MEASUREMENT OF NIP INDUCED TENSION AND CONTACT STRESSES

By

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ABSTRACT

Wound-on-Tension (WOT) is the tension in the outermost layer of a winding roll that is created due to the incoming web tension and the tension induced by the nip roller called Nip-Induced-Tension (NIT). Kandadai and Good [1] presented the analysis of the contact mechanics between the nip roller, incoming web layer and the winding roll and the development of wound-on-tension in a winding process using an explicit finite element formulation. This paper verifies the results presented in Kandadai and Good. Strain in the nip contact zone measured using contact strain gages compare well to the results from finite element analysis presented in Kandadai and Good. WOT measured using load cells compare well to the WOT values from the finite element analysis. Details including measurement devices, instrumentation and techniques are discussed herein.

INTRODUCTON

In the field of winding and web handling, study of the effect of a nip roller on the wound rolls began in the late 1960's. Past studies typically fall either under theoretical or experimental nip mechanics. In this paper only relevant contribution in experimental nip mechanics as related to winding mechanics have been reviewed. Contributions in theoretical nip mechanics have been reviewed in Kandadai and Good [1].

The tension in the outermost layer of a winding roll is commonly referred to as Wound-On-Tension (WOT). The WOT has two components; one due to incoming web tension and the other due to the nip, called the nip-induced-tension (NIT). Studies of wound roll structure based on the WOT measurement started with investigations by Pfeiffer [2, 3]. He observed that the rolls wound in either center or surface wound condition with an impinging nip roller produced harder rolls, as compared to those wound without any nip loading. He used a flat bed rolling nip test bed to understand the nip

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mechanics in the winding process. The tester consisted of a rigid base on top of which a stack of sheets clamped to a load cell at one end were placed. A rigid nip roller traversed across these sheets inducing additional tension in the web. The tension on the exit side of the top sheet increases as the nip starts rolling and saturates to a final value commonly referred to as the NIT.

Rand and Eriksson [4] studied the behavior of the WOT in different winders using strain gages. Strain gages were attached to the webs to record the strain during the motion of the web around an impinging nip roller in a center winder with an undriven nip roller. They observed that the largest increase in circumferential stress occurred in the outermost layer directly under the nip and as more layers were wound, the circumferential stresses decreased. Pfeiffer [5-6] developed a specialized winder called WIT-WOT winder to measure the WOT. In a production winder, the incoming layer becomes the outermost layer of the winding roll. In the WIT-WOT winder, the outermost layer is peeled off of the winding roll, passed through a roller mounted on a load cell before returning the layer back to the winding roll. The roller mounted on the load cell serves to measure the WOT. Pfeiffer observed that the WOT increased with increase in nip load and web tension.

Good and Fikes [7] investigated the internal stresses in the wound roll with the presence of a nip roller. They measured the radial pressure inside the roll using force sensitive resistors (FSR). They used a model similar to Hakiel's [8] to iterate on the wound-on-tension required to produce the pressures measured using FSR's. When the WOT was computed for different nip loads in this manner, the data showed that the WOT was directly affected by web tension prior to the winder and through a constant of proportionality for nip load. This constant appeared to be similar in magnitude proportional to the kinetic coefficient of friction. Good, Hartwig and Markum [9] conducted a series of experiments to study how the WOT differed in a center winder with an undriven nip roller and a surface winder. Studies in a WOT apparatus similar to WIT-WIT winder used by Pfeiffer but with the ability to independently assess the effects of web tension and nip load showed that the WOT method was an interfering test. In surface winding, they observed that the dependence of WOT on web tension increased with increase in nip load. They also found that the NIT was independent of the method of winding.

Gueldenberg [10] used a digital image processing technique to analyze the NIT. The procedure employed combined the principle of the J-Line technique [11] and digital imaging technique that captured strain in each layer through photographs. J-Line technique is a method of studying the deformations in the wound rolls by striking a straight line and observing for deflection of the line due to further addition of the incoming layers. As the roll was wound, an ink jet printer shoots an ink jet at the incoming layer and at the same instant, a CCD camera captured the image. With the help of a counter/timer board and LabVIEW® data acquisition system this process was carried out as each layer was being wound. The purpose of the digital photograph is to determine the two dimensional displacement field of the observed objects in an image relative to a reference image. The marks on the edge of the layers are the observed objects in this case. By comparing the marks in two images, the displacement vectors can be calculated. Based on the strain fields, the tangential stresses due to nip were calculated. In addition, the total displacement of each layer was calculated.

In this paper contact strains in the nip contact zone along with WOT measurements using the load cell method similar to that employed by Good, Hartwig and Markum [9] is presented in the following sections.

MEASUREMENT OF WOUND-ON-TENSION

A closed loop rewinder that comprises an unwind and rewinder is shown in Figure 1A. This line is capable of running at very high speeds (≈1650 MPM) and also at very low speeds (≈0.3 MPM). The control system in the web line is such that the tension in the web can be held at a constant level even at zero velocity. This line is used for WOT and contact strain measurement. One of the ways in which the WOT in a winding process can be measured is by using the load cell method. In the load cell method the incoming web layer is pulled away from the winding roll prior to entering the winding roll, passed through an idler mounted on a load cell and then returned back to the winding roll such that the load cell measures the tension in the outermost layer. The measured tension is equivalent to WOT.

