THE EFFECT OF THE ZONE OF SLIPPAGE BEHIND A NIP ROLL UPON WOUND-ON-TENSION

By

CHIHYIH CHENG

Bachelor of Engineering

National Taiwan Institute of Technology

Taipei, Taiwan

1990

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the degree of
MASTER OF SCIENCE
July, 1994

OKLAHOMA STATE UNIVERSITY

THE EFFECT OF THE ZONE OF SLIPPAGE BEHIND A NIP ROLL UPON WOUND-ON-TENSION

Thesis Approved:

James K. Good

Thesis Adviser

C. E. Price

R. L. Lowery

Thomas C. Collins

Dean of the Graduate College

ACKNOWLEDGMENTS

I wish to express my sincere appreciation to my graduate advisor, Dr.J.K.Good, for his constructive guidance, intelligent supervision and moral support during my graduate study. My sincere appreciation extends to my other committee members Dr.C.E.Price and Dr.R.L.Lowery for serving on my advisory committee..

Moreover, I wish to express my sincere gratitude to Mr. Nandakumar, Mr. Ronald Markum and those who provided suggestions and advice during this study.

This publication is a result of research which was funded by the Web Handling research Center of Oklahoma State University. I would like to thank the sponsors of the WHRC for supporting this research. The sponsors include the National Science Foundation, the Noble Foundation, the State of Oklahoma and an industrial consortium of which Beloit Corporation, Polaroid Corporation, Velmet-Appleton Inc., Fife Corporation, Hoechst-Celanese Corporation, 3M Company, Mobil Chemical Company, E.I.Dupont de Nemours & Co, Inc., ICI Americas, Kimberly-Clark Corporation, Mead Corporation, Westvaco Corporation, James River Graphics, Eastman Kodak Company and Union Camp Corporation are members.

I would also like to thank my parents who have encouraged and inspired my educational endeavors.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure Page

NOMENCLATURE

b	Semi contact width (Inch)
P	Nip load (Lbf)
l	Contact length (Inch)
E	Modulus of elasticity (Psi)
υ	Poisson's ratio
d	Diameter of roller (Inch)
p_x	Hertzian pressure distribution
ε_x	Strain in machine direction (x-direction)
σ_x	Stress in machine direction (x-direction) (Psi)
μ	Kinetic coefficient of friction
T_1	Wound-on-tension (Lbf)
T_2	The portion of wound-on-tension measured by the load cell (Lbf)
NRD	Rolling Distance (Inch)
L_i	Distance between clamped support and the nip roller prior to rolling(Inch)
C	deformation contribution due to unit displacement of the nip roller
N'	Nip load (Pli)
h	Caliper of web (Inch)

CHAPTER 1

INTRODUCTION

A web is a continuous, flexible strip of material such as paper, metal foil, plastic film, textiles and non-woven materials which are stored, at least on an intermediate basis, in wound rolls to accommodate high speed, automated manufacturing operations. Web handling is the science involving the mechanics and dynamics of transporting webs from unwind stations, through process machinery, to rewind stations.

Winding is an integral operation in almost every web handling process. During the course of a web becoming a final product, it may be unwound and rewound several times depending upon the number of web processes which must be performed. Winding exerts stresses upon webs which often can degrade the quality, but it may be seen that the wound roll form is the most efficient and opportune storage format for high speed automated manufacturing processes. It is desirable to control the winding tension of a wound roll to get a stable roll that is free from defects, which can result from too little or too much stress being wound into the roll.

Much of the winding, which is currently performed, is accomplished via a technique which is known as center winding with an undriven nip roll (see Figure 1). This technique requires that the winding torque be provided to the core of the winding roll. An undriven nip roll follows the outside radius of the winding roll. One purpose of the nip is to help exude wound-in air from the wound roll which could lead to an unstable, loosely wound roll package, which is apt to sustain web defects during web storage or transport. The second purpose is to provide an increased tension in the web, above the web line tension, for the winding process.

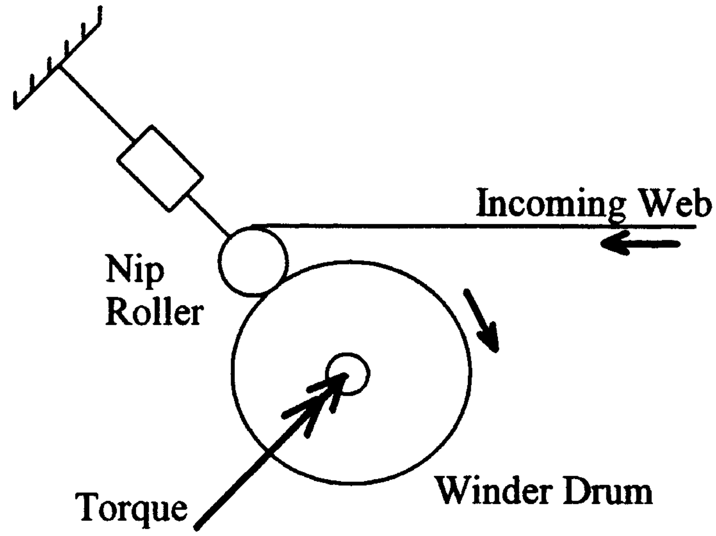


Figure 1. Center Winder with Undriven Nip

Most of the earlier experimental studies on nip mechanism of the WHRC[1] were carried out on the flat nip mechanics test bed. In this study, an attempt will be made to study the effect of the circular wound roll geometry upon the saturated level of the nip induced tension. The experiments were carried out on a circular nip mechanics test bed. Finite element analyses were performed to help explain the results.

A literature review and the objectives are compiled and presented in Chapter II . A description of the experimental setup is presented in Chapter III. The experimental results are presented in Chapter IV. The finite element analysis which was performed and the results of those analyses are discussed in Chapter V. Chapter VI contains a discussion of the results and Chapter VII closed with conclusions and future work.

---

[1] Web Handling Research Center, Department of Mechanical and Aerospace Egineering, Oklahoma State University.

CHAPTER 2

LITERATURE REVIEW AND OBJECTIVE

Literature review

Pfeiffer [3] finished the first study on the effect of nip roller diameter upon a layered structure, a stack of paper. He observed that the nip roller produces a strain inducing mechanism, which increases the web tension on the outgoing side of the nip roller. He correlated the nip induced tension with the nip load, the diameter of the drum on which the web sheet was wound and the web properties. He also noted that, as the rolling progresses, the tension in the layered sheets builds to an asymptotic level. Moreover, a small nip roller was able to produce greater tension.

Pfeiffer [3] noted in his tests that the sheets nearest to the nip would displace in the direction of the moving nip, while some of the sheets near the bottom of the stack would travel in the opposite direction. Using photomicrographs taken from the side of the nip/stack interface, he determined that the instant center of rotation did not lie at the nip/stack interface and, in fact, it was located beneath the interface in the stack. Sheets above the instant center would travel in the direction of the rolling nip, while the sheets below would travel in the opposite direction. An increase in the number of sheets in the stack led to an increase in the nip induced strain. He was able to come to the conclusion that the nip induced stress attains a constant level during the winding of an actual roll, as long as nip force is held constant.

2.1 Experimental Studies

Good et al [1] performed the first verification of this mechanism with a setup in which a nip roll was driven over a thin strip of aluminum restrained at one end, and strains close to the restrained end were monitored using strain gauges. The elongating strain data correlated to the distance moved by the nip roller. It was shown that the nip induced tension tends to saturate after a certain rolling distance. A general form for the nip induced stress, they determined experimentally, is of the form :

$$\sigma_x = C_1[1 - e^{-C_2 x}] + C_3 \qquad \{1\}$$

where σ_x : represents the total machine direction stress

x : represents the distance moved by the nip roller

C_1 : represents the saturated value of the nip induced tension

C_2 : represents the growth rate of the nip induced stress

C_3 : represents the pre-tension.

Good et al [1] have determined the mechanism of nip induced tension. The mechanism is an elongating machine direction strain which exists beneath the nip roll location on the lower side of the web, which is in intimate contact with the wound roll. This elongating strain is due to the compressive Hertzian-like contact stresses which exist through the depth of the web beneath the roller. As the elongating strain advances with the moving nip roll, web material attempts to advance in front of the nip and contract towards the nip in the back of the rolling nip. If the web material in the back of the nip is constrained, a net increase in tension will result due to the nip. It is also mentioned that the saturated value of nip induced tension is defined by summing the product of nip load and kinetic coefficient with the web line tension. It was found that the saturated value of the nip induced tension occurs after short nip rolling distances, when compared to the roll circumference.

