MODELING NIP INDUCED TENSION IN WOUND ROLLS

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ABSTRACT

Web materials are wound into coils by a variety of winders. Some winders center wind only. In this type of winding torque is provided to a core and web winds up on the core. Other types of winders have a roller, often called a nip roller, impinged into the outer surface of the winding roller. In this type of winding equipment the torque required to wind the rolls of web may either be provided to the core or to the nip roller and in some cases torque is provided to both. When the winding torque is provided only or mainly to the nip roller the winder is called a surface winder. When the winding torque is provided only or mainly to the core the winder is called a center winder with an undriven nip roller. When substantial components of the winding torque are provided to both the core and the nip roller the winder is called a combination winder.

It has been documented that the nip roller induces an increment in tension in the outer layer of a winding roll called the nip-induced-tension (NIT). The NIT combines with a component of the web tension to form the wound-in-tension (WIT) in the outer layer of a winding roll. The magnitude of the component of the web tension that becomes part of the WIT is dependent on whether the winder is center, surface, or combination driven. An objective of this paper is to show what wound roll and winder parameters affect the WIT based upon winding experiments. A second objective is to show the derivation of an introductory model whose output yields results that are consistent with winding tests.

NOMENCLATURE

a	half width of contact
E_{md}	web machine direction Young's modulus
E^*, E_1, E_2	Young's modulus

Erf(y)	error function, $\frac{2}{\pi}\int_{-a}^{s} e^{-x^2}\,dx$
f(y)	forcing function
h	thickness of equivalent foundation
K	stiffness of equivalent foundation
K_1, K_2	factors used to relate pressure and strain
NIT	nip-induced-tension, load per unit width
p, p(y)	pressure
P	nip load, load per unit width
R, R_1, R_2	radius
t	web thickness
$T_{cap}(y)$	traction capacity
T_w	web tension, load per unit width
w	penetration of equivalent foundation
WIT	wound-in-tension, load per unit width
z	profiles of rolls in contact
ε	strain
δ	maximum foundation penetration (w(0))
μ_k	kinetic friction between web layers
$\nu_{r\theta}$	Poisson's ratio

INTRODUCTION

Pfeiffer was the first to document that a nip roller increases the tension in the outer layer of a winding roll[1]. He performed tests in which he rolled a nip roller over stacks of paper webs and showed that the uppermost layers would advance in the direction of travel of the nip roll. The motion of layers beneath those layers was retarded and based upon these measurements and photo-micrographs of the motion in the contact zone Pfeiffer determined that an instant center of rotation occurred a few layers below the nip. In later work Pfeiffer developed the WIT-WOT winder (wound-in-tension and wound-off-tension). The method involved extracting the outer web layer away from the surface of the winding roll after the nip and measuring the web tension such that the influence of the nip on the tension in the outer layer could be monitored. Good and Hartwig[2] later determined that WIT measurement method is an interfering method. Extracting the outer layer of the winding roll allowed slippage that was found not to occur in winding tests where the WIT was inferred from pressure measurements in which the outer layer was not extracted. They also found that in some instances the measured WIT data could be corrected to yield the WIT inferred from pressure measurements.

Also flat bed nip mechanics studies combined with finite element contact analyses by Good et al. [3,4] were indicative that the source of the NIT was an elongation of the incoming web in the machine direction due to high radial pressure in the nip contact zone combined with the Poisson effect. Recent work by Jorkama[5] has postulated that the Poisson effect is not what is not responsible for the slippage that results in NIT. Jorkama developed a contact model of the nip and wound roll and computes the slippage and the NIT of the outer layer. His research indicated the NIT is nearly independent of Poisson's ratio but is sensitive to the shear modulus of rigidity. This would suggest that shear strains and stresses are responsible for inducing the slippage between the 1st and 2nd layers that results in NIT.

Whatever the mechanism may be which induces NIT it is known that frictional forces between the layers are responsible for limiting the NIT. Winding tests have verified that the NIT could never exceed the product of the kinetic coefficient of friction between layers and the nip loading. Winding tests were performed in which pressure sensors were wound into rolls during winding[4,6]. The WIT was then iterated within a winding model [7] until the pressures predicted by the model agreed with those measured by the sensors. The following algorithms were derived by such tests:

$$WIT_{\text{center winding}} = T_W + \mu_k P \qquad \{1\}$$

$$WIT_{\text{surface winding}} = \mu_k P \qquad \{2\}$$

where μ_k is the kinetic coefficient of friction between web layers, P is the nip load per unit width, and T_W is the web line tension load per unit width. These algorithms were verified for news, bond, and polypropylene webs using pull tabs when pressures were low and force sensitive resistors when the pressures were high to profile the pressure in the wound rolls as a function of radius. Later experiments demonstrated that for cases of high nip loads or large coefficients of friction that expressions {1} and {2} would over estimate the WIT. In fact the WIT could become nearly independent of nip load as the nip load is increased. It also was apparent in surface winding that a portion of the web tension added to the WIT. This was verified with on-line measurements of WIT and by winding experiments performed by Pfeiffer [1] and Good and Hartwig[2].

EMPIRICAL KNOWLEDGE OF WIT

In Figure 1 parsed WIT data extracted from the center winding of newsprint is shown. The nip roller was 15.24 cm in diameter. Of particular interest is the slope of the data. Any trend is difficult to determine as some tests indicate the WIT is independent of wound roll radius while others show small positive or negative slopes. Within the confines of these tests one must surmise that the slopes that do exist are within the realm of experimental error. Thus it may be concluded that for a web such as newsprint that the WIT is not highly dependent on wound roll radius. Therefore it appears that averaging the data from each winding test should be a good indication of the WIT for that test. Averaged WIT data are shown in Figure 2 as a function of nip load. The data appears to fit the trend of expression {1} and the slope of the data with respect to nip load becomes less with increasing nip load. If the web tension is subtracted from the WIT, per expression {1}, all that should remain is the NIT. This is shown as well in Figure 2 and it appears that the three NIT curves might well be represented by one master curve. Thus it appears the NIT is independent of web tension. Therefore if an expression for NIT can be developed the WIT associated with center winding can be determining by adding the NIT and the web tension.

In Figure 3 parsed WIT data extracted from the surface winding of newsprint is shown. Again the nip roller was 15.24 cm in diameter. There appears to be a trend in the slope of the WIT data with respect to wound roll radius ranging from zero to slightly positive. The slopes that do exist are so small that averaging still presents a reasonable data comparison and the averaged data is shown in Figure 4. In comparison to the center winding data presented in Figure 3 it should be noted that the WIT is independent of web tension at low nip load but becomes dependent on web tension at higher nip loads. Thus expression {2} appears to be a reasonable estimation of the WIT at low nip load.

