be influenced by the strain rate sensitivity of your substrate material? Can you give me a sense if rate sensitivity is important?
Name & Affiliation	Answer
M. Jorkama – Metso Paper, Inc.	We have used linear equations. We haven't accounted for any strain rate dependency. Yes, it will be important in that sense that it will affect the shape of the nip pressure profile and it may affect the nip contact width. This could result in having different traction limits for the shear stresses and that will effect on the wound-on-tension.
Name & Affiliation	**Question**
Curt Bronkhorst – Weyerhaeuser	Do you think it's important to account for strain rate sensitivity in your models, or is it qualitatively similar?
Name & Affiliation	**Answer**
M. Jorkama – Metso Paper, Inc.	Qualitatively, this model reflects reality quite well but we need to account for the nonlinear radial modulus to get good quantitative agreement.
Name & Affiliation	**Additional Comment**
K. Good – OSU	With respect to that last question, consider the time of transit of a section of web from the time it goes into the nip contact zone to the point of exiting contact of Marko's wound on condition. In most winders that will be a fraction of a second and as such the material behavior will be largely elastic. The material would have to have a large strain rate sensitivity for non-elastic effects to have much impact during such short duration times. The non-elastic effects would be much more important during roll storage.