For the measurement of WOT using the load cell method the rewinder was instrumented with a WOT load cell assembly as shown in Figure 1B. A schematic of the WOT load cell system is described in Figure 2. The web from the unwind station passes through a sequence of nip stands that maintain constant web velocity and idlers that support the web between different spans involved. Before entering the rewind station, the web passes through a web guide and through an idler mounted on a load cell. This load cell measures the tension in the web upstream of the rewinder. Also, the signal from this load cell is used in a tension feedback system that maintains a constant web tension.

The web then wraps around an idler at 90^o angle before entering the nip contact zone. The purpose of this idler is to ensure that the web enters the nip contact zone without wrapping the nip roller. Normally, the web would enter the winding roll beyond the nip contact zone. However, in order to measure WOT, the web is peeled away from the winding roll as shown in Figure 2 and passed through an idler that is mounted on a load cell that measures the WOT. The web is then returned to the winding roll as shown in the schematic. Two idlers, one upstream and one downstream of the roller mounted on a load cell that measures the WOT ensures that a constant wrap angle is maintained throughout the winding process. A data acquisition system acquires the tension, nip load and WOT signals and a program written in LabVIEW® continuously records the data as the roll is being wound. The data from a typical experimental run is shown in Figure 3 and is for a center wound roll at a web tension of 5.25 N/cm and a nip load of 16.5 N/cm at 8.3 mpm. The material used is a 1000 gage (0.254 mm) PET whose material properties are given in Kandadai and Good [1].

Since the web tension, nip load and WOT remain constant as a function of wound roll radius, the WOT at different nip loads can be measured in a single test as shown in Figure .4. In this test, the nip load is decreased in a sequence of steps during the course of winding the roll. At each step the nip load is maintained constant until at least some amount of material is wound at that nip load level. The data in Figure 4 represents the behavior of the WOT in center winding at a constant web tension of 5.25 N/cm and at different nip loads.

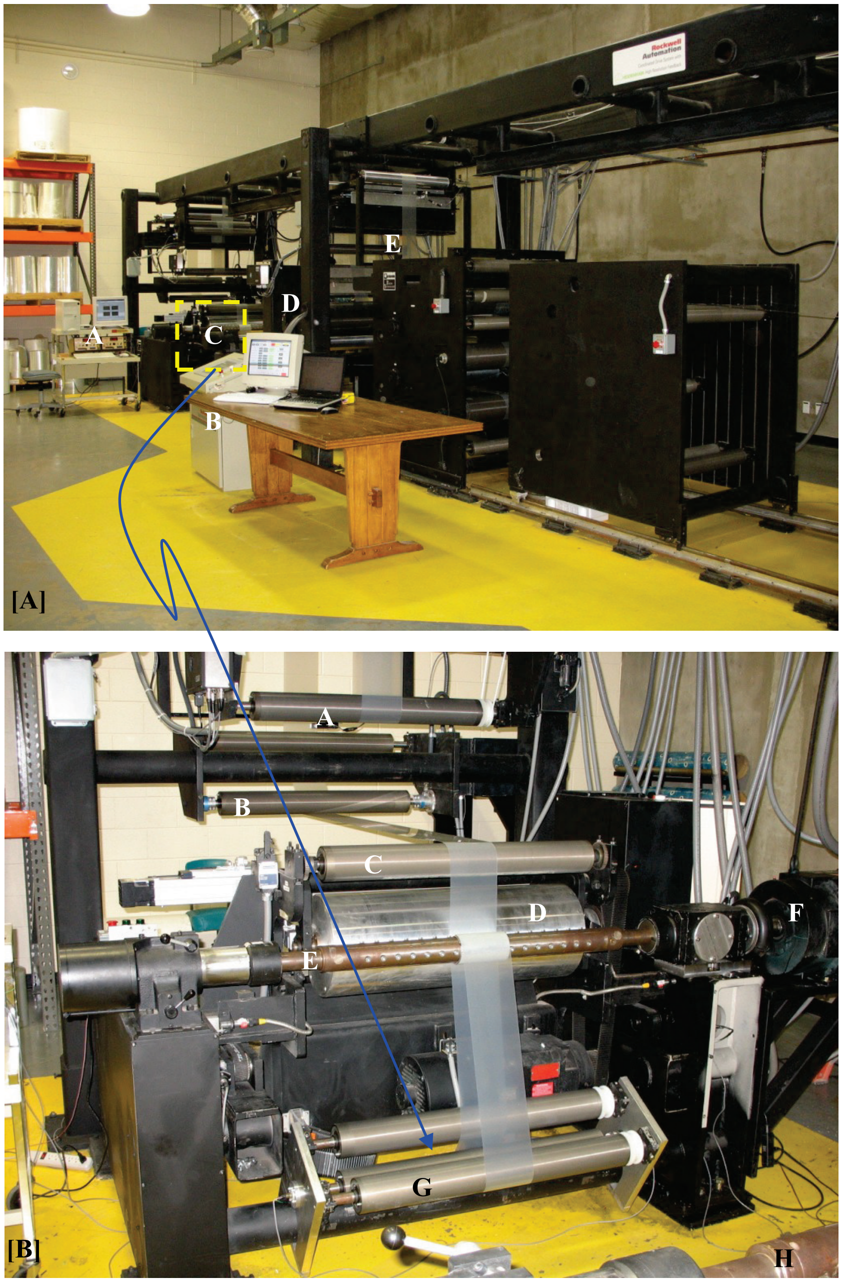

Figure 1 – [A] High Speed Winding Machine (Legend: A-LabVIEW® Data acquisition system, B-Winder control stand, C-Rewind assembly with WOT load cell arrangement, D-Unwind station, E-Intermediate nip stands for velocity control) [B] Close-up of the WOT load cell arrangement (A-Upstream web guide, B-Upstream tension load cell, C-Idler that controls nip roller web wrap, D-10 inches diameter nip roller, E-rewind core shaft, F-Rewind motor, G-WOT LC assembly, H-Unwind shaft).