In Figure 5 averaged WIT data for center winding newsprint is shown for 3 nip roller diameters. Note that at low nip loads the WIT appears to be a function of nip load alone while at higher nip loads the smallest diameter nip roller yields the highest nip loads.

Also note at the highest nip loads that the WIT becomes nearly constant and independent of nip load.

In Figure 6 averaged WIT is shown for surface winding newsprint. These tests were run starting at high nip load and then reducing the nip load in increments throughout the wind. One test was conducted with a bare surfaced aluminum roller that has a kinetic coefficient of friction of 0.22 when in contact with the newsprint (established by band brake friction tests). A second test was conducted with the same nip roller but a coating made by Dow Chemical (Dow 236) was added. The coefficient of friction between this coating and newsprint was 2.36. The coating is not an adhesive. Note that even though the friction coefficient is 10 times larger that the WIT data is nearly identical. Thus it appears that slippage between the nip roller and the web is not necessary for the generation of the WIT. It should be noted that nip roller with a smaller friction coefficient less than 0.2 may have resulted in less WIT that will be discussed later.

Based upon the empirical data presented the following conclusions regarding WIT and NIT can be formed:

- The WIT does not exhibit much dependency if any on wound roll radius.
- The WIT is dependent on nip load. It appears to be proportional to nip load per expressions {1} and {2} at low nip loads but the slope decays with increasing nip load.
- The WIT is directly dependent on web tension at all nip loads when center winding.
- The WIT is independent of web tension at low nip loads when surface winding but develops a proportionate dependency at high nip loads.
- The NIT appears to be independent of web tension.

DISCUSSION

Clearly this is a contact mechanics problem. The question is what detail is required in modeling to capture the features of the WIT. Contact problems usually involve slippage that may be limited or constrained by frictional forces. To calculate frictional forces the pressure in the contact zone must be known.

Determining the Zone of Contact and the Contact Pressure Profile

Johnson[8] describes an elastic foundation model for rolling contact problems. The difficulties of elastic contact stress theory arise because the displacement at any point in the contact surface depends upon the distribution of pressure throughout the contact zone. Part of this difficulty can be avoided if the solids in contact can be modeled by a Winkler elastic foundation rather than an elastic half-space. The model is illustrated in Figure 1. The elastic foundation of depth *h*, rests on a rigid base and is compressed by a rigid indenter. The profile of the indentor, z(y), is taken as the sum of the profiles of the two bodies being modeled:

$$z(y) = z_1(y) + z_2(y) \qquad \{3\}$$

There is no interaction allowed between the springs in the Winkler foundation and thus shear between adjacent elements of the foundation is ignored. If the penetration at the origin is denoted by δ, then the normal elastic displacements of the foundation are given by:

$$w(y)=\begin{cases}\delta-z(y), & \delta>z\\ 0 & ,\ \delta\le z\end{cases} \qquad \{4\}$$

The contact pressure at any point depends only on the displacement at that point, thus:

$$p(y)=\frac{K}{h}w(y) \qquad \{5\}$$

where K is the elastic modulus of the foundation. For the two-dimensional contact of long cylinders:

$$w(y)=\delta-\frac{y^2}{2R}=\frac{\left(a^2-y^2\right)}{2R} \qquad \{6\}$$

Substituting expression {6} into {5} yields:

$$p(y)=K\frac{\left(a^2-y^2\right)}{2Rh} \qquad \{7\}$$

When {7} is integrated over the contact width the nip load per unit width is obtained:

$$P=\int_{-a}^{a}p(y)dy=\frac{2}{3}\left(\frac{Ka}{h}\right)\frac{a^2}{R} \qquad \{8\}$$

The classical expression for cylinders in contact from Hertz is:

$$P=\frac{\pi}{4}E^*\frac{a^2}{R} \qquad \{9\}$$

where R and E* represent combined radii and moduli per:

$$E^*=\frac{1}{\frac{1}{E_1}+\frac{1}{E_2}} \text{ and } R=\frac{1}{\frac{1}{R_1}+\frac{1}{R_2}} \qquad \{10\}$$

Comparing expressions {8} and {9} it appears that if an exact answer per Hertz is to be obtained, then the following equivalence must be valid:

$$\frac{K}{h}=\frac{3}{8}\pi\frac{E^*}{a}\approx 1.178\frac{E^*}{a} \qquad \{11\}$$

Application to Wound Rolls

Compression tests of stacks of web have shown the relation between pressure and strain is nonlinear and thus the radial modulus becomes state dependent on either stress or strain. Pfeiffer [9] developed a relationship between pressure and strain that appears to model this behavior reasonably well for a broad range of materials:

$$p=K_1\left[e^{K_2\varepsilon}-1\right] \qquad \{12\}$$

As well it has been shown in these compression tests that the download curve is not necessarily identical to the upload curve and that the difference is time dependent that implies viscoelasticity is present. During winding the rolling nip is moving at speeds which makes viscoelasticity insignificant in the calculation of NIT but viscoelasticity may have a profound impact on the stresses in the wound roll through time. Nevertheless the nonlinear elastic behavior given by {12} must be accounted for. Substituting expression {11} into {7} yields:

$$p(y)=\frac{3\pi}{8}\frac{E^*}{a}\frac{\left(a^2-y^2\right)}{2R} \qquad \{13\}$$

This implies that the equivalent z direction strain is:

$$\varepsilon_z(y)=\frac{3\pi}{8}\frac{\left(a^2-y^2\right)}{2Ra}=\frac{3\pi}{8}\frac{w(y)}{a} \qquad \{14\}$$

Please note that the factor of 3π/8 was determined in an attempt to make the elastic foundation theory yield the same result as Hertz's elastic theory. Substituting expression {14} into {12} yields:

$$p(y) = K_1\left[e^{3K_2\pi\frac{(a^2-y^2)}{16aR}} - 1\right] \qquad \{15\}$$

and the maximum pressure occurs at the center of the contact width:

$$p_{max} = p(0) = K_1\left[e^{\frac{3K_2\pi a}{16R}} - 1\right] \qquad \{16\}$$

The pressure distribution {15} yields the nip load when integrated over the contact width:

$$P = \int_{-a}^{a} p(y)dy = K_1\left[4\sqrt{\frac{Ra}{3K_2}}\,e^{\left(\frac{3\pi K_2 a}{16R}\right)}\,\mathrm{Erf}\left[\sqrt{\frac{3\pi K_2 a}{16R}}\right] - 2a\right] \qquad \{17\}$$

Expression {17} can be used to establish the relation between contact width and nip load for a nip in contact with a wound roll. To determine the efficacy of expression {17} an experiment was conducted. A material testing system was used to compress three aluminum rollers of diameters 63.5, 152.4, and 254 mm in diameter into a stack of news print ($R_2 = \infty$). For this newsprint K_1 was 24.25 KPa (3.52 psi) and K_2 was 24.49. In the experiment a force sensitive resistor array[1] was used to measure the width of contact at a controlled nip load. Results from expression {17} are shown to be satisfactory when compared to the experimental data in Figure 2.