Prabhakar[4] performed research on the flat test bed, which can provide nearly 100 inches of rolling distance for the nip roller and can accommodate nip rollers with diameters up to 60 inches. He concluded that the rate of nip induced stress depended on the nip diameter, and the saturated value of nip induced stress depended on both nip load and nip diameter.

Markum [2] constructed the circular test bed in his research. He verified that the results obtaining on the flat test bed in Wu's [9] work were similar to the results on the circular test bed with the similar set up manner. He observed that effect center winding with an undriven lay on roller are coefficient of friction of the web against itself, the nip load and the web line pretension. He also noted that nip diameter and wound roll diameter do not effect the nip induced tension to any degree. To find the correct saturated value of the nip induced tension, Markum installed an idler on the circular nip mechanics test bed to isolate the first layer of web (see Figure 2).

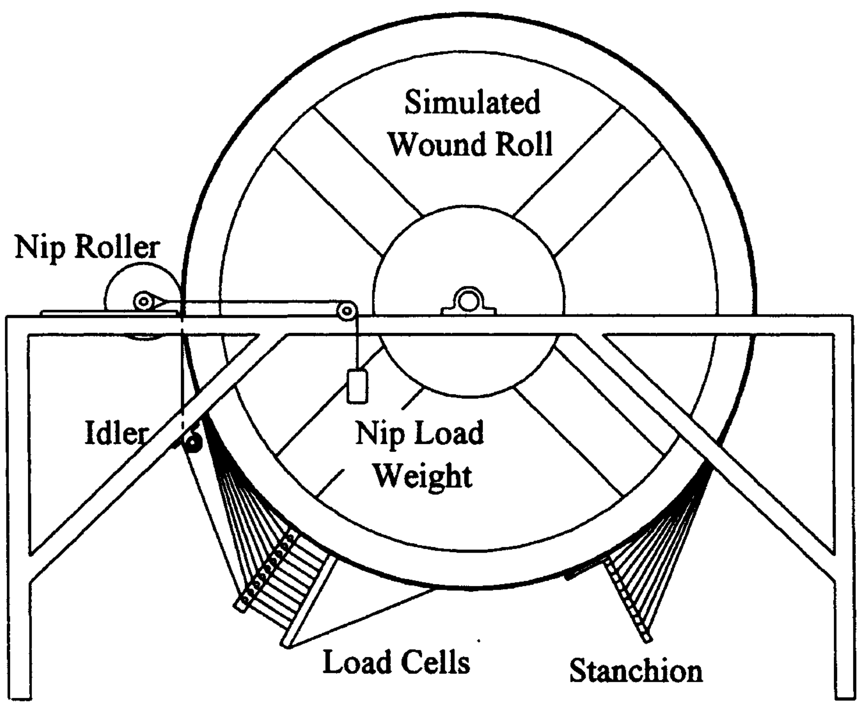


Figure 2. Circular Nip Mechanics Test Bed with Idler

Through this idler, the first layer of web was held away from the under layers so that the only contact that the first layer had with the second layer is in the immediate area of the nip roller. From the experimental results of this isolated layer, he discovered the nip induced tension saturated within 3 inches of the starting position and the saturated value of nip induced tension is close to the value of multiplying the kinetic coefficient of friction and nip load. This result indicated that slippage between webs was occurring most of the time.

2.2 Finite Element Analysis

Using finite element analysis, Good et al[1] completed a simulation successfully. A model was generated to simulate the problems of nip mechanics. Similar models were composed by Nandakumar[8], Wu[9] and Prabhakar[4] in their studies on nip mechanics.

In all the above, several assumptions were made while modeling these problems using finite element analysis

1. The problem is considered as a two dimensional plane strain problem as the width of the web is quite large comparing to the thickness.
2. There is no displacement along the width of the web.
3. The problem is solved in the elastic region.
4. Viscoelasticity is not considered for the web material.
5. Friction exists between the web and the test bed.

The web was modeled as two-dimensional plane strain elements. Gap elements were introduced at the lower surface to accommodate slippage between the web and test bed. Spring elements were introduced at the clamped end to represent the axial stiffness of the web between the nip and the clamped support. The problem of a nip rolling over an elastic material was approximated as a Hertzian contact problem. The lower boundary of the specimen was fully restrained vertically, but only partially restricted horizontally, to accommodate slipping and, hence, friction. In successive time steps, the Hertzian pressure profile was moved to the right one element width.

Good et al [1] observed the elongating machine direction strain on the lower surface of the web strip and found that the strain plot was nearly identical for all the time steps, except that the plot was moved one element to the right at each time step. They noted that the elongating strain, which exists across the nip, is due to the combination of the Hertzian pressure profile moving to the right over the upper surface and the frictional forces on the lower surface. Therefore, the area under the strain plot is a measure of the deformation contribution from the nip rolling over a plane strain element, and was converted to the deformation contribution due to unit displacement of the nip roller. Good et al[1] formulated an equation for the strain in the web as:

$$\varepsilon_x = \frac{C * NRD}{L_i + NRD} \qquad \{2\}$$

where C : represents the deformation contribution due to unit displacement of the nip roller

NRD : represents the total nip rolling distance

L_i : represents the initial distance between the clamped support and the nip roller prior to rolling.

For large rolling displacements, the nip induced strain predicted from equation {2} will approach a constant value. From earlier observations, it is seen that this constant value can be no greater than the product of the coefficient of friction and the nip load.

Prabhakar[4] proved that increasing nip diameter decreases C and that the saturated value of the nip induced tension can be much less than the product of the coefficient of friction and the nip load.

Objective

On a wound roll, or on a circular nip mechanics test bed, the web tension, and the nip induced tension in the outer layer, serve to create a normal pressure between the first and second layer. This normal pressure, multiplied by the surface area of contact and the coefficient of friction, produces a resistive force which will affect the nip induced tension, by allowing slippage of the outer layer to occur over a sector prior to arrest. It is the objective of this research to study the sector over which slippage occurs and how this affects the final value of the wound-on-tension.

CHAPTER 3

EXPERIMENTAL SETUP

The experimental set up in this research includes two major components which are the circular nip mechanics test bed and data acquisition system. They will be described in following paragraphs.

3.1. Circular Nip Mechanics Test Bed

In order to complete the experiments of this research, a circular nip mechanics test bed was employed(see Figure 3). It consists of a frame, the large diameter roll which simulates a wound roll, the nip roller, the drive system and two weight hangers. On this circular test bed, the tension in up to 9 layers of web can be monitored with strain gauge load cells. One end of the web is attached to a load cell mounted on the simulated wound roll. The other end is attached to a stanchion on the simulated wound roll. The nip load is adjusted by hanging dead weights on the weight hangers. The drive system can turn the simulated wound roll either clockwise or counter clockwise. While the simulated wound roll turns, the nip induced tension is recorded by a data acquisition system which will be described later.

The frame functions as a platform where the simulated wound roll and the nip roller can be mounted and aligned. Also, the DC motor and motor control system which drive the simulated wound roll are mounted on the frame.

The simulated wound roll is 60 inches diameter and the nip roller dimensions are 4.935 inches diameter and 3.25 inches wide.