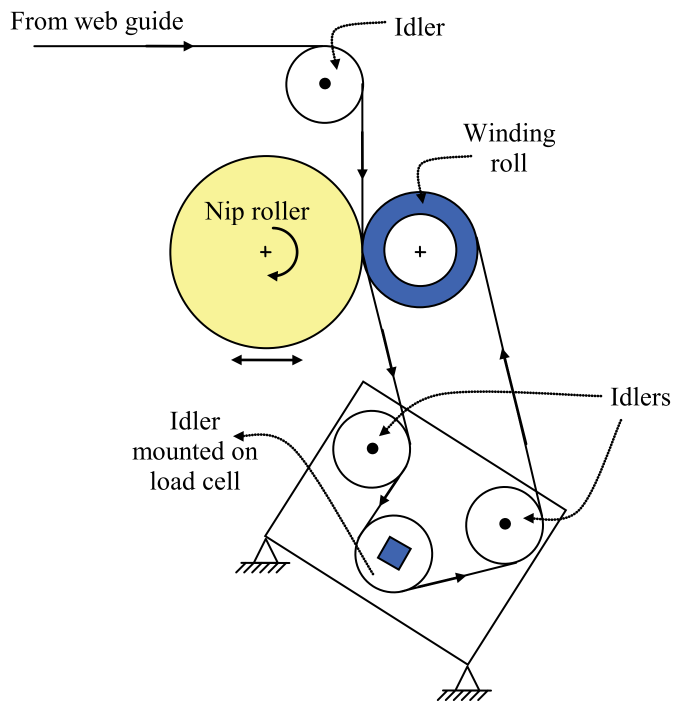

Figure 2 – Schematic of the WOT load cell assembly.

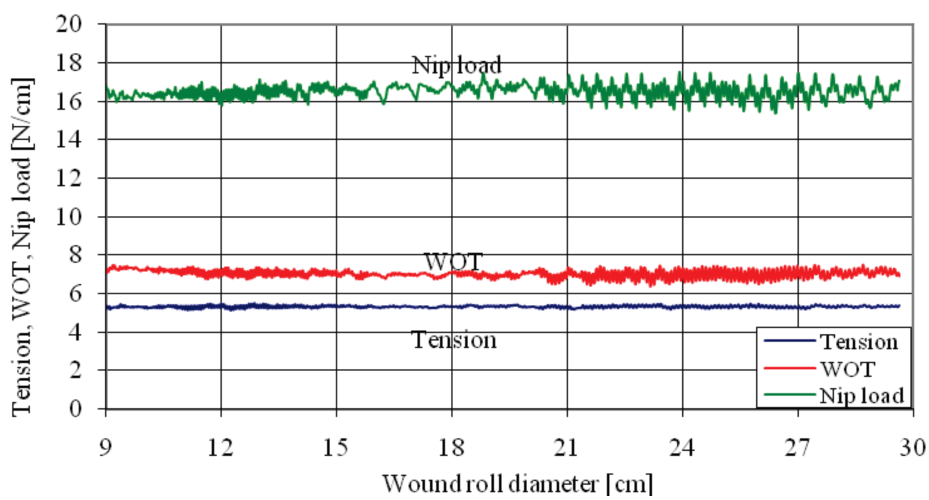

Figure 3 – Behavior of web tension, nip load and the WOT in center winding.

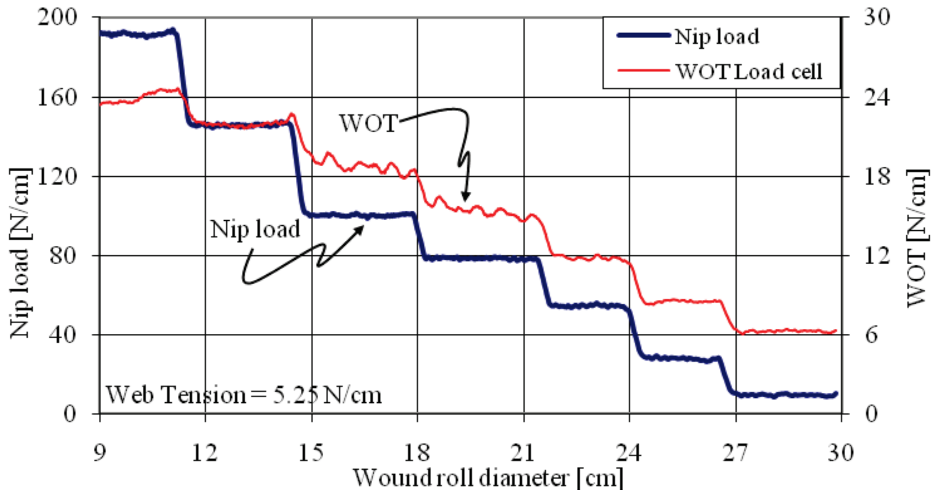

Figure 4 – Behavior of the WOT at different nip load levels.