The Traction Capacity

With expressions that define how the pressure varies throughout the contact zone the level of the friction forces between the 1st and 2nd layers can be estimated. The traction capacity is defined as the cumulative frictional force between the leading edge of the contact zone (i.e. y=-a) and some point y within the contact zone. It is calculated on a unit width basis per:

$$T_{cap} = \int_{-a}^{y} \mu_k p(y)dy = \int_{-a}^{y} \mu_k K_1\left[e^{3K_2\pi\frac{(a^2-y^2)}{16aR}} - 1\right]dy \qquad \{18\}$$

where μ_k is the coefficient of friction between web layers and p(y) from {13} has been substituted. Integration of {17} yields:

$$T_{cap}(y) = \mu_k\frac{K_1}{3}\left[2\sqrt{\frac{3Ra}{K_2}}\,e^{\left(\frac{3\pi K_2 a}{16R}\right)}\left[\mathrm{Erf}\left(\sqrt{\frac{3\pi K_2 a}{16R}}\right) + \mathrm{Erf}\left(y\sqrt{\frac{3\pi K_2}{16Ra}}\right)\right] - 3(a+y)\right] \qquad \{19\}$$

The maximum value of the traction capacity occurs when integrated over the entire contact width:

$$T_{cap,max} = \int_{-a}^{a} \mu_k p(y)dy = \mu_k P \qquad \{20\}$$

As discussed in the *Introduction* this is the maximum amount of NIT that can be sustained between the 1st and 2nd layer in the contact zone. Note the traction capacity described using expressions {18-20} has units of force per unit width (N/m, pli, etc.).

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[1] Tekscan Inc., South Boston, MA

A Potential Source of Slippage

The following is offered as a hypothesis whose validity will be proven later in this publication by experiment.

First it will be assumed that the friction between the nip roller and the web is sufficient to prevent slippage between the nip roller and the outer layer. This appears reasonable for some cases based upon the WIT data presented in Figure 6. Although it is almost certain that there will be some webs that slip to some degree on both surfaces this appears reasonable for the webs discussed herein.

The strain in the z-direction {14} will induce a strain in the machine direction (y) in the outer layers as they are compressed in the contact zone due to the Poisson effect.

$$\varepsilon_{md,v}(y)=\frac{3\pi}{8}\nu_{r\theta}\frac{w(y)}{a}=\frac{3\pi}{8}\nu_{r\theta}\frac{\left(a^2-y^2\right)}{2Ra} \qquad \{21\}$$

These Poisson's ratios ($\nu_{r\theta}$,which would relate radial pressure to circumferential strain) have been reported to be on the order of .01 for paper to as high as .02 for polyester[7,10, 11]. This is an order of magnitude less than the values of Poisson's ratio that are traditional for engineering materials, but nonetheless could induce significant MD strains since the z-direction strains can be large.

As the web enters the contact zone, refer to Figure 9, it begins to undergo compression in the z-direction. If it assumed that no slippage can exist between the outer layer and the nip roller then it is improbable that the tension in the outer layer will change while the web is transgressing the contact zone. Slippage can occur between the outer layer and the layer beneath (the 2nd layer). Prior to slippage between the outer layer and the layer beneath, a compressive y-direction force builds within the 2nd layer resulting from the machine direction strain in expression {21}. This force can be determined per:

$$f(y)=\frac{3\pi\nu_{r\theta}E_{md}}{8}\frac{\left(a^2-y^2\right)}{2Ra}t \qquad \{22\}$$

For some range in the y coordinate (from *–a* to *s* in Figure 9) f(y) will exceed the traction capacity. Slippage will occur from the *s* location all the way to the entry of the contact zone[12]. The value of f(y) at the location where stick behavior begins (f(s) in Figure 9) will be the value of the NIT. The outer edge of the outer layer will expand after the web exits the contact zone.

Determining the NIT

Based upon the hypothesis presented above the NIT will be determined from the intersection of the f(y) curve from expression {22} and the $T_{cap}(y)$ curve from expression {19}. At the *y* location *s* where stick begins the values of f(s) and $T_{cap}(s)$ become equivalent and that value is the NIT. In Figure 10 examples of f(y) and Tcap(y) are presented for two nip loads for a 15.24 cm nip roller in contact with newsprint. At the lower nip load of 8.75 N/cm the intersection of the two curves is at 1.62 N/cm, very close to the maximum value of NIT that can be sustained between the two layers (i.e. $\mu_k N$=1.66 N/cm). At the higher nip load of 35 N/cm the two curves intersect at 5.29 N/cm, somewhat less than the maximum value of 6.65 N/cm. This exhibits a behavior that was concluded earlier from WIT experiments in which the NIT was found to be proportional to nip load per expressions {1} and {2} at low nip loads but became less dependent on nip load at higher levels of nip load. Thus whenever $T_{cap}(y)$ is less than f(y) throughout the whole zone of contact expressions {1} and {2} yield realistic predictions of the WIT.

EXPERIMENTAL VERIFICATION

The model was used to estimate the WIT for the cases shown in Figure 5 on newsprint. The tests involved center winding and thus the NIT was added to the web tension to produce the WIT. Of all the inputs the only parameter not well known was Poisson's ratio. The value was varied until the results matched the WIT results for one nip diameter. After that Poisson's ratio was held constant at 0.016 for all calculations for all nip roller diameters. Although 0.016 is certainly in the range of Poisson's ratio presented by other authors, no source has been able to measure the parameter accurately. The results are shown in Figure 11 in which good agreement is seen between theory and experiment. The input parameters for newsprint are shown in Table 1.

Next a polyester web was tested. Polyester film is similar in in-plane modulus to newsprint but the radial modulus is significantly larger, see Table 2. First a set of WIT tests were conducted to determine what factor friction might play between the nip and wound roll, refer to Figure 12. These tests were similar to those conducted and displayed in Figure 6 for newsprint with the exception that nip load was held constant throughout the wind. As in Figure 1 note that the slope of the WIT appears to be nearly independent of wound roll radius. The kinetic coefficient of friction between the polyester and the bare aluminum roller was 0.2 but was in excess of 4 when the nip was covered with the DOW 236 coating. Again even though the friction coefficient is now 20 times larger the WIT data is nearly identical.

The WIT results calculated from the model are shown in Figure 13 overlaid upon experimental results for a set of center winding tests at three different web tensions on the polyester web. Again the model results and the tests compare well. The behavior of the WIT with respect to nip load is somewhat different than that exhibited by newsprint in Figure 11. It appears that the higher radial modulus of polyester causes stick in the contact zone to occur more readily and at nip loads greater than 20 N/cm the WIT becomes nearly independent of nip load. A Poisson's ratio of 0.01 was used in the model computations.

