WOUND-IN-TENSION IN A NON-WOVEN WEB

by

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ABSTRACT

Literature on wound roll structure of non-homogeneous webs is scarce. Experimental and analytical research on wound roll structure of homogeneous materials such as plastic films and paper has been reported extensively, although at some scale the homogeneity of paper can be questioned. This paper will focus on a non-woven polyethylene. Results from the literature for film and paper webs show proportionality between wound-in-tension and nip load at lower nip loads and at higher nip loads the wound-in-tension becomes independent of nip load in both surface winding and center winding with an undriven rider roller. The proportionality between wound-in-tension and nip load at lower nip loads has been shown to approach the kinetic coefficient of friction between web layers for those materials. In the non-woven polyethylene web studied the proportionality was much less than the kinetic coefficient of friction. Tests conditions, including slip velocity, are known to affect measured friction coefficients. Wound-in-tension is the result of micro-slippage and elongation of the web in the contact zone beneath the rolling nip which involves the field of contact mechanics. Theorists in this field have presented arguments that friction coefficients used in contact analyses must be appropriate for the conditions of micro-slip which occur in the contact zone. Results of winding tests and finite element contact analysis will be presented which focus on this problem.

NOMENCLATURE

WIT	Wound-in-Tension, load per unit width
NIT	Nip Induced Tension, load per unit width
T_w	Web tension
μ_k	Kinetic coefficient of friction between web layers
N	Nip load, load per unit width
$\mu_{w/R}$	Kinetic coefficient of friction between web and nip roller
E_θ	Circumferential/tangential modulus of web

E_r	Radial modulus of web
K_1	Constant relating pressure and strain
K_2	Constant relating pressure and strain (Springiness factor)
P	Pressure
ε_{web}	Strain in the web in machine direction
δL	Total strain in 1cm distance
L_i	Initial length
N.R.D	Nip Rolling Distance
ε_r	Radial strain
ε_θ	Circumferential strain
$\upsilon_{r\theta}$	Poisson's ratio in radial direction
$\upsilon_{\theta r}$	Poisson's ratio in circumferential/tangential direction
$\sigma_{r\theta}$	Radial stress
$\sigma_{\theta r}$	Circumferential/Tangential stress

INTRODUCTION

Wound-in-tension (WIT) is the tension in the outermost layer of a winding roll. It has been measured by passing the outermost layer of a winding roll over an idler roller mounted on a load cell and returning it back to the winding roll. This method was first introduced by Pfeiffer [1]. The results of his experiments showed that the WIT increased with increase in web tension and nip load and there was a certain nip load for a given tension level below which winding would not be possible due to stalling. Since the web is pulled away from the winding roll frictional losses due to slippage that would not have occurred in a winding roll makes this an interfering test and was proven by Good and Hartwig [2]. In some instances they were able to correct the measured WIT values to yield WIT inferred from pressure measurements. Flat bed nip mechanics tests combined with finite element contact analysis by Good et al. [3,4] alluded to the presence of an elongating machine direction strain existing underneath the first layer in contact with the nip as the primary cause of nip-induced tension (NIT). For materials like newsprint and polypropylene webs, initial algorithms to compute WIT given in equations {1,2} were based on Amonton's law of friction and they predicted well at lower nip loads.

$$WIT_{center\ winding} = T_w + \mu_k N \qquad \{1\}$$

$$WIT_{surface\ winding} = \mu_k N \qquad \{2\}$$

Cai [5] studied the effects of nip roller compliancy in center and surface winding and was able to demonstrate that the NIT was same in both center and surface winding. Equation {2} was modified to include the frictional loss in tension for surface wound rolls based on band-brake expression as given in {3} and were able to verify experimentally.

$$WOT_{surface\ winding} = \frac{Tw}{e^{\mu_w/_k \phi}} + \mu_k N \qquad \{3\}$$

Good et al. [2] used equations {1,3} to predict WIT in surface winding with good agreement in experimental results. Based on the experimental results, they were able to prove that the NIT was independent of web tension and equation {2} was only valid at low nip loads. At high nip loads a proportional increase of the web tension was observed becoming part of the WIT. It has also been shown in the past that the WIT behavior in winding newsprint also follows the same trend [2]. Theorists [6,7] have agreed that the mechanics of slippage at the contact zone determine the behavior of NIT and WIT. Simple equations determined from Amonton's law may work well in some cases, but the inability to predict the micro-slip and the actual friction that exists in the contact zone requires sophisticated solutions. Jorkama [6] developed a computer based algorithm founded on contact mechanics of the nip roller and wound roll. His results show that the shear strains are responsible for the slippage between the top two layers and result in the NIT. Good [7] hypothesized an algorithm to compute NIT based on assumptions of slip and stick zones at the entry point of web into the wound roll and friction between the web surfaces to be greater than the friction between the web and nip roller. Based on the traction capacity (which is the ability to resist slip) and compressive stresses developed in the layer beneath the top layer due to extensional strains in the bottom surface of the top layer, he was able to compute NIT which was later verified experimentally. Though both Good's and Jorkama's theories are different, it is apparent from their theories that NIT is limited by the frictional forces between the layers. So how important is it to know what exactly happens at the nip contact zone to predict WIT? Do these theories hold good for behavior of wound roll structure of non-woven webs? This paper addresses these questions using experimental tests on a non-woven polyethylene web and FE analysis of contact mechanics of nip roller and webs.