COMPARISON OF EXPERIMENTAL MEASUREMENT OF WOT WITH FINITE ELEMENT MODEL RESULTS

Kandadai and Good [1] presented the finite element model results for WOT at various nip loads. The model results are compared with experimental measurements of WOT using the load cell method as shown in Figure 5. The experimental data shown in Figure 5 is calculated by averaging the nip load and WOT shown in Figure 4 at each nip load level. Overall, the winding model results agree well with experimental measurements even though the load cell method may be an interfering technique. In this case, the WOT initially increases linearly for nip loads less than ≈ 100 N/cm and starts to taper off beyond this level. Observe that the slope of the linear part is approximately equal to 0.14.

Kandadai and Good [1] used a value of 0.16 for $\mu_{Web/Web}$, the dynamic coefficient of friction in their Abaqus Model and this value was measured using flat bed rolling nip tests. Kandadai [12] demonstrated that measurement of $\mu_{Web/Web}$ using a flat bed rolling nip test bed mimics the winding contact conditions closely than an ASTM measurement method. Due to the same reason the winding model results compare well with the experimental measurements of the WOT. Although there is some minor disagreement between the results the difference can be due to other factors including the potential for the load cell method of WOT measurement to be an interfering test.

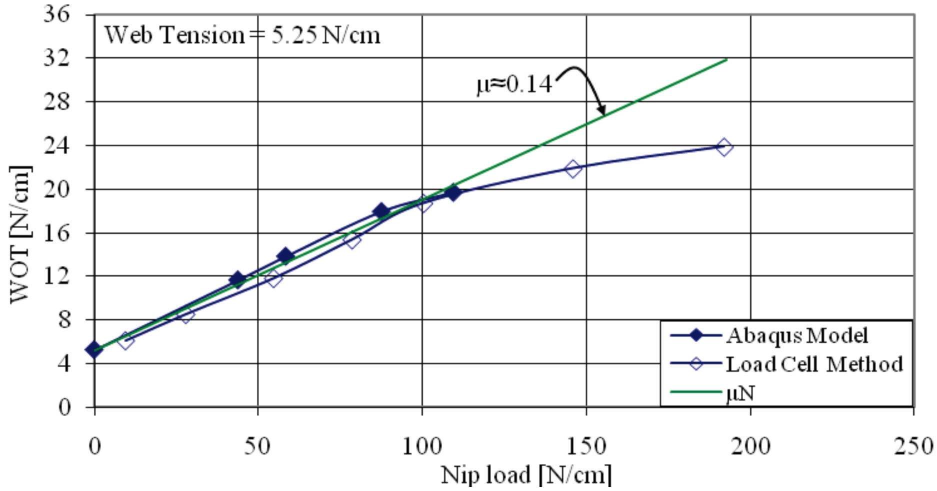

Figure 5 – Comparison between experimental and model results of WOT in center winding.

MEASUREMENT OF CONTACT STRESSES

In this section the behavior of the stresses in the contact zone between the winding roll and the nip roller is discussed and compared to the model results. Stain gages have been used to measure the WOT by Rand and Eriksson [3]. However they used the strain gages to measure the overall WOT in the incoming web. Strain gages that have sensing area much less than the contact width are commercially available. A schematic of the strain gage that is used to measure the contact strains and, hence the stresses is shown in Figure 6.

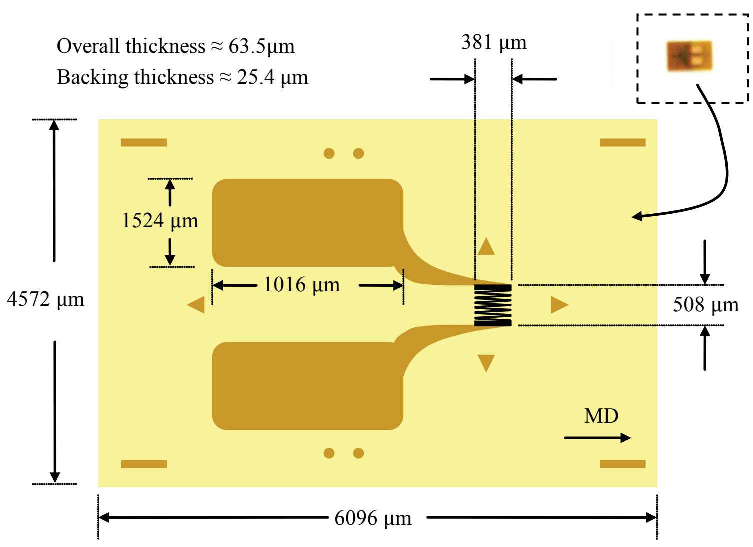

Figure 6 – A schematic of the contact strain gage.