CONCLUSIONS

A working model for the prediction of NIT has been presented whose output satisfies trends that have measured in the laboratory. The model requires input of a Poisson's ratio that is small and difficult to measure. For the newsprint and polyester web results presented herein this parameter ranged from .01 to .016 and for those interested in applying the model selecting this parameter appears reasonable. By adding the web tension to the NIT a good predictive model for the WIT for center winding with a rider roller is obtained that can be used with wound roll models to predict the internal roll stresses. This model assumes that slippage between the nip roller and the web affects the NIT little however the cases examined to date have had friction coefficients that were smaller between the web surfaces than between the web and nip roller. In cases where the web to nip roller friction is less more complex modeling maybe required that examines slippage on both sides of the incoming web layer.

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REFERENCES

1. Pfeiffer, J.D., "Nip Forces and their effect on wound-in tension," Tappi Journal , Vol. 60, no. 2, February 1977.
2. Good, J.K., Hartwig, J. , and Markum, R., "A Comparison of Center and Surface Winding Using the Wound-In-Tension Method," Proceedings of the Fifth International Conference on Web Handling, Oklahoma State University, Stillwater, Oklahoma, June 6-9, 1999.
3. Good, J.K. and Wu, Z., "The Mechanism of Nip Induced Tension in Wound Rolls", Journal of Applied Mechanics, Vol. 60, No. 4, December 1993.
4. Good, J.K., Wu, Z., and Fikes, M.W.R., "The Internal Stresses in Wound Rolls in the Presence of a Nip Roller", Journal of Applied Mechanics, Vol. 61, No. 1, March 1994.
5. Jorkama, M., "Contact Mechanical Model of a Winding Nip," PhD dissertation, Helsinki University of Technology, Finland
6. Good, J. K., Pfeiffer, J.D., and Giachetto, R.M. "Losses in Wound-On-Tension in the Center Winding of Wound Rolls," AMD Vol. 149, Web Handling – 1992, edited by J. K. Good, American Society of Mechanical Engineers, pp. 1-12.
7. Hakiel, Z. "Nonlinear Model for Wound Roll Stress," Tappi Journal, Vol. 70, no. 5, pp. 113-117, 1987.
8. Johnson, K. L., Contact Mechanics, Cambridge University Press, 1985, pp. 104-106
9. Pfeiffer, J.D., "Measurement of the K2 Factor for Paper," Tappi Journal , Vol. 64, no. 4, April 1981.
10. Bhushan, B., Mechanics and Reliability of Flexible Magnetic Media, Springer-Verlag, 1992, pp. 123-124.
11. Willett, M. S. and Poesch, W. L., " Determining the Stress Distributions of Wound Rolls of Magnetic Tape Using a Nonlinear Finite-Difference Approach," Journal of Applied Mechanics, Vol. 47, December, 1980.
12. Johnson, K. L., Rolling Contact Phenomena, edited by J. B. Bidwell, Elsevier Publishing, 1962, pp 6-25.

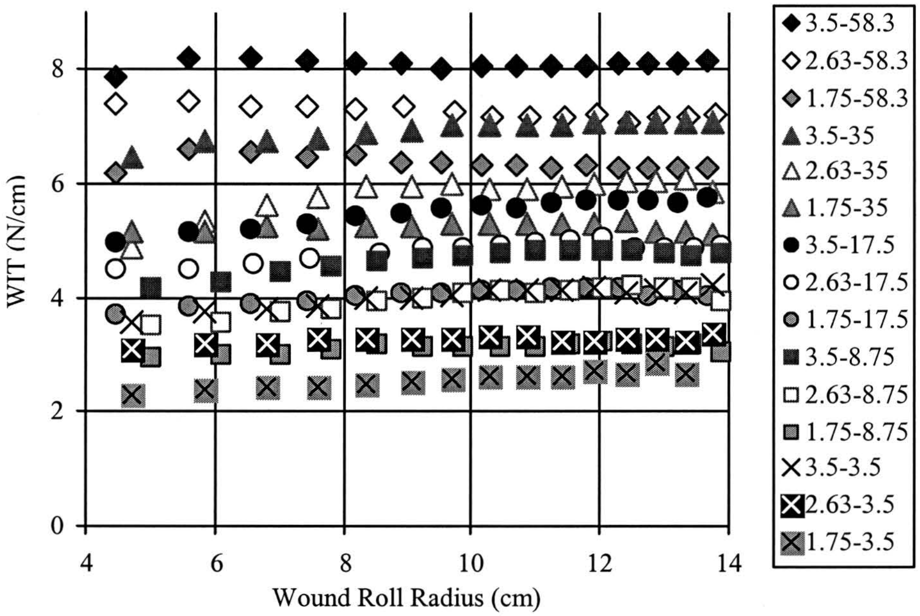

Figure 1 – Center Winding Newsprint – WIT Data (Legend Tw (N/cm) – Nip Load (N/cm))