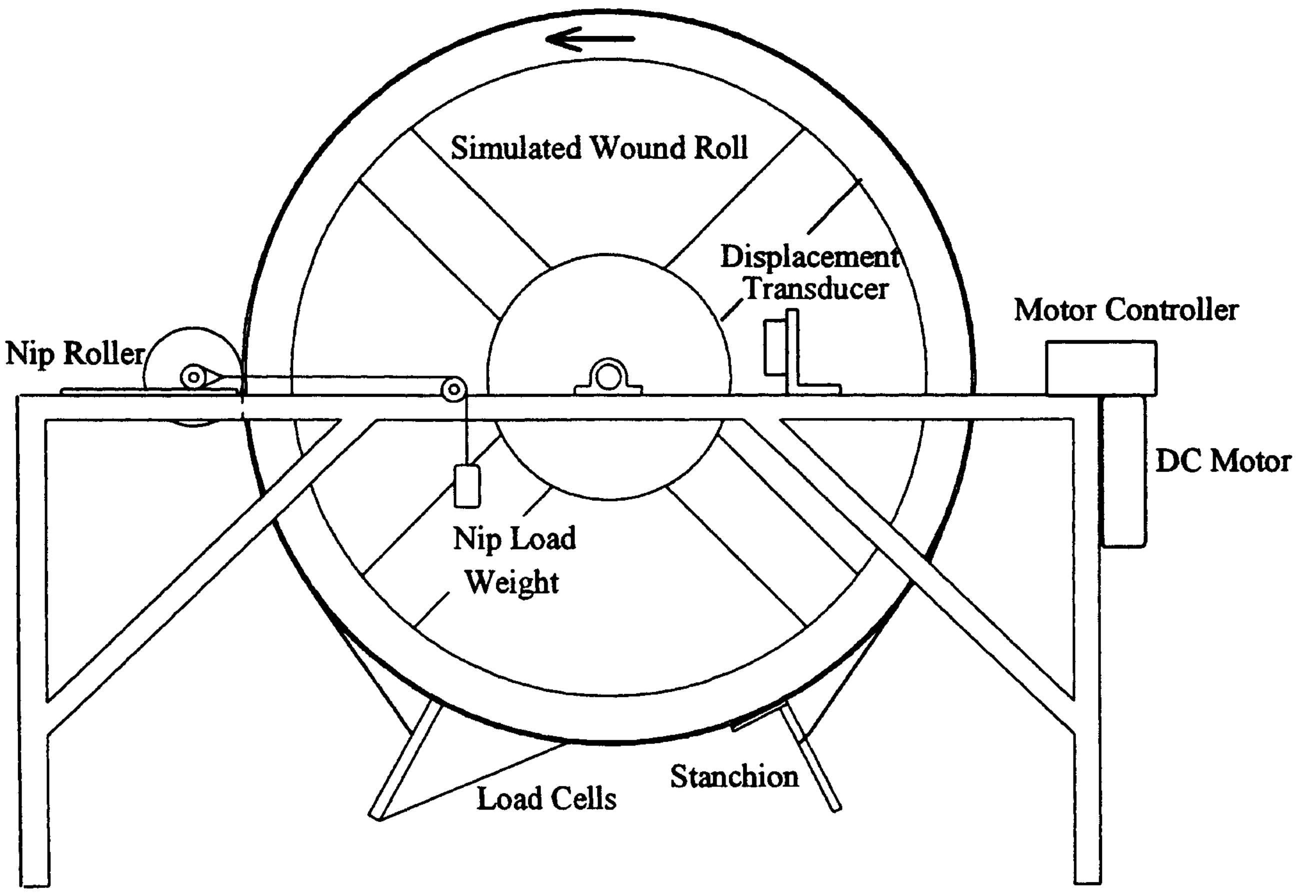


Figure 3. Circular Nip Mechanics Test Bed

A DC motor was used so that speed of the simulation roll can be controlled precisely, yielding simulated wound roll surface velocities from 1.25 fpm to 150 fpm. The motor controller controlled the speed and direction of rotation of motor. Since the motor controller is connected to the data acquisition system, all operations can be done from a personal computer which could be far away from the motor controller.

3.2 DATA ACQUISITION SYSTEM

For data acquisition, the Keithley 500 Data Acquisition and Control System[2] was used. Three operations are performed by the data acquisition control system. These three operations are sending a voltage output controlling the DC motor, reading the load cell which was monitoring the nip-induced-tension and measuring the rolling distance around the circumference of the simulation roll(see Figure 4).

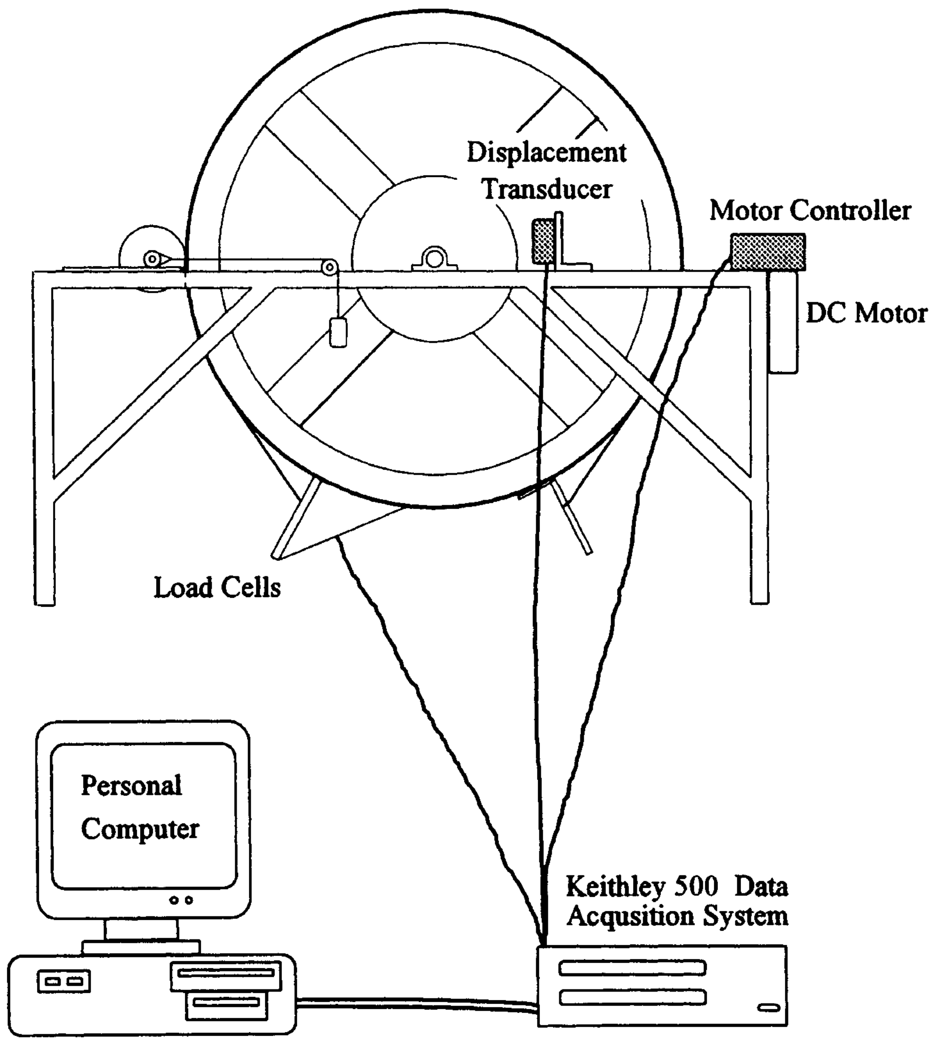


Figure 4 Data Acquisition System

[2]KDAC500/I, Keithely Instruments Inc., 28775 Aurora Road, Cleveland, Ohio 44139

To control the DC motor, the Keithley AOM2 module is used. Two different signals were sent to DC motor controller from two channels, channel 0 and channel 1. The voltage output from channel 0 is for DC motor speed and direction control. This voltage varies from -10 volts to +10 volts. A negative voltage output causes counter clockwise rotation, and positive voltage causes clockwise rotation of the simulated wound roll. The DC motor will take no action unless the input voltage is beyond 3 volts in absolute value. The relationship between voltage input and surface speed of simulation roll is shown in Figure 5. The voltage output from channel 1 is used to start and stop the DC motor. Zero volt starts the DC motor and Five volts, stops the DC motor.

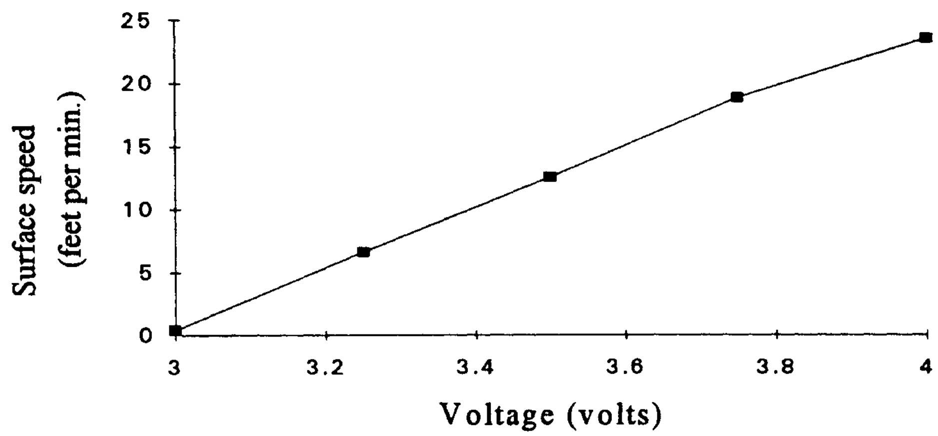


Figure 5. The relationship between input voltage and wound roll surface speed

The Keithley AIM 8 module is used for reading the signals from the load cell. The load cell is simple cantilever beam type. The beam is instrumented with four strain gauges, two on top and two on bottom. The strain gauges are wired in to a Wheatstone bridge and provides active temperature compensation. There are four ends on the Wheatstone bridge arrangement's strain gauges. Two ends are for excitation voltage which is 10 volts and the others are for signal(voltage) output. Figure 6 shows the relationship between the amplified strain gauge voltage output and force. The AMM2 A/D card reads the output of the AIM8 card.