EXPERIMENTAL RESULTS AND DISCUSSION

Non-woven high density polyethylene (HDPE) webs with material properties shown in Table 1 were surface wound for a range of web tensions and nip loads. The behavior of the WIT and wound roll structure was observed. Stack tests were conducted to determine the radial modulus of HDPE and were expressed based on Pfeiffer's expression [8,9] given in equation {4}.

$$E_r = K_2(K_1 + P) \qquad \{4\}$$

Although the radial modulus is comparable to that of newsprint, the in-plane modulus of HDPE is ten fold less. Since the WIT test method based on extracting the web after the nip and measuring the WIT using an idler on load cells was proven to be an interfering test method another method was employed [2]. Radial pressure measurements were collected in rolls wound at differing web tensions and nip loads. Pre calibrated pull-tabs were inserted into the wound rolls for measurement of radial pressure in surface winding with an 180° wrap. Rolls were wound on rigid aluminum cores of 16.55 cm diameter to an approximate wound roll outer diameter of 33 cm. Winding tests were performed at tension levels of 0.88, 1.75, 2.63 N/cm and nip loads of 7, 14, 28, 42, 56, 70 N/cm and the results are shown in Figure 1. Each data point in the figure represents an average of 3 test results. Due to stall problems, winding was not possible at low nip loads for tension levels of 1.75, 2.63 N/cm respectively. At low nip loads of 7, 14, 28 N/cm and tension levels of 0.88, 1.75 N/cm, the pressure curves are similar and show no influence of web tension at low nip loads. As the tension and nip load increases, more web tension comes into play as is seen in increased pressure levels. This is in agreement with how newsprint, films behave though the pressure levels are different.

K_1	135.83 KPa
K_2	11.66
E_θ	406.79 Mpa
$\mu_{k\ nip/web}$ (ASTM)	0.15
$\mu_{k\ web/web}$ (ASTM)	0.15
$\upsilon_{r\theta}$	0.03-0.14 (Pressure dependent)
$\upsilon_{\theta r}$	0.3
t	152.4 μm
Width	15.24 cm

Table 1 - Material properties of non woven HDPE

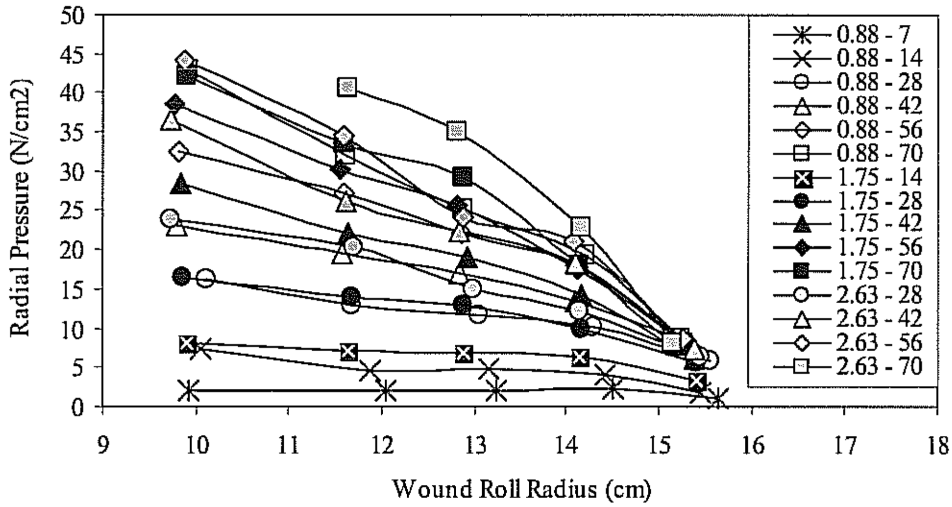

Figure 1 - Radial pressure data from surface wound HDPE rolls (0.88 - 7 (Tension (N/cm) - Nip load (N/cm)))

Based on Hakiel's model [10], the WIT was iterated to produce the same radial pressure profiles as was measured in experiments. WIT measurements were made in surface wound rolls of similar diameter by passing the outermost layer of the winding roll over an idler roll mounted on a load cell and returning it back to the winding roll. The averaged values of WIT for each winding condition are represented in Figure 2. These values were compared to the iterated values of the WIT and the comparison is shown in Figure 2. It is evident from the figure that the direct measure of the WIT using the load cell method is indeed an interfering test.

Using WIT computed from pull-tab measurements, the NIT was calculated using equation {3} and is represented in Figure 3. WIT increases almost linearly at all tension levels for all nip loads except at the highest nip load of 70 N/cm when the WIT appears to taper off. The proportionality between WIT and nip load at lower nip loads has been shown to approach the kinetic coefficient of friction between the web layers in materials like Newsprint, but in this case it is much less. On the other hand, the NIT behaves independent of the web tension as shown in Figure 3 and this behavior agrees with how newsprint and films behave [2].