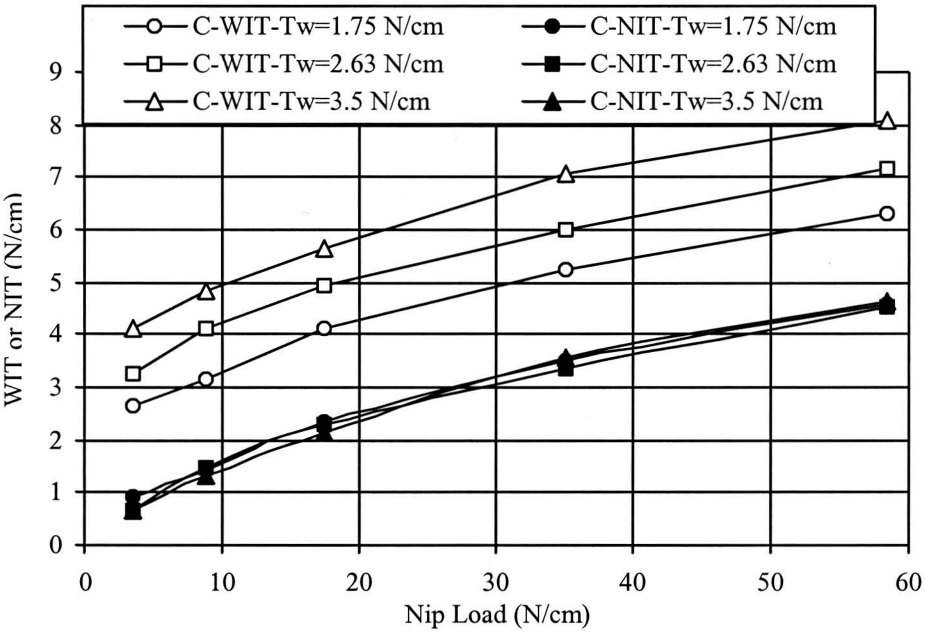

Figure 2 – Center Winding Newsprint – Averaged WIT Data

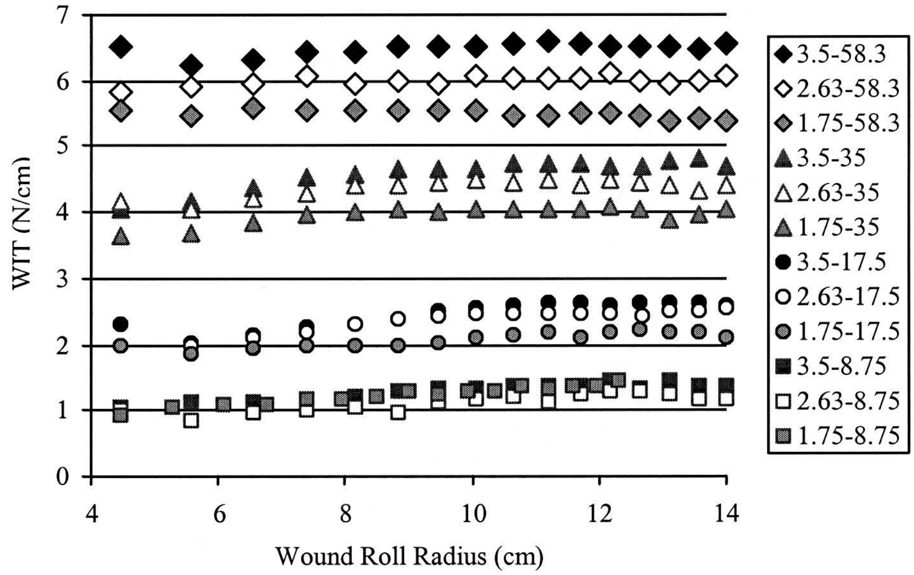

Figure 3 – Surface Winding Newsprint – WIT Data (Legend Tw (N/cm) – Nip Load (N/cm))