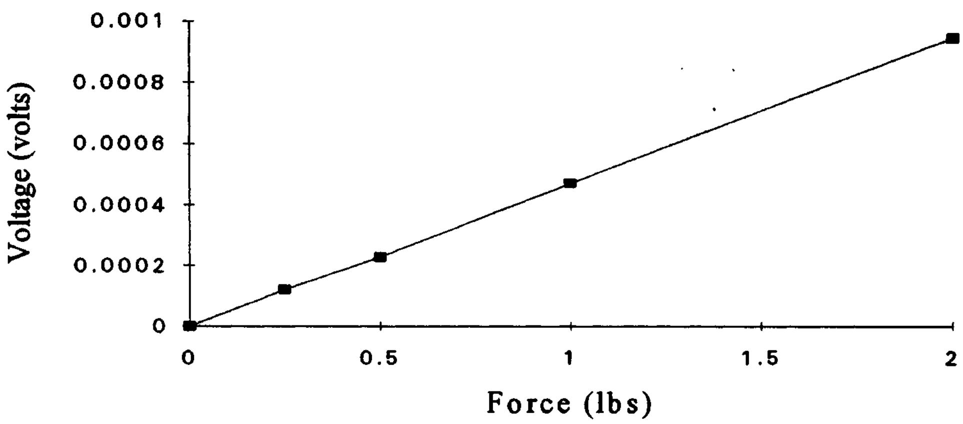


Figure 6. The relationship between strain gauges voltage output and force

A potentiometer,model number 1850-40A-PL-SMM, is used for a displacement transducer to monitor the rolling distance of the nip and Keithley AMM2 module reads the signal(voltage) output from this potentiometer. The relationship of displacement transducer's voltage output and displacement is showed in Figure 7.

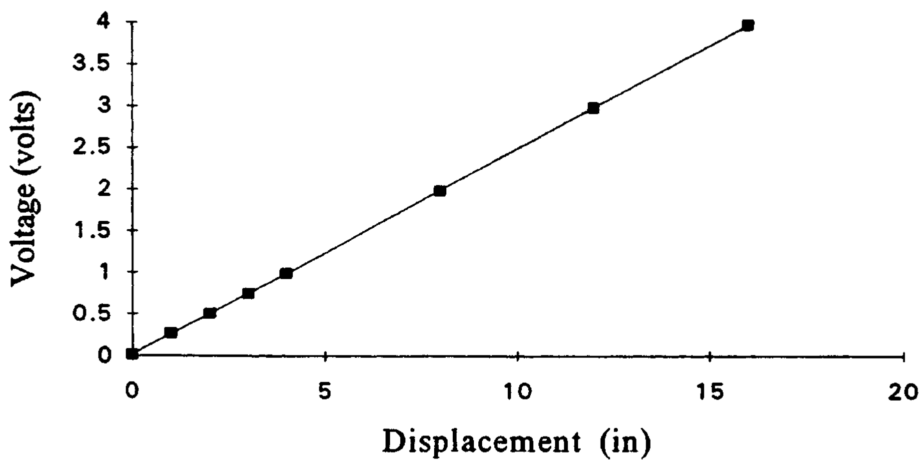


Figure 7. The relationship between displacement transducer voltage output and displacement

To monitor these three signals with the data acquisition system, a BASIC code was developed(see Appendix I). The functions of this program were providing a voltage output to the DC motor controller to control the DC motor, and converting the voltage input from strain gauges and displacement transducer to force and displacement units.

CHAPTER 4

EXPERIMENTAL RESULTS

The purpose of this experiment is to determine the saturated level of nip induced tension on the circular geometric model. In the earlier experiments by Good et al [1] on aluminum strips, and Prabhakar [4] on newsprint paper, a flat test bed was employed. In this study, a circular test bed was employed to study a light weight coated paper web, 3 inches wide and 0.002 inch thick.

4.1 Experimental Method

Two different initial setups were used in this experiment. The first involved testing a single layer and the second test involved testing a 5 sheet stack of web strips . In the multiple layer tests, only the tension in the first sheet of web was monitored. A 0.2 pounds of pre-load was applied to the web in each experiments. This pre-load will provided 33 pre-tension which made sure a well contact between the web and wound roll. In the experiments, the start position was on the position 1 which is the tangential point of the web and wound roll, and the end position was on position 2 which was after 90 degrees rotation of the wound roll(see Figure 8). 24 pounds of load applied to the nip roller provided 8 pli of nip load. In each experiment, the rolling distance was around 40 inches.

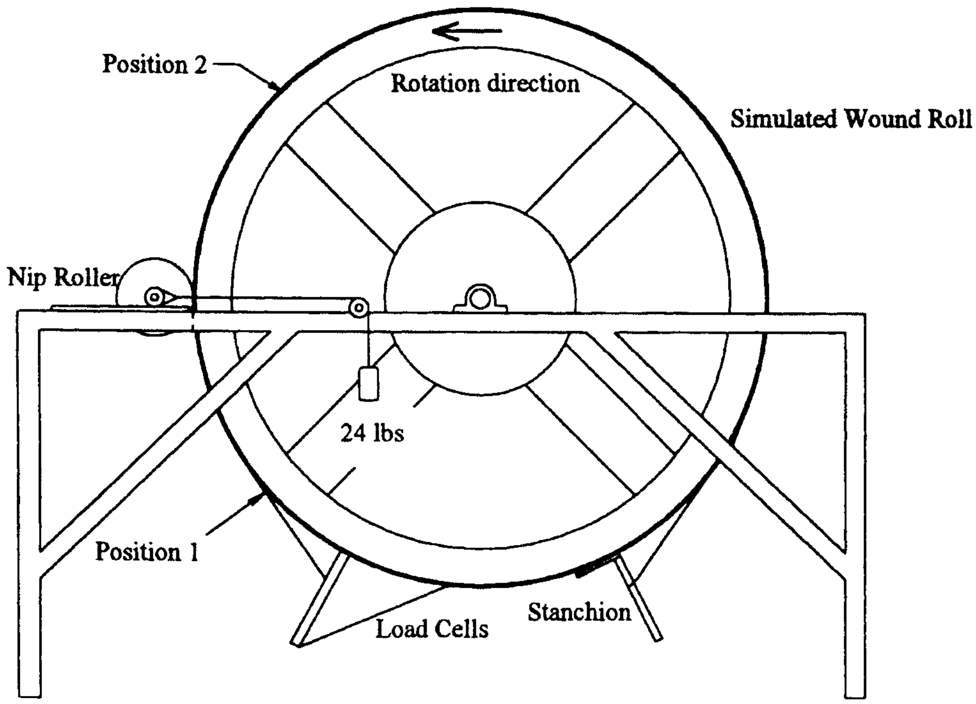


Figure 8. Initial set up of circular test bed

In single layer experiments, 5 tests were conducted and each web strip was used only once in order to avoid a reduction of the friction coefficient due to the passage of the nip. In multiple layer testing, each test was repeated 5 times.

4.2 Results

The experimental results for single layer tests are shown in Figure 9. The results for multiple layer tests are shown in Figure 10.