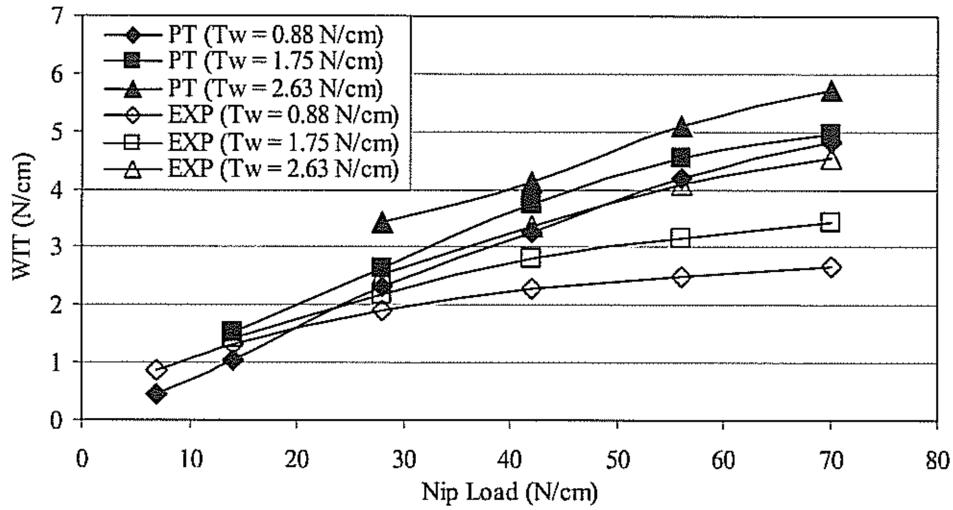

Figure 2 - Surface wound HDPE rolls - WIT data (Legend PT - Pull Tab inferred WIT, EXP – Experimentally measured WIT)

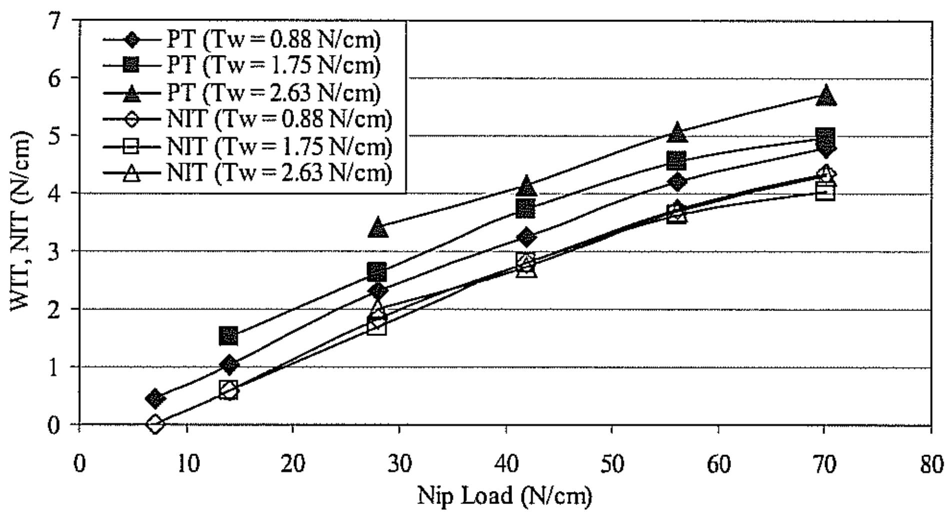

Figure 3 – Surface wound HDPE rolls - NIT data (Legend PT - Pull Tab inferred WIT, NIT - Nip-Induced-Tension)

It has been proven that, in surface winding other webs [2], web tension does not affect the wound roll pressures at lower nip loads while significant tension contribution to the WIT can be observed at higher nip loads. This can be confirmed from the radial pressure plots shown in Figure 1. If this were true why is there a disagreement in proportionality observed in the WIT curves? Is it possible that the operating parameters or winding conditions change between or during tests and thus cause this anomaly? In order to make sure the winding conditions remained same, parameters like winding speed, web tension and nip load were recorded and were observed to remain constant during the experiment within the realms of experimental errors. The rolls were wound at low speeds of 100 ft/min and the nip exudes the air that might otherwise enter the wound roll thus eliminating the possibility of air entrainment as a cause.

WIT was inferred by iterating on the web tension in a wound roll model until the model generated equivalent wound roll pressures measured using pull-tabs. If the web was viscoelastic, wound roll pressures would drop over a period of time and this would mean that the inferred WIT data is erroneous. A roll was wound in center winding condition at a web tension of 2.92 N/cm and the roll pressures were monitored over a time period of 30 hours. The roll pressures dropped less than 5% of the initial value as shown in Figure 4. and this difference could be within the experimental limitations. It is evident that viscoelasticity could not be a possible cause.

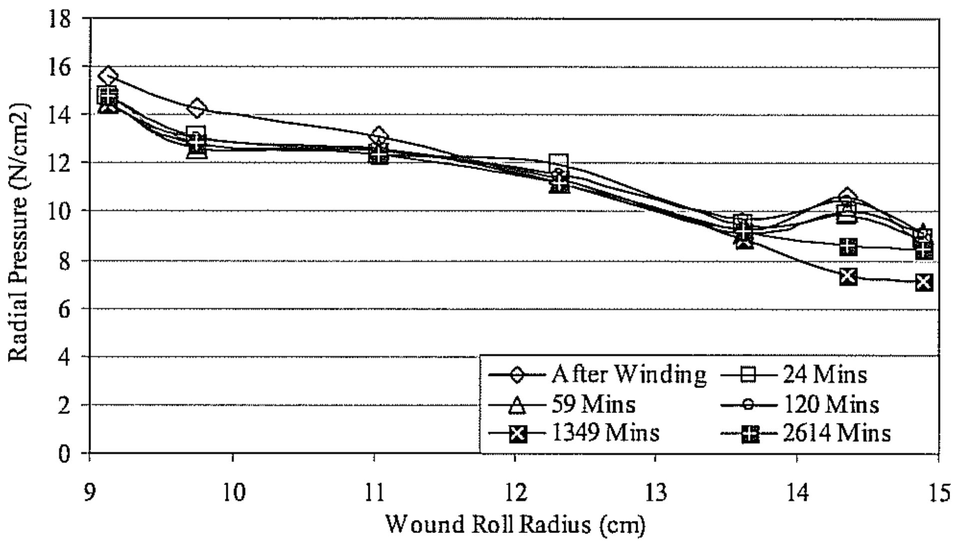

Figure 4 – Viscoelastic behavior of a center wound roll at 2.92 N/cm tension (Legend – Time after winding)