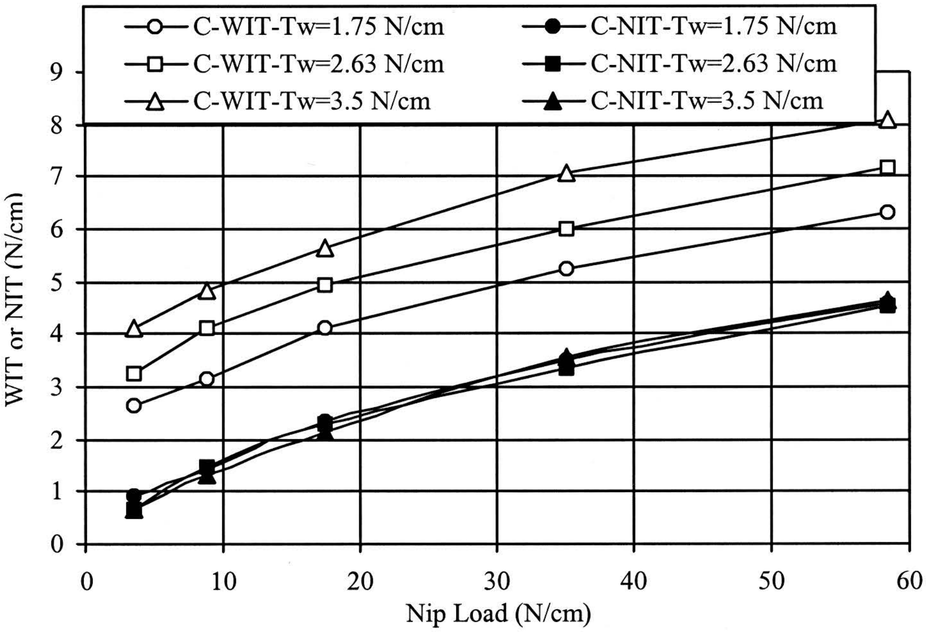

Figure 4 – Surface Winding Newsprint – Averaged WIT Data

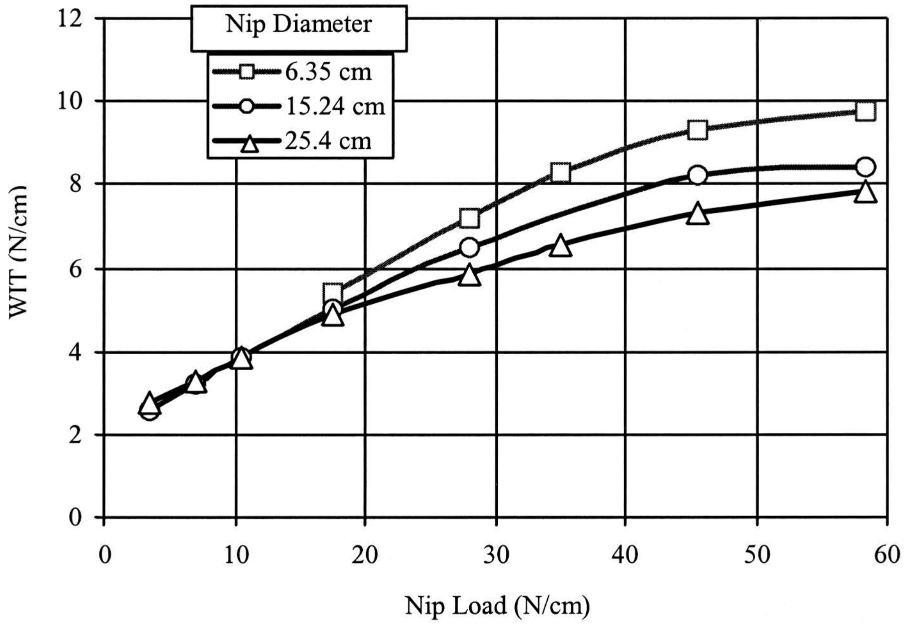

Figure 5 – Center Winding Newsprint – Averaged WIT Data – Tw = 1.75 pli

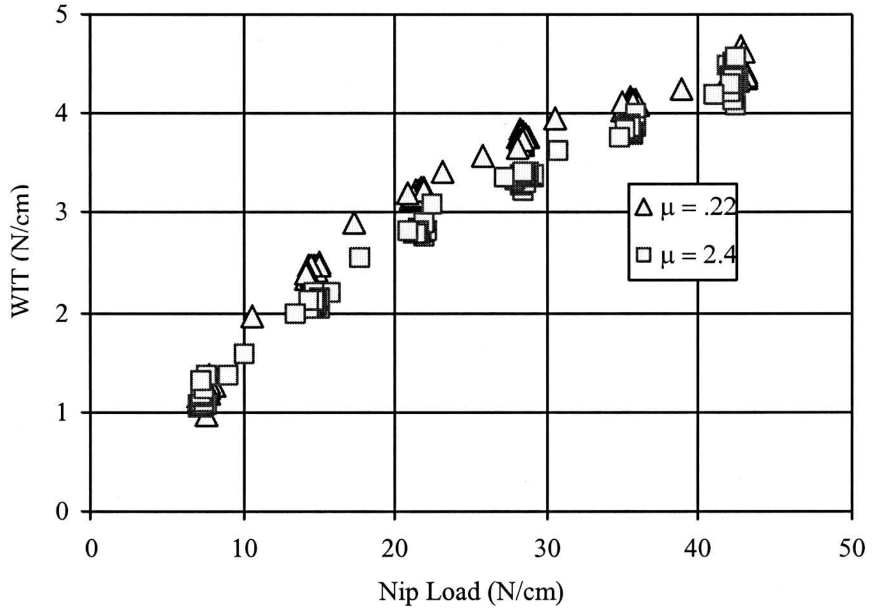

Figure 6 – Surface Winding Newsprint with an Aluminum 12.54 cm OD Roller that was either bare or covered with DOW 236 – T_w = 0.6 N/cm