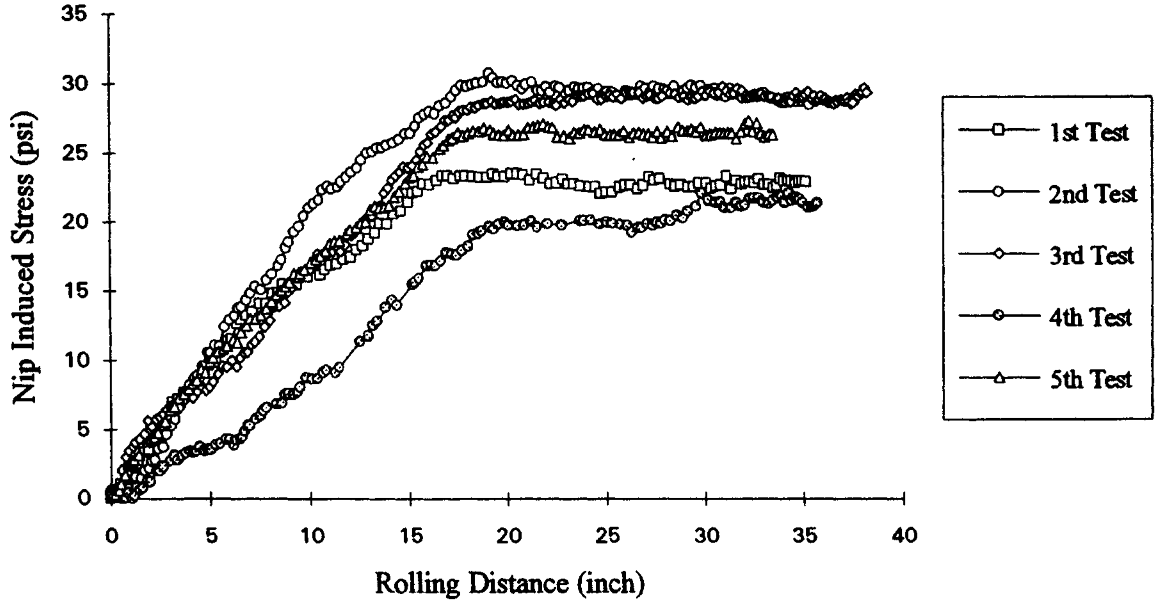


Figure 9. The experimental results for single layer tests

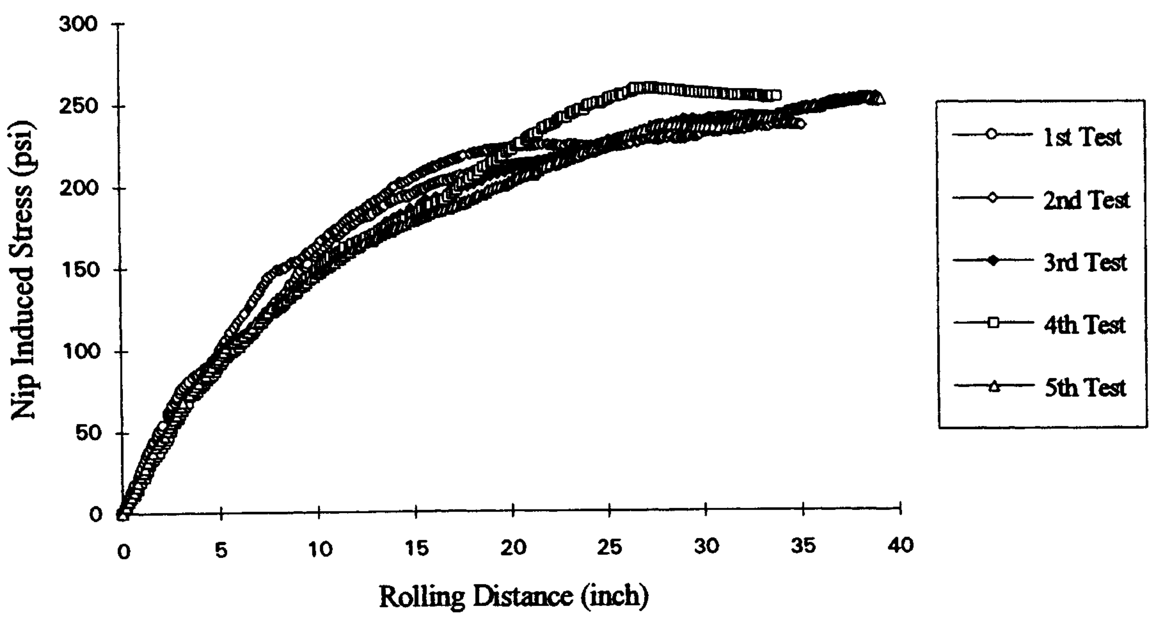


Figure 10. The experimental results for multiple layer tests

It was found that after approximately 17 inches of rolling distance, the nip induced stress increased to the saturated level of about 25 psi in the single layer case, Figure 9. For multiple layer tests, Figure 10, it was observed that the nip induced stress saturated after about 25 inches of rolling at a value of about 250 psi.

CHAPTER 5

Finite Element Analysis

ANSYS[3], a commercial finite element analysis software package, was used to simulate the problem. To solve the problem, a ANSYS input code was developed(see Appendix II). This code included two major parts, geometric modeling and nip load modeling.

5.1 Geometric Modeling

The geometric model mimics the web which laid on the circular test bed(see Figure 8). Since the width of the web is much larger than the thickness of the web (3 inches vs. 0.002 inch), the web was assumed to conform to plane strain conditions.

Figure 11 shows the geometric model. Because of the restriction of computer memory, the plane strain elements were divided into two regions - a low density region and a high density region. The low density region was used to simulate the web between the load cell and the tangent contact point of web strip and the circular test bed. The length of this portion is 9.5 inches which is the same length as the experimental set up. The total number of elements in this portion are 500 elements where each element is 0.2375 inch wide and 0.0002 inch thick. The high density region was used to simulated the web which laid on the circular test bed. Figure 12 shows the detail of this region. In this region, plane strain elements are used to mimic the web and interface gap elements are used to accommodate slippage between the web and the circular test bed. There are 1000 plane strain elements and 101 interface gap elements in this region. Each plain strain element is 0.001087 inch wide and 0.0002 inch thick.

[3]ANSYS, Swanson Analysis Systems Inc., P.O.BOX 65, Houston, PA 15342

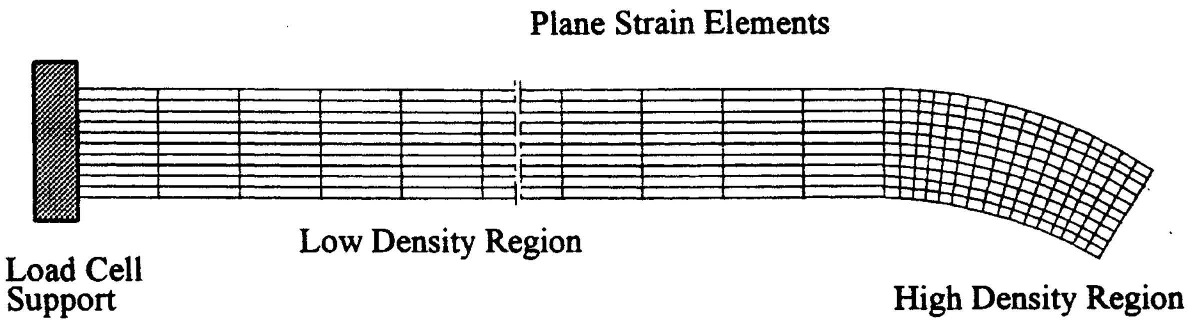


Figure 11. Finite Element Model

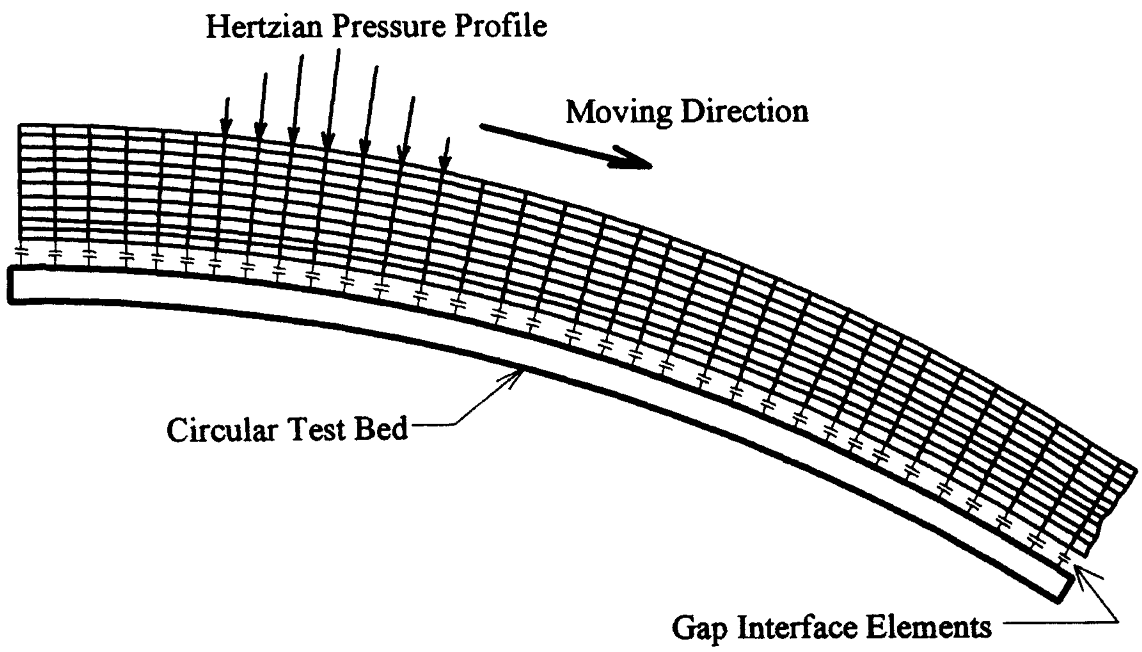


Figure 12. Details of The Finite Element Model

5.2 Nip Load Modeling

The contact of the nip roller acting on the web strip was modeled as a Hertizan contact problem. The contact area is a rectangle whose width is a function of nip load, web width, the diameters of the contacting cylinders and the associated material properties, which include Young's modulus and Poisson's ratio. The half contact width is given by the following equation(Shigley [7]):

$$b = \sqrt{\frac{2P}{\pi l} \frac{[(1-\upsilon_1^2)/E_1] + [1-\upsilon_2^2)/E_2]}{(1/d_1)+(1/d_2)}} \qquad \{3\}$$

where b : represents the half of contact width

P : represents pressure between nip roller and web

l : represents width of web

ν : represents Poisson's ratio

E : represents Young's modulus

d : represents diameter.