Other possible causes for the difference in behavior could be the coefficient of friction or non-homogeneity of the web. The possible friction factors that might affect the wound roll structure would be the kinetic coefficient of friction between the web layers and kinetic coefficient of friction between the web and the nip roller. Is it possible that the slippage between nip roller and the outermost layer of the winding roll might cause this behavior? To investigate this, special friction tapes (DOW 236) were applied to the nip roller and tests were conducted to study the behavior. The coefficient of friction between web and nip roller and web and web was measured using the ASTM standards [11]. The measured coefficient of friction between the roller with friction tape and web was many times more than that of the bare aluminum roller case. It is evident that the addition of friction tapes only decreases the WIT as is shown in Figure 5.

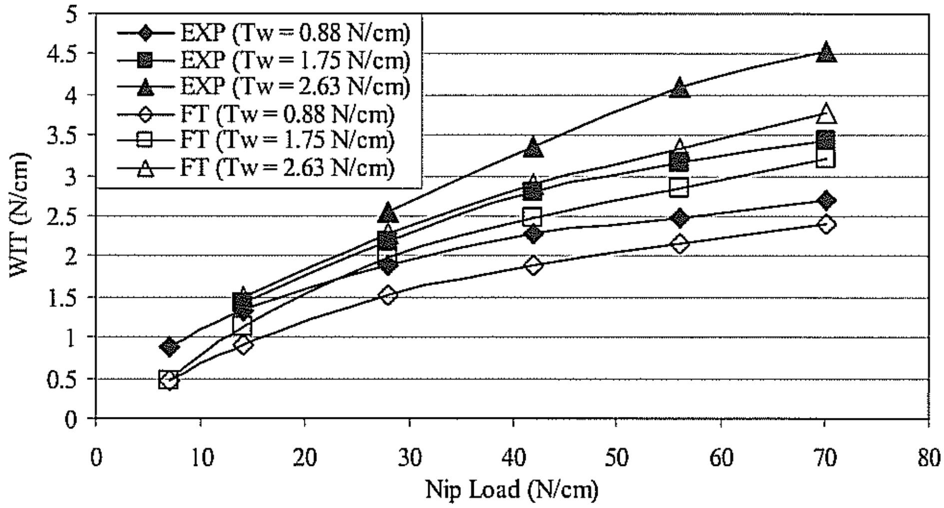

Figure 5 – Comparison of experimentally measured WIT using the load cell method (Legend EXP – Aluminum nip roller, FT – Aluminum nip wrapped with friction tapes)

Johnson [12,13] studied the existence of stick-slip zones and micro slip zones in rolling contact problems and proved that the rolling friction can be drastically different from friction values measured using ASTM standards. Winding is a rolling contact problem and it is likely that the measured friction values does not correspond to the actual friction that exists in the rolling contact zone. Since it is impossible to measure the actual friction that exists at the rolling interface in a winding scenario, it has to be inferred by other means. A flat bed rolling contact mechanics tester as shown Figure 6. was designed for the friction measurement.

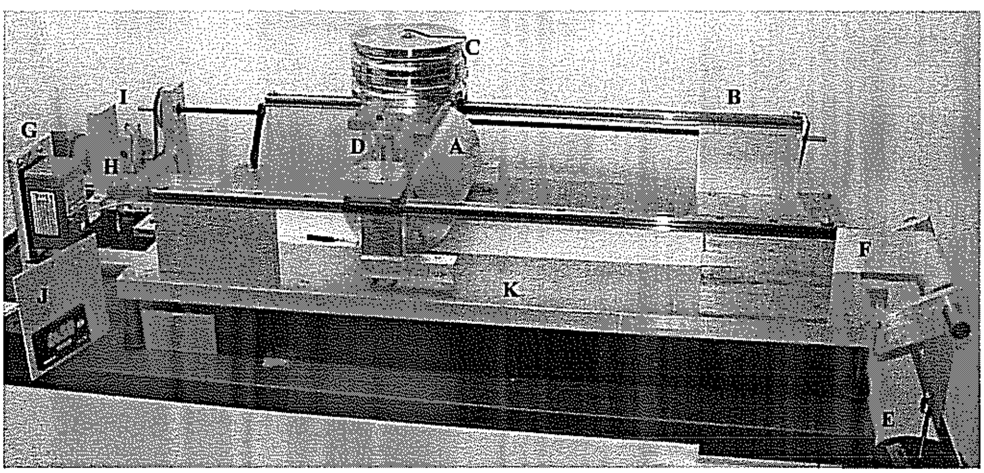

Figure 6 – Flat bed contact mechanics tester (Legend A-6 in diameter Aluminum roller, B-Horizontal guideways, C-Weights for nip load, D-Vertical guideways, E-Weights for web tension, F-Top layer under tension with layers underneath, G-Position transducer, H-Tension Load cell, I-Motor lead screw assembly, J-Tension indicator, K - Base)