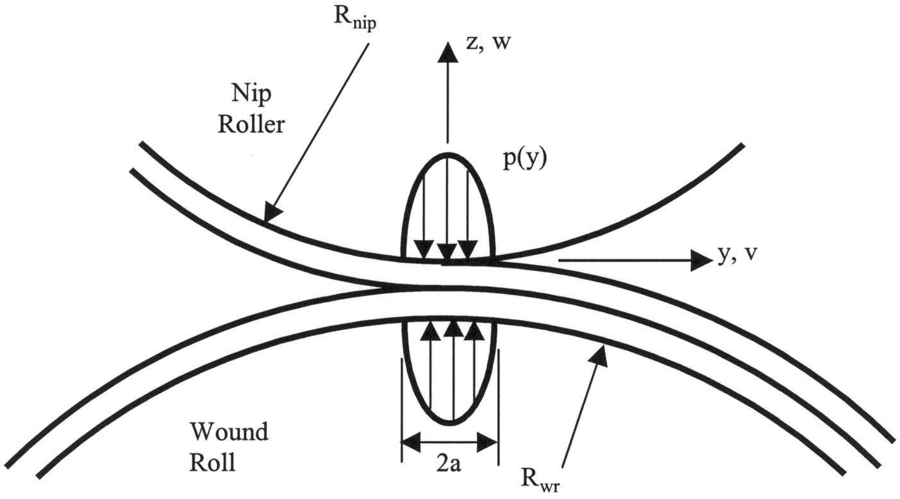

Figure 7 – The Incoming Web Becoming the Outer Layer

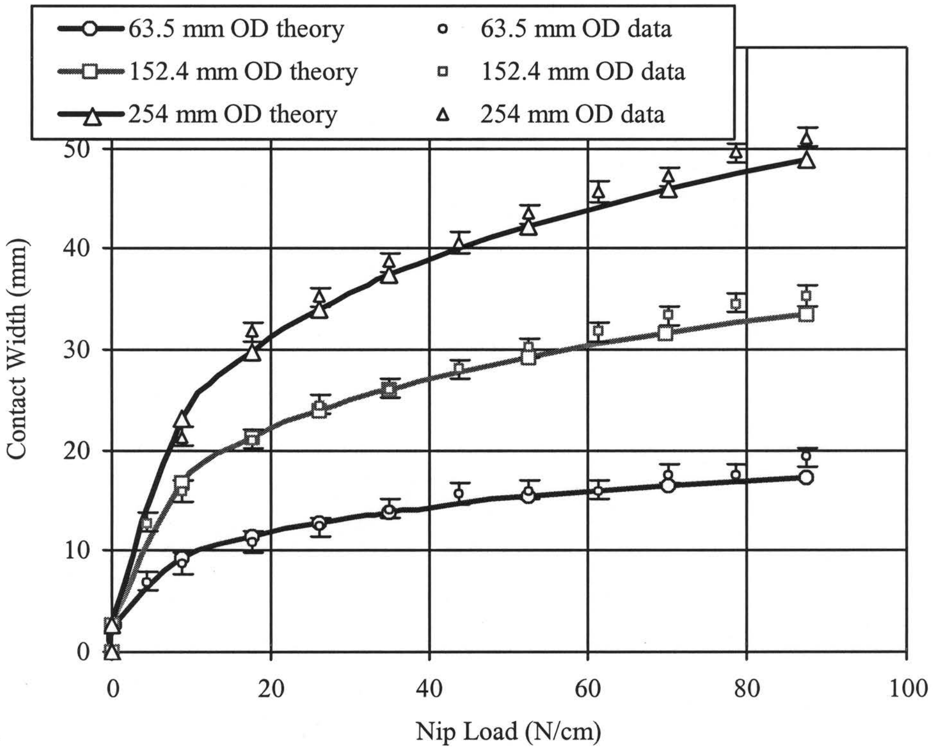

Figure 8. – Comparison of Theory and Experiment on Contact Width for News

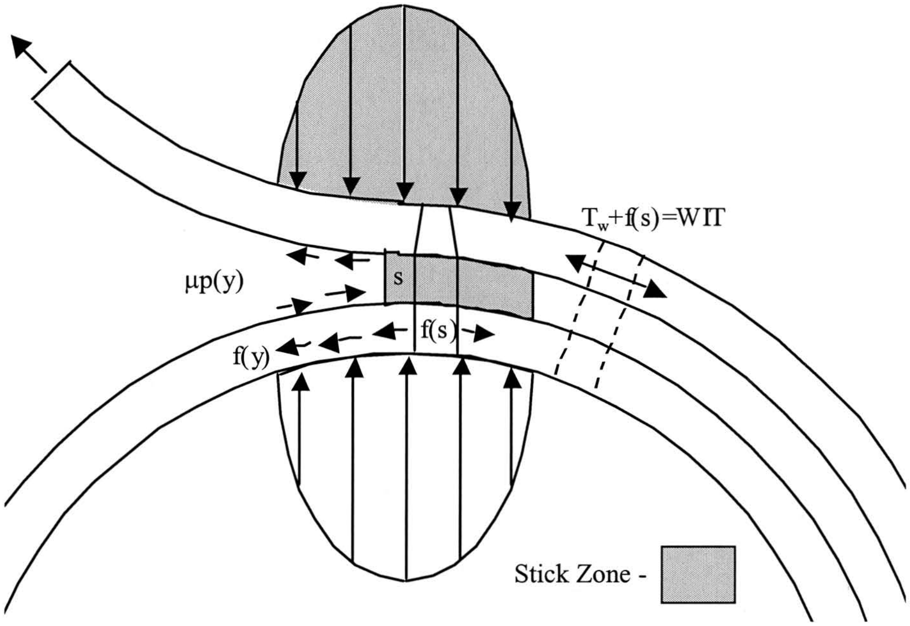

Figure 9 – Influence of Nip/Outer Layer Friction on WOT

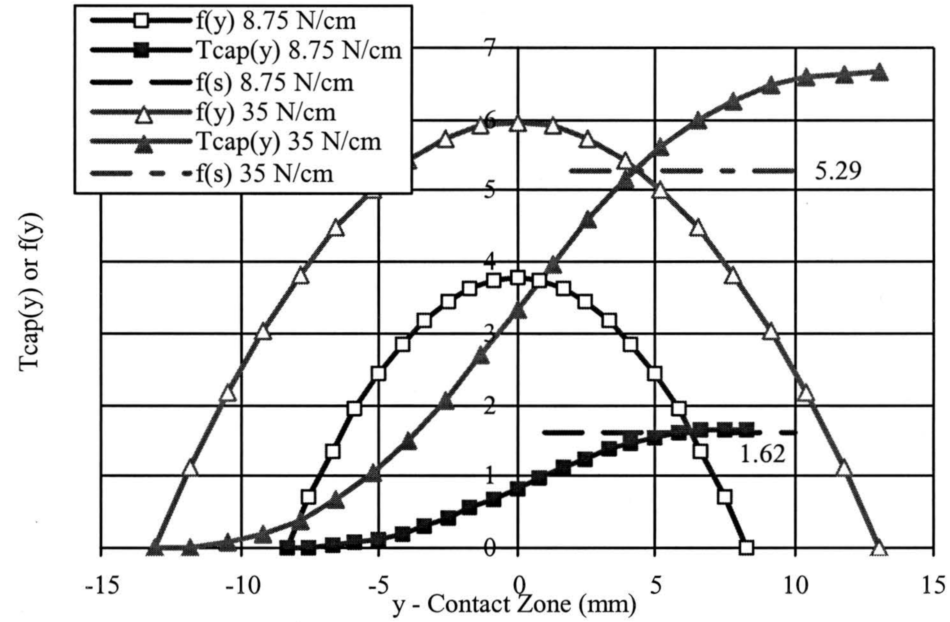

Figure 10 – Establishing the Intersection of the f(y) and Tcap(y) Curves for Nip Loads of 8.75 and 35 N/cm for a 15.24 cm Nip on Newsprint

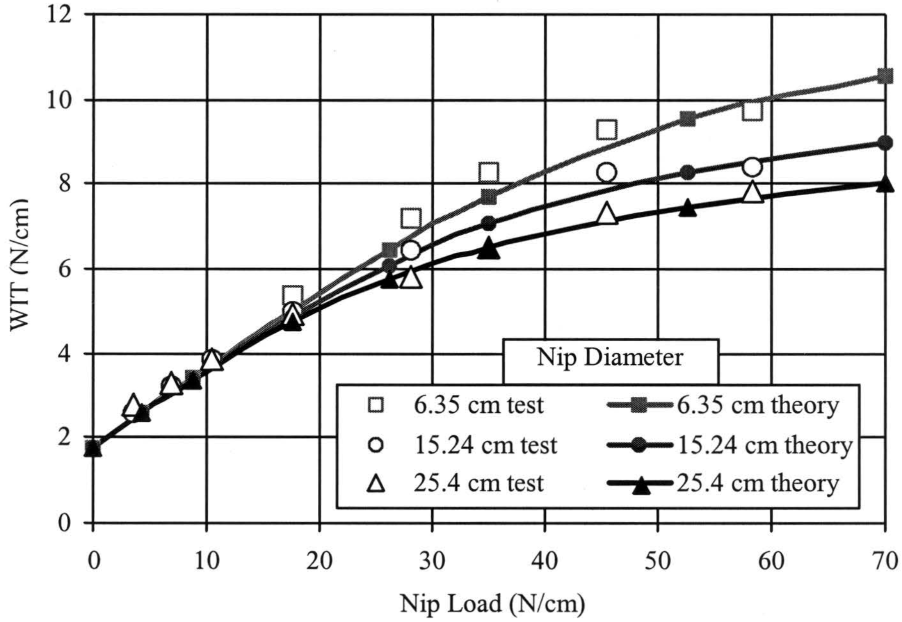

Figure 11 – WIT – Theory versus Experiment for Newsprint Center Wound with a Web Tension of 1.75 N/cm and a Range of Nip Loads.

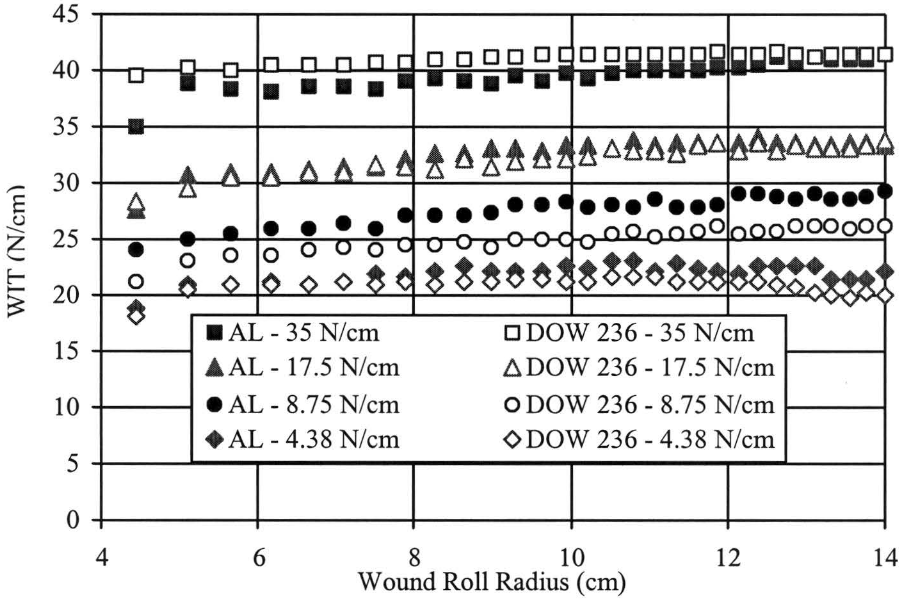

Figure 12 – Center Winding PET with an Aluminum 12.54 cm OD Roller that was either bare or covered with DOW 236 – Tw = 3.5 N/cm. (Legend – Nip Load)