The subscripts of 1 and 2 represent the contact bodies , nip roller and web(see Figure 13).

The Hertzian pressure distribution is assumed to be elliptical and given by following equation(Radzimovsky[5]):

$$p_x = \frac{2P}{\pi b^2 l}\sqrt{b^2 - x^2} \qquad \{4\}$$

where p_x represents the pressure distribution as a function of x, a coordinate whose origin lies upon the line of symmetry of the contacting bodies.

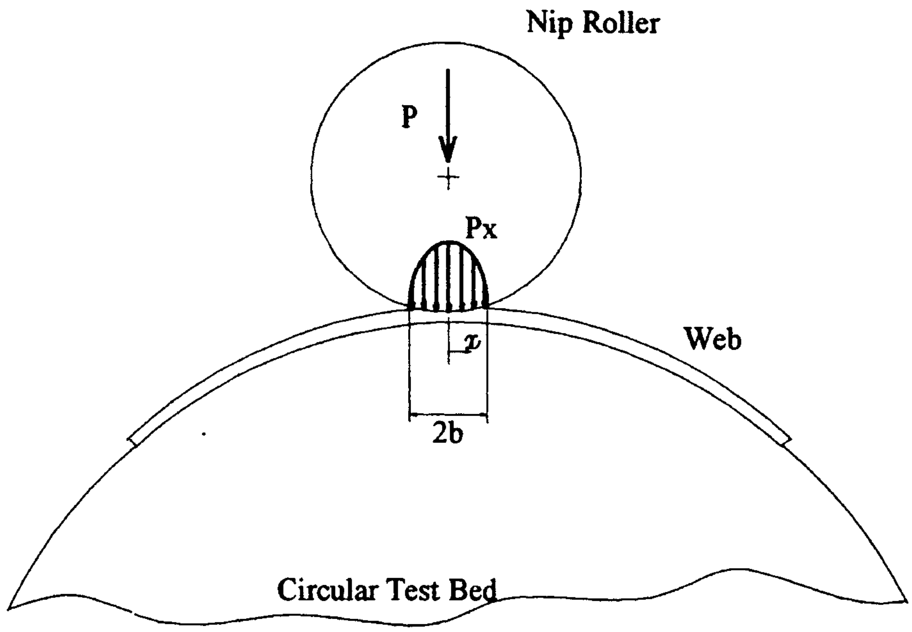


Figure 13. Hertzian contact profile between nip roller and web

In this study, nip load is 8 pli(8 lbs of load per in of width inch contact). The nip roller was made of aluminum with a diameter of 4.935 inches and the web material is light weight coated paper. According to the material properties in Table I, the half contact width is $4.8916*10^{-3}$ inches and the pressure distribution of the profile is

$$p_x = 1.83493*10^5*(6.94*10^{-5} - x^2)^{1/2}$$

Table I

The properties of materials

Material \ Properties	Young's Modulus	Poisson's Ratio
Aluminium	10,000,000	0.33
Light Weight Coated Paper	1,000,000	0.01

The previous analysis considered about the contact between the nip roller and the web whose Young's modulus(E_t) are shown in Table I. The nip roller and the circular test bed are constructed as aluminum shells. A shell radial stiffness equation was developed in Roisum[6] expresses the modulus as

$$E_c = E_{cm} \frac{r_0^2 - r_c^2}{r_0^2 + r_c^2 - \mu_c (r_0^2 - r_c^2)}$$

where E_c = core modulus used in winding models

E_{cm} = core material modulus

μ_c = core Poisson ratio

r_0 = roll inner (core outer) radius

r_c = core inner radius

Two other cases were also considered for the contact bodies with aluminum shell stiffness. One was the contact between the nip roller and the circular test bed which had the half contact width of 0.032 inch. The other case was the contact between the nip roller and the web with Young's modulus in radial direction(E_r) and the half contact width was 0.034 inch. Although the contact width in these three cases are different, the area under the strain curve, which is C in equation {2},per finite element analysis was found to be nearly the same in these three cases. Thus the various possible assumptions for the moduli in equation{3} did not affect the finite element result to any degree.

Next, the contact width was divided into 9 segments. Each segment had 0.001087 inch length which is the same as the length of high density plane strain elements in finite element geometric model. In the finite element model analysis, 9 elements will have pressures individually applied in each load step. The magnitude of each element pressure is evaluated by integrating the pressure distribution between each segment length. For example, the pressure acting on the middle element (the fifth element) is obtained from

$$P = \int_{-5.435*10^{-4}}^{+5.435*10^{-4}} p_x dx \,/\, Area = 1073.7 psi.$$

Similarly, the pressure acting on other elements were evaluated(see figure 14). In successive time steps the pressure profile is moved to the right by one element length to simulate the nip rolling over the web.

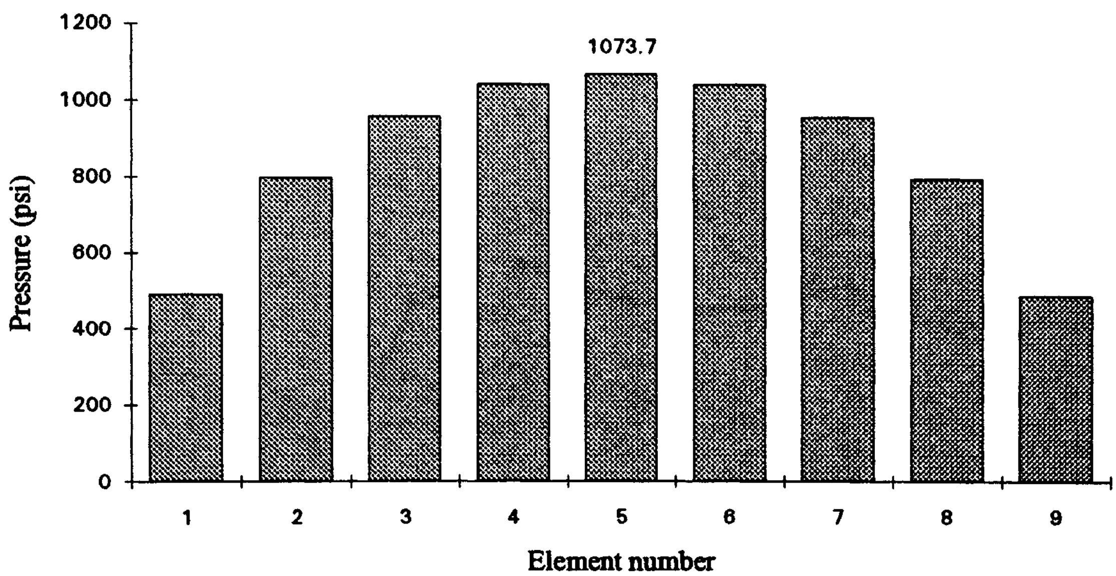


Figure 14 The pressure distribution on elements

5.3 Finite Element Results

The finite element results were obtained by observing the elongating machine direction strain on the lower surface of the web strip beneath the nip roller. After several load steps, the elongating machine direction strain would be nearly identical, except that the curve would have moved by one element length to the right. This shows that an elongating machine direction strain exists in the web due to the combination of the Hertzian pressure profile moving to the right over the upper surface of the web strip and the frictional forces on the lower surface. As the nip passes over the web strip, every point on the lower surface witnesses the elongating strain distribution, and the extension of the web strip due to the nip rolling over one finite element will be the integral of the strain curve. Figure 15 is the strain curve at the tenth load step. The area under the curve is found to be $3.35*10^{-7}$ inches, which is the deformation contribution from the nip roller rolling over an element length which is 0.001087 inch.