The set up consists of parallel guide ways fixed on to a flat bed. Vertical linear slide ways that support a roller that can be nipped using weights moves along the horizontal slides. The roller moves at a constant linear velocity and the experiment is conducted by clamping a few sheets of HDPE to the base (Note K in figure 6) on the left and attaching the top layer to a load cell. The sheets underneath the top layer act as a infinite radius wound roll. A dead weight hanging from the other end of the web (E) simulates the web tension. A nip load (C) is then applied to the roller and the roller is rolled across the sheets to observe the NIT. As the NIT is monitored using the load cell, a linear potentiometer measures the position simultaneously to record the behavior of the NIT as a function of position. The measured NIT should be equal to that given in equation {1}. Thus friction that actually exists in the rolling contact interface can be inferred from these experiments. Flat bed nip mechanics tests were carried at the same conditions as the HDPE winding conditions although only a fewer nip load levels were used. The NIT was found to increase but then reach a steady constant level after the nip had rolled 0.75 cm to 3 cm depending on the nip load and tension and is shown in Figure 7. This steady constant level is sometimes called the saturated level of the NIT. Lower tension and nip loads produced quicker saturation and the averaged saturated values of WIT, NIT is represented in Figure 8. Each data point in the figure represents the average of three test results. The slope of the NIT curve is representative of the coefficient of friction between the web layers in rolling contact and was calculated to be 0.104.

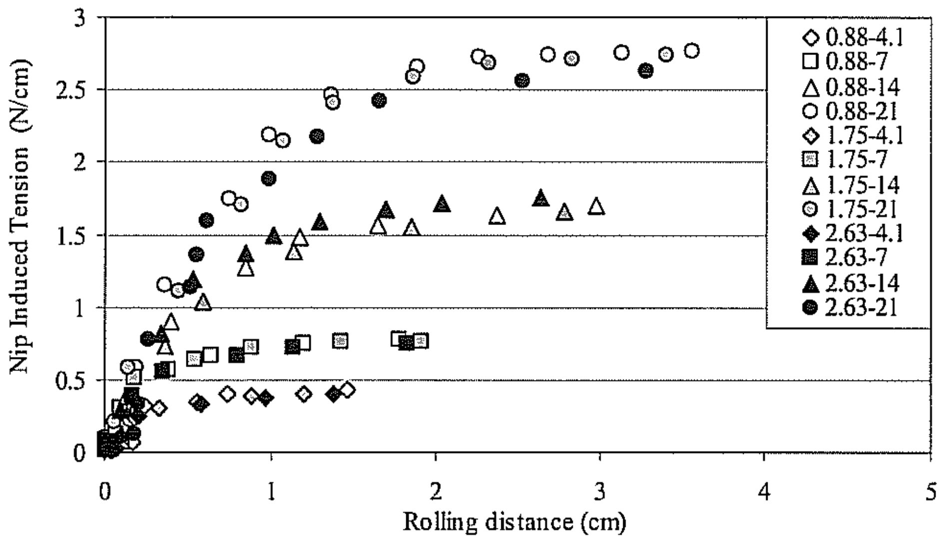

Figure 7 – Nip Induced tension as a function of rolling distance at different nip loads and web tension. (Legend 0.88-4.1 – Web tension (N/cm) – Nip load (N/cm))

The value of friction that exists in the contact zone is much less than the kinetic coefficient of friction measured by ASTM standards (Table 1). Although, this value does not compare well with the friction inferred from WIT values, it should be borne in mind that this scenario represents a winding roll of infinite radius approximating a flat bed. In real winding scenario, the friction value could be even less than what was observed in flat bed mechanics tests. This friction value was then used to compute the radial pressures and WIT based on the algorithm proposed by Good [7]. The results predicted by the model were completely different from experimental values. It was noted that this model was extremely sensitive to Poisson's ratio $\upsilon_{r\theta}$. In order to see the effect of Poisson's ratio on machine direction strain, finite element analysis was conducted and the discussion is carried out herein.

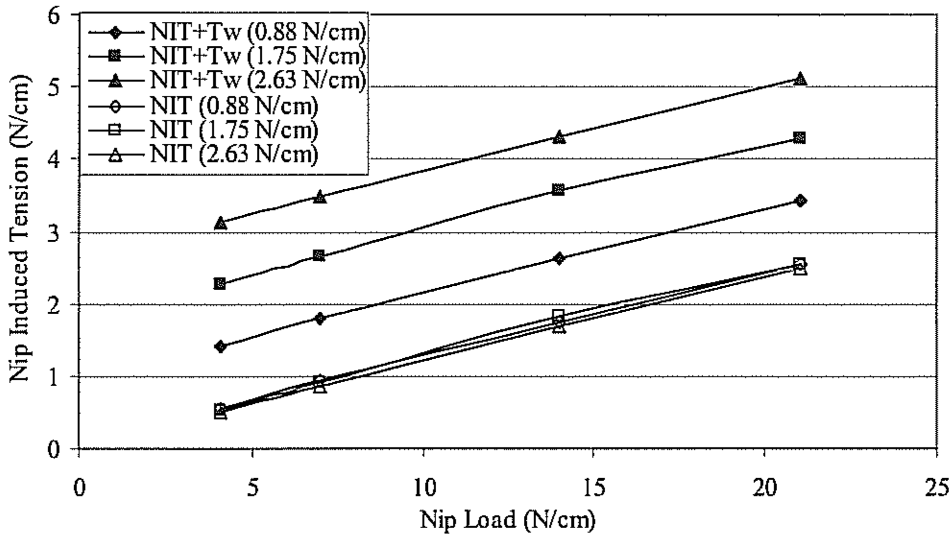

Figure 8 – Average saturated values of nip induced tension plus web tension and nip induced tension (Legend NIT + Tw – Nip Induced Tension + Web tension, NIT – Nip Induced tension, value in parentheses indicates web tension)

FINITE ELEMENT ANALYSIS

Good et al [3] were the first of the researchers to employ finite element analysis to determine the mechanism of nip induced tension. They employed a moving Hertzian contact pressure profile to observe the strain on the lower surface of the web. An altered approach was followed in this research. A stack of webs was indented with a rigid nip roller and the strain on the bottom surface of the top layer was observed. This strain is responsible for the NIT. As the rolling distance increases, the total strain in the back of the nip increases until saturation could be observed in the NIT as a result of slippage. A schematic of the FEM model has been shown in Figure 9.