The gage consists of a constantan grid completely encapsulated in polyimide, with large, rugged copper-coated tabs. This type of gage is primarily used for general-purpose static and dynamic stress analysis when the normal operating temperatures of the strain gage is between -100^o F and 400^o F. The resistance of the strain gage is 120±0.3% ohms and has a gage factor of 2.085. The strain gage has a range of ±3% and has a fatigue life of 10^5 cycles at ±1500 microstrain (μm/m). The sensing length of the strain gage is 381μm is much smaller than the contact width. When strain gages are used for strain measurements in thin films, the effect of reinforcement caused by the strain gage needs to be evaluated and this factor is referred to as the reinforcement factor. The PET film used in experiments is 254 μm thick and is ten times thicker than the strain gage. The reinforcement factor is calculated as the ratio of the measured strain compared to theoretical strain and for this web it was equal to one.

Measurement of the strain in the web in the free span and on the wound roll is accomplished using the following steps:

1. The surface of the web is prepared and conditioned such that a strain gage can be glued on. The location for the strain gage along the web length is chosen such that the strain gage will enter the wound roll as the fifth lap is laid on. This ensures that the comparison with model results will be made for the same lap. Recall that the WOT is calculated as the average 'σ_{11}' stress in the fifth lap from ABAQUS model results presented in Kandadai and Good [1].
2. The strain gage is then glued on to the web surface and 30 AWG wires are soldered to the copper tabs with minimal solder such that the solder joints do not protrude significantly on top of the strain gage surface. These wires are connected to a strain indicator.
3. Before the winding process is started, the tension level in the web is brought to the desired level using the winder controls. The winding process is then started and as the strain gage passes beyond the idler and enters the span between the idler and the winding roll as shown in Figure 7, the winding process is temporarily halted. During this time, the web tension is held constant.
4. The strain gage output is balanced to read zero such that the effect of web tension is cancelled.
5. The winding process is then continued and the strain in the web is monitored and recorded continuously using a data acquisition system.

The strain gage output is recorded in a center winding process wherein the nip roller is not used and at a constant web tension of 5.25 N/cm. The behavior of the strain in the free span and on the wound roll is shown in Figure 8. Note that the results of three different tests under the same winding conditions are shown in the figure. Observe that the strain measurements are very repeatable and compare well to theoretical bending strain calculated using linear bending theory as given in Equation 1. Also, the tension in the web remains constant through the winding process even through the pause period when the strain gage output is balanced.

$$\varepsilon_{Bending} = \frac{u}{R} \qquad \{1\}$$

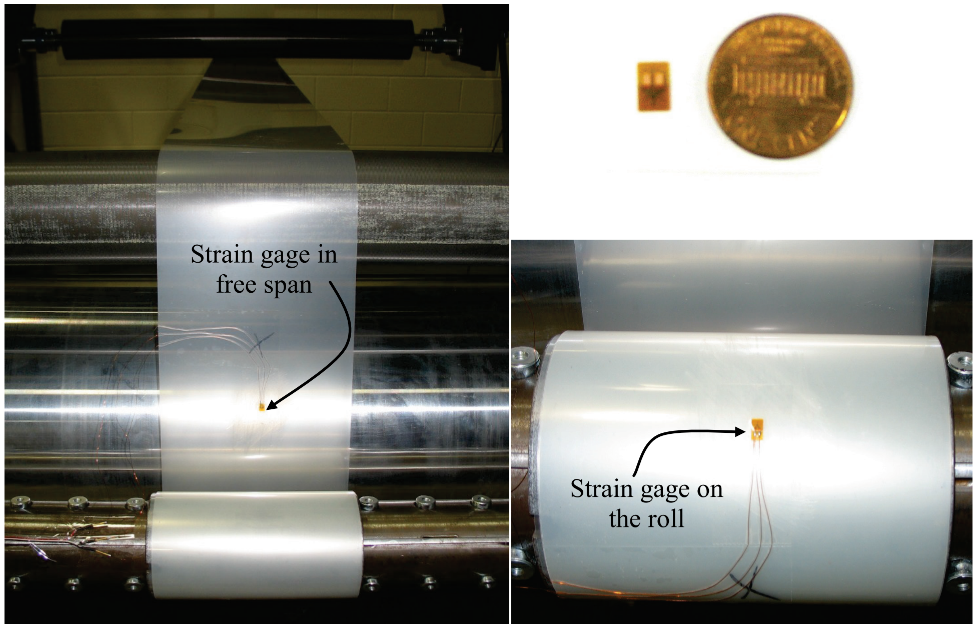

Figure 7 – Strain gage on the web in the free span and on the wound roll.

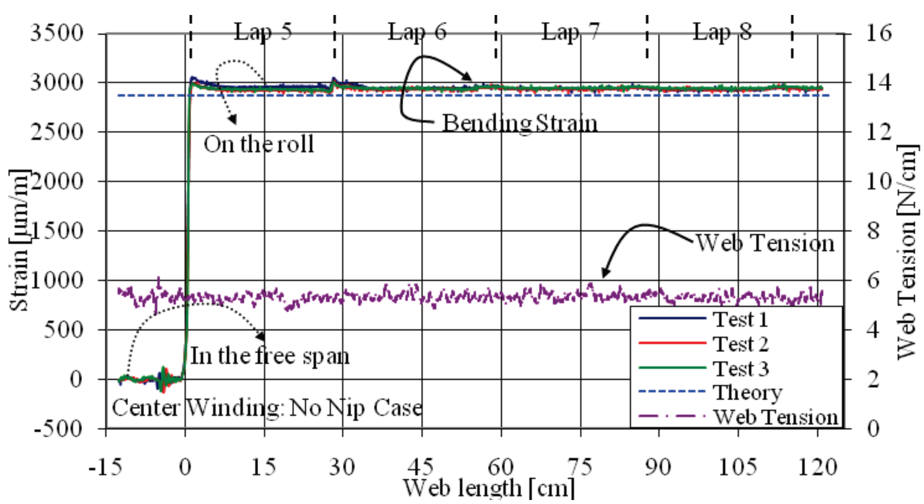

Figure 8 – Behavior of web tension and strain in the web measured using the contact strain gage as a function of web length.