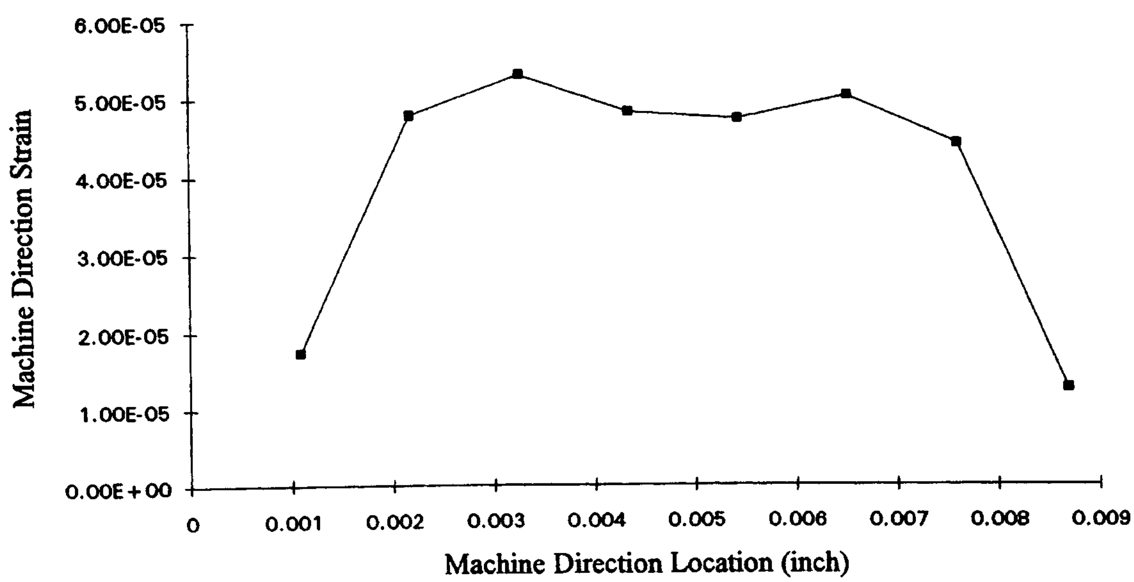


Figure 15. Machine direction strain plot at the tenth load step

The deformation due to the nip roll moving 1 inch will be $3.35*10^{-7}*$ (1/0.001087) inch or $3.08*10^{-4}$ inch for every 1 inch of rolling distance. The strain in the web strip can be calculated from equation {2} formulated by Good et al [1].

$$\varepsilon_x = \frac{C * NRD}{L_i + NRD} = \frac{3.08*10^{-4} * NRD}{L_i + NRD} \qquad \{5\}$$

It was noted that equation {5} is nonlinear with respect to the nip rolling displacement and has similar form to equation {1}.

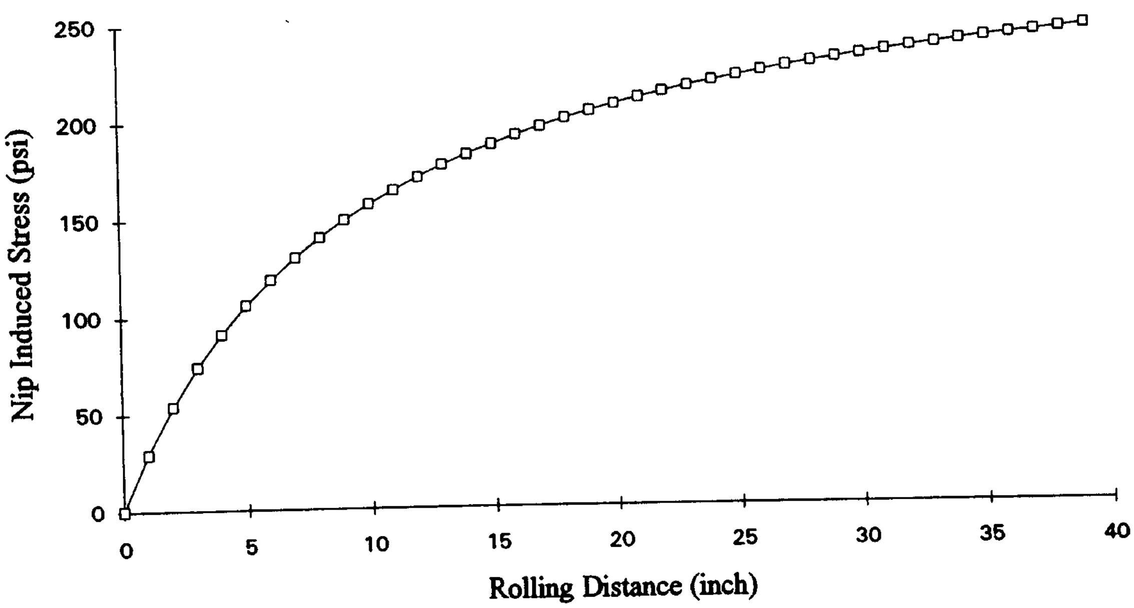


Figure 16. The result of nip induced stress in finite element analysis

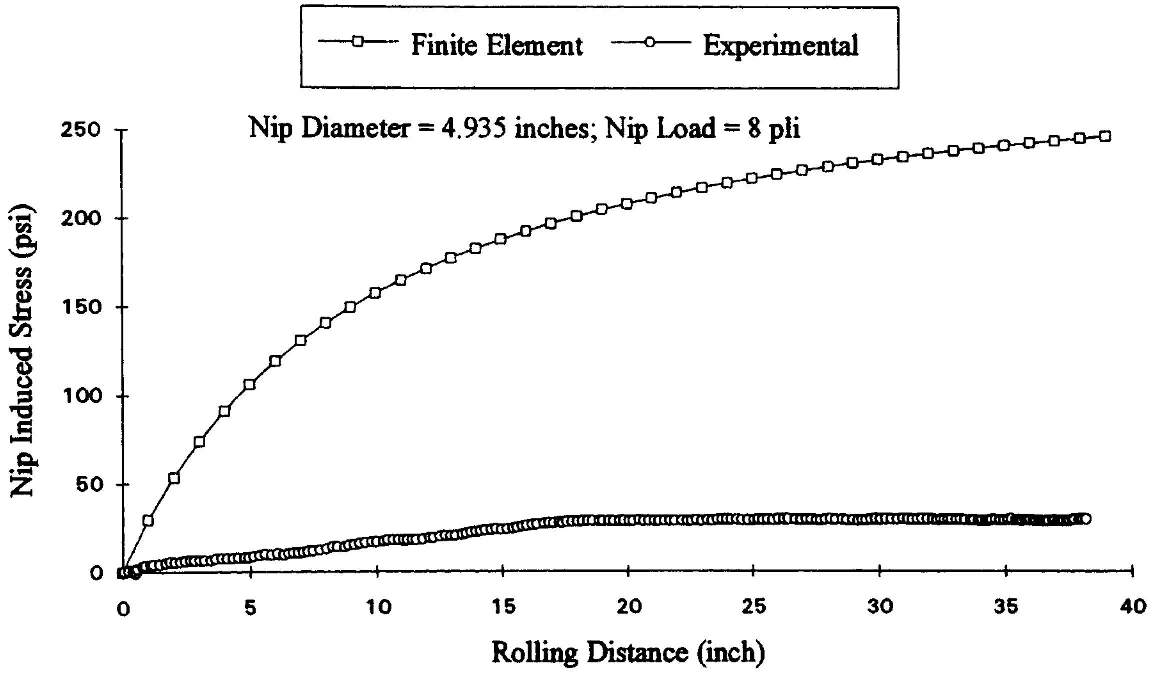
The nip induced stress can be calculated by multiplying the nip induced strain and Young's modulus. Figure 16 shows the nip induced stress plot of finite element analysis in single layer case. It is clear that the predicted value of nip inducted stress at 17 inches rolling distance is 200 psi.

CHAPTER 6

DISCUSSION

6.1 Experimental Versus Finite Element Results

The comparison of the results from experiment and finite element analysis in single layer test is shown in Figure 17.



Experimental results are measured by load cell.

$$\text{Finite Element Results} = E * \varepsilon_x = E * \frac{C * NRD}{L_i + NRD}.$$

Figure 17. The comparison of experimental and finite element analysis results for single layer test

In flat bed nip mechanics tests, the experimental results and finite element results are expected to be the same. For the circular nip mechanics test bed, the nip induced tension behind the nip is not equal to the tension at the load cell, unless the coefficient of friction is equal to zero($\mu=0$).

It is obvious that the finite element analysis predicted a much higher value of nip induced stress compared to the experimental results. One reason that could have caused this lower value of nip induced stress in the experiments was that the non-idea contact condition between the nip roller and circular test bed. Therefore, an investigation of the contact condition of these two contact bodies was performed.