Each layer was modeled with properties of HDPE and the analysis was carried out in plane strain conditions as the width was large compared to the thickness of the material. ABAQUS®, a commercial FEM code was employed for the purpose of this analysis. The interaction between the layers was modeled using penalty approach and the friction between the webs was set equal to the value inferred from the flat bed nip mechanics tests. The strain in the machine direction in the bottom surface of the top layer of web in contact with the nip is given in Figure 10. The total nip-induced strain in the top layer can be computed from equation {5} and is similar to how Good et al. [3] computed. The value of Poisson's ratio used in this case was 0.01.

$$\varepsilon_{web} = \frac{\delta L \times N.R.D}{L_i + N.R.D}, \quad \delta L = \frac{Area\ under\ strain\ curve \times 1\,cm}{Element\ length} \tag{5}$$

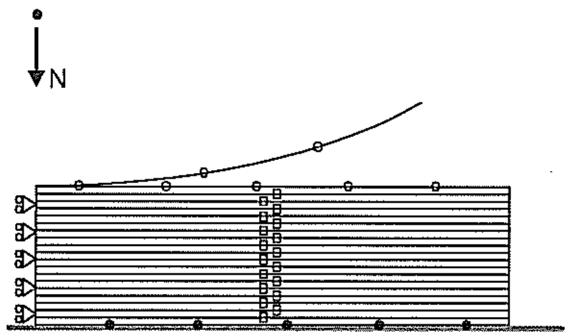

Figure 9 – Schematic of finite element analysis setup of the contact problem of a nip roller indenting stacks of sheets (Legend – N-Nip load, μ-Kinetic coefficient of friction)

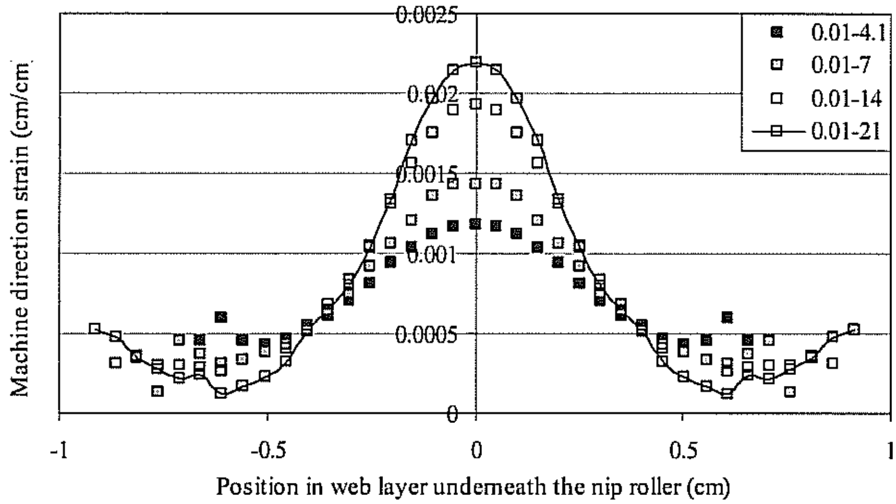

Figure 10 – Machine direction strain in the bottom surface of the top layer in contact with the nip roller (Legend – 0.01-4.1 Poisson's ratio $\upsilon_{r\theta}$ - Nip load (N/cm))

The rate of nip-induced tension was found to be much higher than what was observed experimentally. The effect of Poisson's ratio on the machine direction strain was studied and the results are shown in Figure 11. It is interesting to note that, the strain in the lower surface of the top layer changes significantly for increasing values of Poisson's ratio.

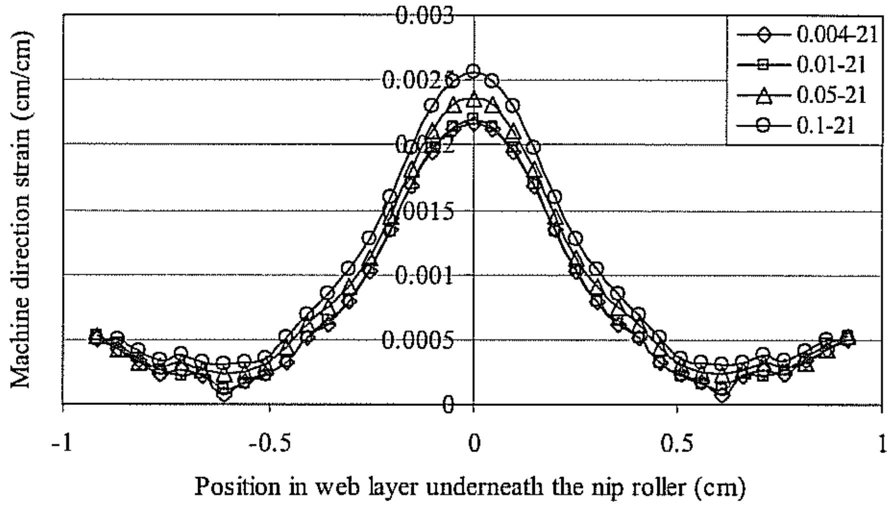

Figure 11 – Effect of Poisson's ratio $\upsilon_{r\theta}$ on the elongating strain in the lower surface of the top layer (Legend – 0.01-4.1 Poisson's ratio $\upsilon_{r\theta}$ - Nip load (N/cm))