When a nip roller is used and a nip load of 43.8 N/cm is applied during the winding process, the behavior of the stresses on the wound roll is shown in Figure 9. The stresses are calculated by multiplying the measured strain with the machine direction modulus. Since a nip roller is used in this case, the strain in the web measured using the strain gage includes both the bending component as well as the nip induced component of the strain. So the top and the bottom surface strains need to be measured in order to accurately compute the WOT. Figure 9 shows both the top and bottom surface stresses in the web on the wound roll.

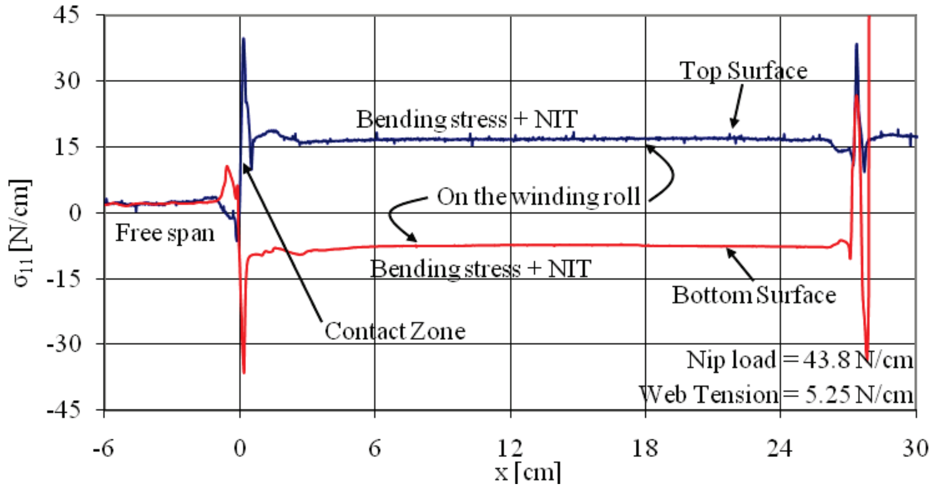

Figure 9 – Behavior of the top and bottom surface stresses in the web in a center winding process at a web tension of 5.25 N/cm and a nip load of 43.8 N/cm.

The measured stresses in a center wound roll with an undriven nip roller at a nip load of 43.8 N/cm and a web tension of 5.25 N/cm is compared to the model results for the top and bottom surface stresses in Figure 10 and Figure 11 respectively. In the free span the average value of the stresses compare well to the model results. In the contact zone, the overall behavior of the contact stresses is very similar between the model results and the experimental measurements. The peak stresses in both the figures between the model results and experimental measurements do not match and this is due to the solder joints. As the nip roller rolls on top of the solder joints in the strain gage the bending stresses become very high as seen in the figures. Note that the contact width is also comparable between experimental values and model results.

When the top and bottom surface stresses are compared on the wound roll, they differ considerably between model and experimental values. However when the average of the top and bottom surface stresses is compared to the model results, they agree well as shown in Figure 12. The actual magnitude of the surface stresses do not compare well on the wound roll because of many factors like effect of backing thickness, significant bending and unbending of the web experienced in and beyond the contact zone. The average stresses compare well because, the effects explained above cancel each other between the top and the bottom surface stresses to leave the membrane stresses unaffected.

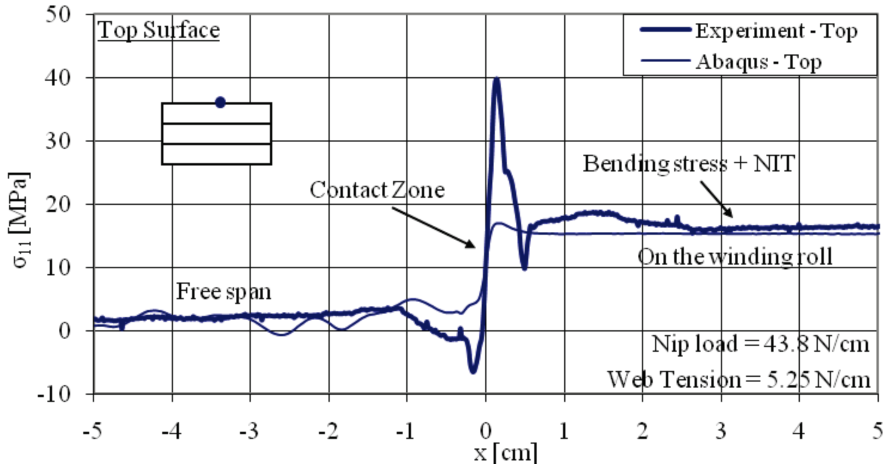

Figure 10 – Comparison of the top surface stresses in the free span, contact zone and on the wound roll between the model results and experimental measurements.