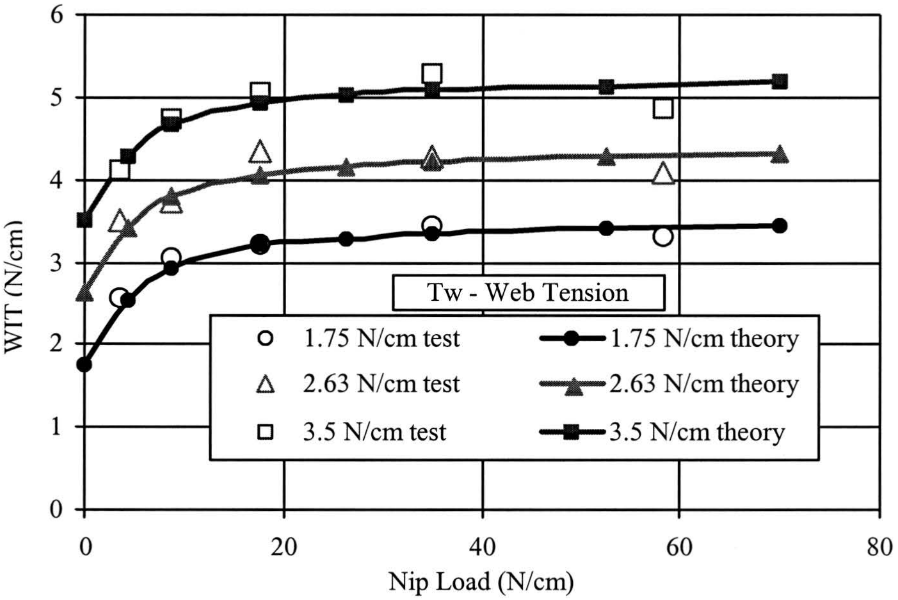

Figure 12 – WIT – Theory versus Experiment for Polyester Center Wound with a Range of Web Tensions and Nip Loads and a Nip Diameter of 15.24 cm.

K_1	24.25 KPa
K_2	24.49
E_{md}	5.14 MPa
μ_k	0.19
t	70.5 μm
$\nu_{r\theta}$	0.016

Table 1. – Model Inputs Used for Newsprint

K_1	8.61 KPa
K_2	62.3
E_{md}	4.79 MPa
μ_k	0.2
t	54.6 μm
$\nu_{r\theta}$	0.010

Table 2. – Model Inputs Used for Polyester

Name & Affiliation	**Question**
R. Lucas – GL&V	Back in the 1970's, there was an excellent paper that was written by Erikson & Rand that had to do with amongst other things using a strain gauge in winding experiments.
Name & Affiliation	**Answer**
K. Good – OSU	They adhered strain gauges on webs and they wound them into single drum winders, center winders and two drum winders.
Name & Affiliation	**Question**
R. Lucas – GL&V	How do your answers correspond to their results?
Name & Affiliation	**Answer**
K. Good – OSU	I'm glad Leif Erikson is here today because I do have interest in going back and comparing to his results. My own experience is that putting down strain gauges on webs and then winding them around things and then into a roll has yielded poor results. The trends shown in Leif's data makes sense to me but I do not believe that I should be trying to compare absolute values of his data taken on another web to my results at this point.
Name & Affiliation	**Question**
R. Lucas – GL&V	When you perform a compression stress strain test on paper, there is significant hysteresis on your upload cycle versus download, and would have a significant change in the shape of your contact pressure curve. Have you considered that?
Name & Affiliation	**Answer**
K. Good – OSU	So the nip rolling over the wound roll is an occurrence of upload and down. With hysteresis there will be rolling resistance. The rolling resistance is due to the pressure being different on the exiting side than it is on the incoming side. How do I expect that to alter things? There may be a small component of nip induced tension that is rolling resistance related. This has not been factored in here. It will change the shape of the pressure curve. It will no longer be symmetrical about the center of contact.
Name & Affiliation	**Question**
R. von Hertzen – Helsinki University of Technology	Is your derivation for cylinders of homogenous material? It is well known that the paper is orthotropic. How can the solution be used?

Name & Affiliation	**Answer**
K. Good – OSU	Yes. The radial modulus is always state dependent on the radial stress and small compared to the in-plane modulus for the vast majority of paper and film webs. In most cases, including paper webs, the Poisson's ratios which couple radial strain to circumferential stress are very small, so small that they defy measurement. Thus it was assumed the contact of a rigid nip with a wound roll of web material is governed mainly by the radial modulus.
Name & Affiliation	**Question**
J. Dobbs – 3M	Did you keep track of where the stick and slip zone is? That is, are they in the front half or the back half?
Name & Affiliation	**Answer**
K. Good – OSU	I'm afraid that nobody can prove that at this point, so that is a hypothesis. I presented a model that seemed to give good results assuming that the majority of the slip occurs in the front portion of the contact zone where the web has just entered. Marko Jorkama of Metso Paper has a different model that he presented at the last IWEB which has different boundary conditions and different material property inputs and he can show good correlation as well. I don't think we have good proof at this point of where is all the slippage occurring. So a theory has been promoted that yields reasonable results.
Name & Affiliation	**Question**
D. Pfeiffer – JDP Innovations	There's another area of slip and that is that when you are tensioning the web prior to entering the winder, to the left in your diagram, and that means that the excess paper that you pull out has to go, follow to the left, and it has to slip along the incoming drum surface.
Name & Affiliation	**Answer**
K. Good – OSU	Yes. In surface winding with large angles of wrap between the web and nip roll we see little impact of web tension on WIT until we reach significant nip loads. This morning we saw in K. Tanimoto's paper that he had included a band break type term to a nip induced tension equation.
Name & Affiliation	**Question**
D. Pfeiffer – JDP Innovations	That's why I would say that you didn't see any great effect of web carrying tension in the surface winding case because you had enough wrap around the incoming surface that you spilled off the incoming web tension.
Name & Affiliation	**Answer**
K. Good – OSU	I have shown wound-in-tension curves for surface winding in this presentation. Those would in fact be altered somewhat by angle of wrap. In the results shown, all tests were carried out with 180 degrees of web wrap about the nip prior to entry of the winder.
Name & Affiliation	**Question**
D. Pfeiffer – JDP	My original measurements were at about a 5-degree angle

Innovations	of wrap so I did see an influence of web tension on WIT.
Name & Affiliation	**Answer**
K. Good – OSU	Yes, I agree that you should have. This is a difficult computation problem. The angle of wrap over which slippage occurs is not necessarily the angle of wrap between the web and the nip. The elasticity of the web, the amount of slippage induced upstream by the nip, and friction characteristics will dictate over what wrap angle the slippage will occur. Thus the web may contact the nip roller and retain full web tension for some angle of wrap prior to slippage occurring at which point the web tension will decrease until it enters the nip contact zone.