DISCUSSION ON THE EFFECT OF POISSON'S RATIO ($\upsilon_{R\theta}$)

As was discussed, the results of the model with Poisson's ratio values of 0.01 or less did not yield results comparable to experimental values. In order to yield comparable WIT values, Poisson's ratio was iterated in the wound roll model. The iterated values of Poisson's ratio fell between 0.03 and 0.06 depending on the nip load and the results of the same are shown in Figure 12. Typically, researchers have quoted the value of $\upsilon_{r\theta}$ to be ranging from 0.01 to 0.02 for materials like newsprint, films, etc. Willet and Poesch [14] have recorded values of Poisson's ratio as high as 0.07 for magnetic tapes. Poisson's ratio $\upsilon_{r\theta}$ for non-woven webs has never been recorded or published to the knowledge of the authors.

Measuring Poisson's ratio $\upsilon_{r\theta}$ can be a challenge and the typical procedure involves subjecting a stack of web to a compressive pressure and observing the same for extension in the machine direction. A strain gage was mounted on the top surface of the web that was cut to 15.24 X 15.24 cm^2 and the instrumented web was placed in the middle of a stack of same material cut to the same dimensions. The stack was then compressed at a constant strain rate to observe for extensional strains in the web. The constitutive relations for an orthotropic material in plane stress conditions are shown in equation 6. Since the tangential stress is zero in the case of a stack test, the equations in {6} can be reduced to equation {7}. Poisson's ratio was then computed based on equation {7} and is shown in Figure 13. as a function of pressure. It is apparent that the Poisson's ratio $\upsilon_{r\theta}$ is pressure dependent similar to the radial modulus.

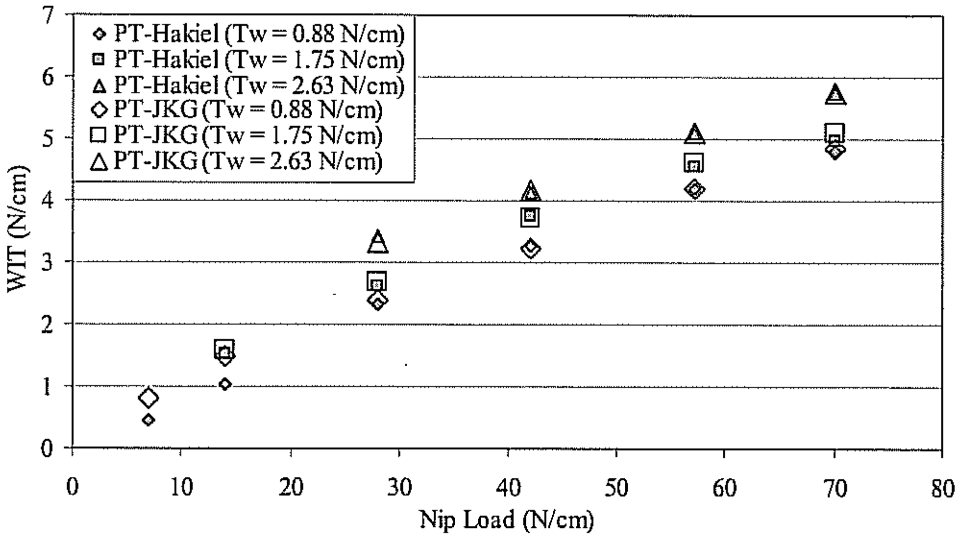

Figure 12 – Comparison of WIT inferred from pull-tabs using Hakiel's and Good's model (Legend PT – Hakiel – Pull-tab inferred WIT using Hakiel's model [10], PT – JKG – Pull-tab inferred WIT using Good's model [7])

$$\varepsilon_r = \frac{\sigma_r}{E_r} - \frac{\upsilon_{\theta r}\sigma_\theta}{E_\theta}, \varepsilon_\theta = \frac{\sigma_\theta}{E_\theta} - \frac{\upsilon_{r\theta}\sigma_r}{E_r} \qquad \{6\}$$