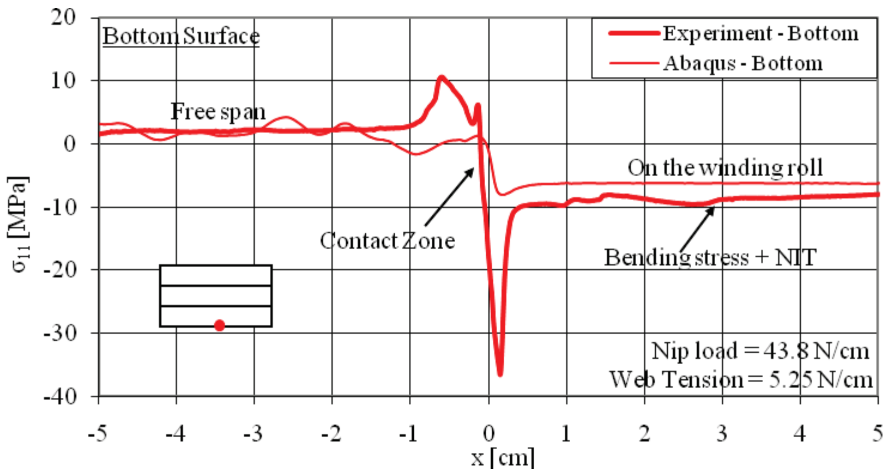

Figure 11 – Comparison of the bottom surface stresses in the free span, contact zone and on the wound roll between the model results and experimental measurements.

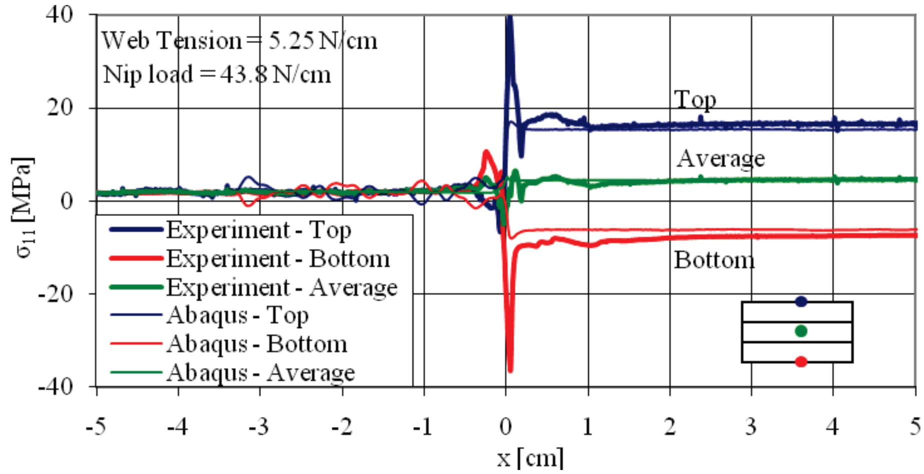

Figure12 – Comparison of the top, bottom and average stresses in the free span, contact zone and on the wound roll between the model results and experimental measurements.

The membrane stresses computed as an average of the top and bottom surface stresses is averaged and is represented as the WOT in the outermost layer of a winding roll. This value is compared to the model WOT results and to the WOT measured using the load cell method as shown in Figure. 13. Note that the measurement of WOT using this method is very difficult and only two different nip loads of 43.8 N/cm and 87.6 N/cm respectively were attempted. The figure shows that the measurement of WOT using the strain gage compares well with the model output. The verification efforts discussed thus far show that the model results compare well with experimental measurements.

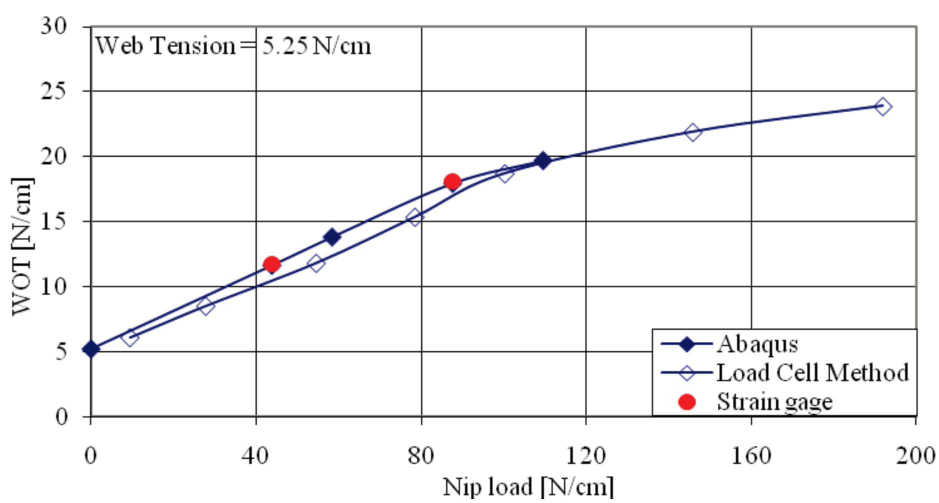

Figure 13 – Comparison between WOT from model output, load cell method and strain gage measurements.