$$\upsilon_{r\theta} = -\frac{\varepsilon_r}{\varepsilon_\theta} \qquad \{7\}$$

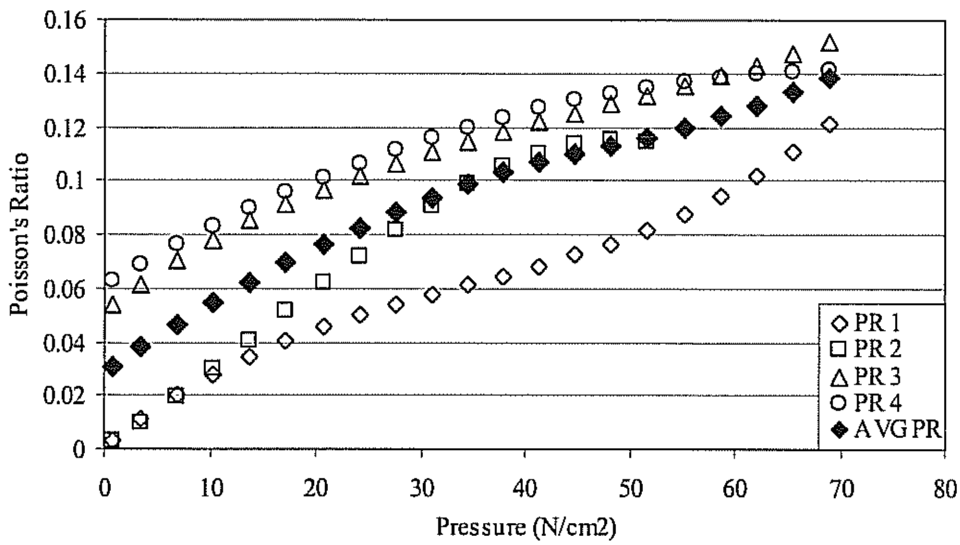

Figure 13 – Poisson's ratio ($\upsilon_{r\theta}$) as a function of pressure (Legend – PR - Poisson's ratio $\upsilon_{r\theta}$, 1 – Test number, AVG PR – Average Poisson's ratio $\upsilon_{r\theta}$ from 4 tests)

The validity of Maxwell's relation {8} can be questioned if $\upsilon_{r\theta}$ is indeed pressure dependent. Since all the wound roll and WIT models have assumed that Maxwell's relation is valid, it is important to understand the effect of the pressure dependence of Poisson's ratio. Hakiel's model predictions of radial pressure and circumferential tension do not change appreciably with $\upsilon_{r\theta}$, however, Good's model for WIT is extremely sensitive to $\upsilon_{r\theta}$. Although Good uses Hakiel's model for computing radial pressures and circumferential tensions, his WIT algorithm makes his model $\upsilon_{r\theta}$ sensitive. This was evident from results shown in Figure 12.

$$\frac{v_{\theta r}}{E_\theta} = \frac{v_{r\theta}}{E_r} \qquad \{8\}$$

CONCLUSIONS

The proportionality between wound-in-tension and nip load at lower nip loads has been shown to approach the kinetic coefficient of friction between web layers for those materials. In the non woven web that was tested, this value was much less. Although the first statement is true, the method of measurement of friction coefficient is very important as WIT is a result of slippage between the top two layers, which in turn is dependent on the coefficient of friction in the contact zone. In some cases wherein ASTM friction values do not yield accurate results, flat bed nip mechanics tests can yield representative values of friction that will be close to the actual friction in the nip contact zone. Although Hakiel's model in itself is not sensitive to $\upsilon_{r\theta}$, WIT algorithms such as the one proposed by Good [7] are extremely sensitive to $\upsilon_{r\theta}$. For the non woven web that was tested, model predicted values of WIT, radial pressure was found to be comparable with experimental values for varying values of $\upsilon_{r\theta}$ of 0.03 to 0.06. These values of $\upsilon_{r\theta}$ were verified with experimental measurements and $\upsilon_{r\theta}$ was found to be pressure dependent, which questions the validity of Maxwell's relation for webs.

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Wound-on-Tension in a Non-Woven Web

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Name & Affiliation Marko Ilomäki Sonoco Alcore	**Question** In one of the slides, I saw a finite element model of a layered structure. I would like to hear how many layers you modelled, because this is quite interesting. This is the first time I have seen this.
Name & Affiliation K. K. Balaji Oklahoma State University	**Answer** In flat bed nip mechanics tests, I used about 25 layers underneath the top layer which was subjected to web tension. In ABACUS, I modeled about 25 layers with the same properties as high density polyethylene. It was in fact homogenous in terms of numerical simulations, but the many thing we were interested in this situation, was to observe the effect of Poisson's ratio, the thickness direction of Poisson's ratio in extensional strains. What we did was model each of these layers as an orthotropic material. If you consider Maxwell's relation and the stress/strain relationships for orthotropic materials, these relationships have some enhanced assumptions built into them. There are certain materials laws that must be obeyed. When increasing Poisson's ratio, I would make sure that those material laws were in fact obeyed which might require a second parameter to change. For a particular nip load I might input 3-4 different Poisson's values and then increase the nip load. I would then compare the cases.
Name & Affiliation Tim Walker TJWalker & Associates	**Question** Nonwovens are quite vast in their designs. This is Tyvek, I believe you are working with?
Name & Affiliation K. K. Balaji Oklahoma State University	**Answer** Yes.
Name & Affiliation David Pfeiffer JDP Innovations	**Question** Twenty-five sheets is interesting because that is the number of sheets I used in my rolling nip mechanics in 1968 and I think there might be some additional constraints necessary for your finite element model to get proper agreement in the 25 sheet model. It should predict the same type of trajectories for the rolling nip kinematics to show where the instant centers are. But it might be necessary to constrain the sheets on the opposite side as well and model the tensile modulus properties of the sheets intermediate. It might not be giving you good agreement to let all the sheets be free for rolling expansion in the one direction.
Name & Affiliation K. K. Balaji Oklahoma State University	**Answer** I will consider that, thank you.

Name & Affiliation	Question
Marko Jorkama Metso Paper	I think Kilwa Arola presented three years ago a quite similar paper. If I remember correctly, his conclusion was that the Poisson's ratio did not have much effect on the nip induced tension. Do you have a comment on that?
Name & Affiliation	**Answer**
K. K. Balaji Oklahoma State University	I have read his papers. Your results are going to be very much dependent upon the way the boundary conditions are set. In my case, these are the boundary conditions. In his case they are different. His case was a dynamic analysis. He focused on the tensions that were induced in the top sheet by the rolling nip. I have tried to replicate his results and I was not successful at it, so I cannot really comment on that.