CONCLUSIONS

WOT measured using the load cell method compares well with the model results presented in Kandadai and Good [1]. Strain gages with sensing area much smaller than the width of the nip contact zone can be used to measure the contact surface and bending strains. The results show that the contact strains measured using the strain gages compare well to the model results. Also, WOT calculated from measured strains agree well with model results.

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Measurement of Nip Induced Tension and Contact Stresses	**B. K. Kandadai & J. K. Good**, Oklahoma State University, USA

Name & Affiliation	**Question**
Dan Perdue, Goss International	When data matches simulations poorly that is troublesome. When data matches simulations really well that can also be troublesome. In regard to relative stiffness of strain gauge as it is attached to the web material itself, was the strain gauge much less stiff than the material you were attaching it to?
Name & Affiliation	**Answer**
Balaji Kandadai, Kimberly-Clark Corporation	These simulations and tests were conducted on a 1000 gauge polyester web. This web was selected to minimize any reinforcement the strain gage and the mounting adhesive might have on the web. In off-line tests I measured the reinforcement factor for the strain gauge by subjecting the web to a known tensile strain and measuring the strain using the strain gages. Test and theory agreed and thus it was proven the reinforcement factor was negligible for this combination of strain gage and web.
Name & Affiliation	**Question**
Cagri Mollamahmutoglu, Oklahoma State University	My question relates to your chart of nip-induced-tension versus the nip load. Your data fits very well. We see a bilinear behavior – at low nip load we see the envelope behavior which is limited by the total nip load and friction, and at higher nip load there is deviation from the envelope behavior but it also appears to be linear with respect to nip load. Can you say something about that linearity?
Name & Affiliation	**Answer**
Balaji Kandadai, Kimberly-Clark Corporation	In this case we are witnessing what might appear to be linear behavior in Figures 1 and 4 at higher nip loads but it is not. Dr. Good has presented previous results that show that once the wound-on-tension (WOT) deviates from the initial linear range that the slope decreases nonlinearly until finally the WOT is constant with respect to nip load (hence zero slope). This behavior is governed by how large the stick zone is on the bottom surface in comparison to the total contact zone width. When stick is occurring over all the contact zone width the WOT will become independent of nip load. It is not necessarily linear in the second phase even though it may appear so in my figures over a limited domain in nip load.
Name & Affiliation	**Question**
Dilwyn Jones, Emral	I believe your nip roller was rigid. Could you comment on what might happen if the nip roller had a rubber layer on it? Would this still be applicable?

Name & Affiliation	Answer
Balaji Kandadai, Kimberly-Clark Corporation	Dr. Good has conducted experimental WOT measurements when a rubber covered nip is employed. For a high durometer cover with a Poisson's ratio approaching 0.5, the WOT will be comparable to that of a rigid nip roller. If you were to use a foam covered roller with low durometer and Poisson's ratio, you might see a completely different behavior. You may not have any WOT at all.
Name & Affiliation	**Question**
Kevin Cole, Optimation Technology	When the web passes through the nip obviously the rigid pressure roller is going to indent the outer layer creating a curvature that is in reverse to the radius of the roll. I am a little confused why the top bending stress is positive while the bottom bending stress is negative. I was thinking that it would be the opposite. Do you have an explanation?
Name & Affiliation	**Answer**
Balaji Kandadai, Kimberly-Clark Corporation	On the top surface, that area is the contact zone. The rest is not contact. So once it passes the contact zone, you are going to see extension on the top surface. The bottom surface is going to go into compression.
Name & Affiliation	**Question**
Kevin Cole, Optimation Technology	In the contact zone would the web bend such that the curvature is such that the bending stress is positive on the bottom and negative on the top?
Name & Affiliation	**Answer**
Balaji Kandadai, Kimberly-Clark Corporation	No. This web is very stiff in the radial direction, thus the indentation caused by the nip and nip load can be very small. The lower surface of the web is attempting to conform to the layer beneath while the upper surface is attempting to conform to the surface of the nip. Note that the nip diameter was 10.16 cm while the core diameter was 8.89 cm. In this case the curvature of the web was such that compressive stress was expected on the lower surface while tensile stress was expected on the upper surface. This situation could reverse if the nip diameter was smaller than the core/wound roll diameter.
Name & Affiliation	**Comment**
J. K. Good, Oklahoma State University	Kevin, Balaji is trying to verify the modeling results that you saw earlier. There are only about 5 laps of material on the rigid core. As the wound roll got larger, you would see more bending strain due to the indentation of the material when you had several hundred wraps on. The bending strains that you are seeing predominantly are those associated with the core since it is smaller in diameter than the nip.
Name & Affiliation	**Question**
Michael Desch, Technical University of Darmstadt	In Figure 4 you showed the top and bottom surface stresses. Please explain why the top surface stress has a larger magnitude than the bottom surface stress. It is not the same value – positive and negative.

Name & Affiliation	Answer
Balaji Kandadai, Kimberly-Clark Corporation	The overall layer is experiencing the nip-induced-tension which subjects the web to a tensile, positive stress. The web is also experiencing bending stresses and strains as the outer layer attempts to conform to the layer beneath it. Thus the combination of these stresses result in a tensile stress on the upper surface that is larger in magnitude than the compressive stress on the lower surface. The strain and stress caused by the nip-induced-tension is responsible for this asymmetry.