A TEKSCAN [4] pressure sensitive array was used to test the pressure distribution between nip roller and test bed. Two different locations were chosen between the start position (position 1) and the end position(position 2) of experiment(see Figure 8). The results are shown in Figure 18 and Figure 19 whose X-axes represents the contact position along the nip roller width, 3.25 inches, and Y-axis represents the magnitude of pressure distribution.

[4]TECKSCAN, Tekscan, Inc., 451D Street, Boston, MA 02210.

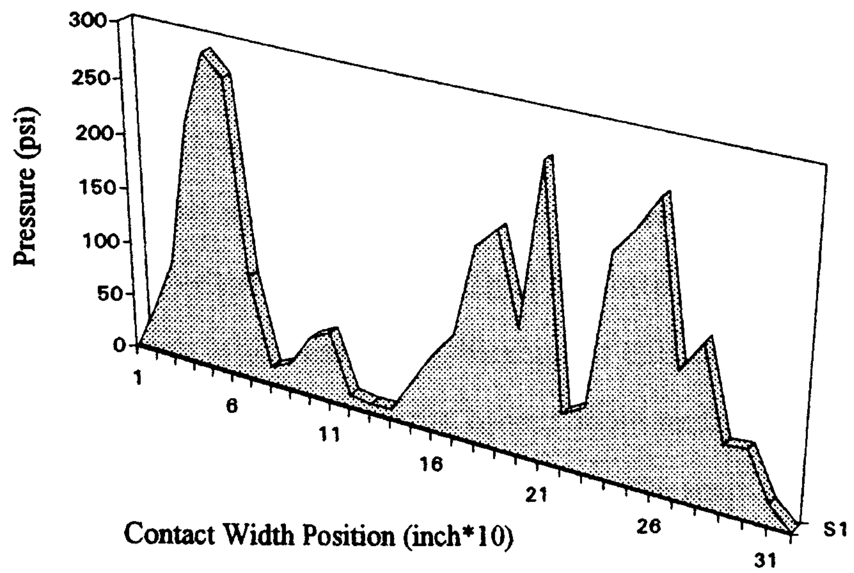


Figure 18. The first contact condition test result between nip roller and test bed for single layer case

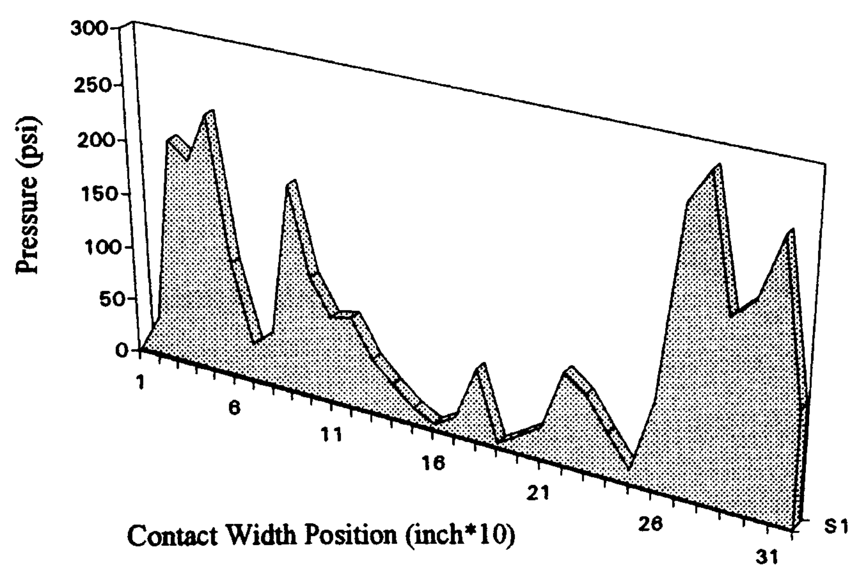


Figure 19. The second contact condition test result between nip roller and test bed for single layer case

From these results, it was shown that contact condition along the circumference of wound roll between the nip roller and wound roll was very uneven. Since the thickness of the TEKSCAN array is 0.005 inch which is 2.5 times of the thickness of one layer of the paper web, the contact condition for a single layer experiment is even worse than the result of the above test due to the adding of the force sensitive resistors.

For a 5 layer stack, which has a total thickness of 0.01 inch, the contact condition was improved. The thicker stack made the contact more uniform across the width as shown in Figure 20 and Figure 21 which were tested at the same positions as previous test positions.

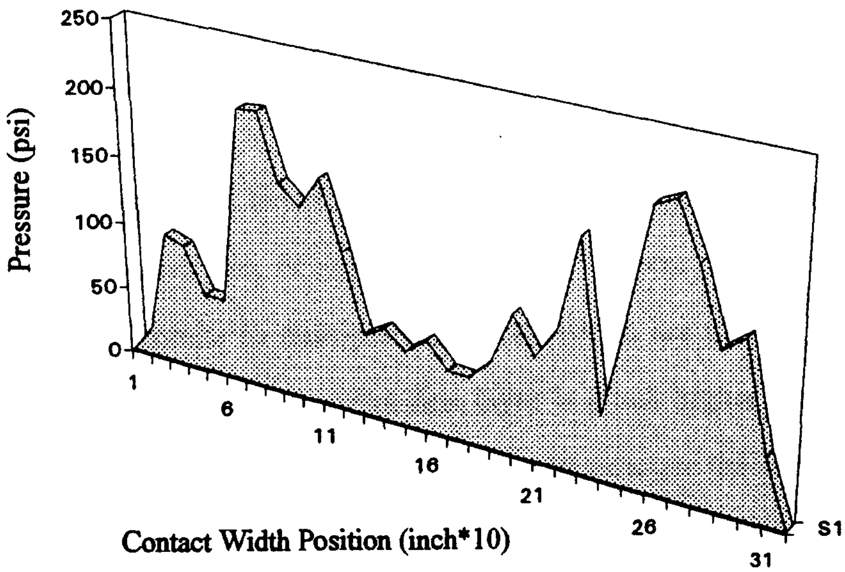


Figure 20 The first contact condition test result between nip roller and test bed for multiple layer case

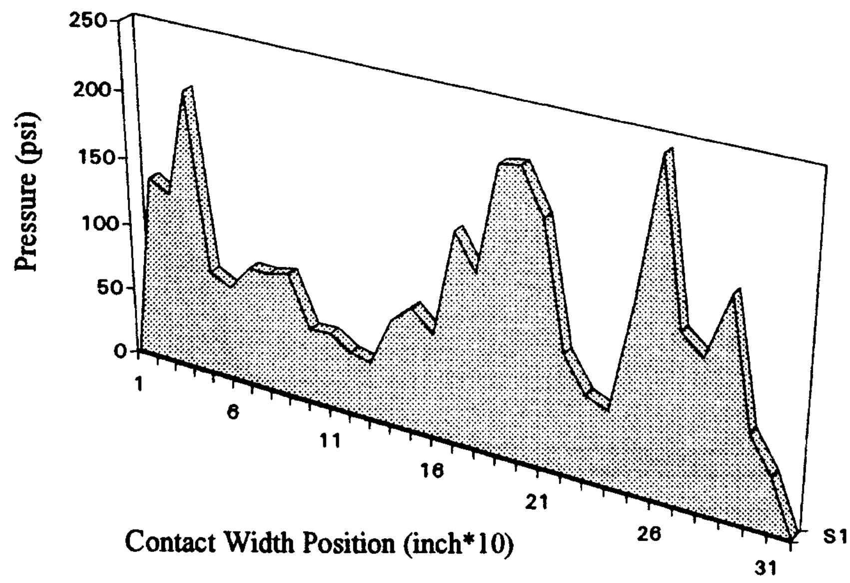


Figure 21 The second contact condition test result between nip roller and test bed for multiple layer case

In multiple layer tests, the slippage occurred not only between the first layer and the second layer but also can occurr between other layers. However, according to Wu's[9] experimental results in multiple layer tests which are shown in Figure 22 and Figure 23, the nip induced tension in the first layer is much higher than another layers. In this experiment in which dead loads were applied to simulate the interlayer pressure in the stack, the nip induced tensions for the sheets were almost equal to zero except for the first layer. Noted in Figure 23, that the slippage occurred almost only between the first layer and the second layer in the multiple layer tests. Therefore, the slippage between 2nd and 3rd layers, 3rd and 4th layers,...etc. are negligible in multiple layer tests, in which the interlayer pressure is simulated. One of the initial reasons for constructing the circular nip mechanics test bed was that the interlayer pressures developed by the wound-on-tension should be identical to that of the winding roll simular to the flat bed tests with simulated pressure. Almost all slippage is restricted except between the 1st and 2nd layer.

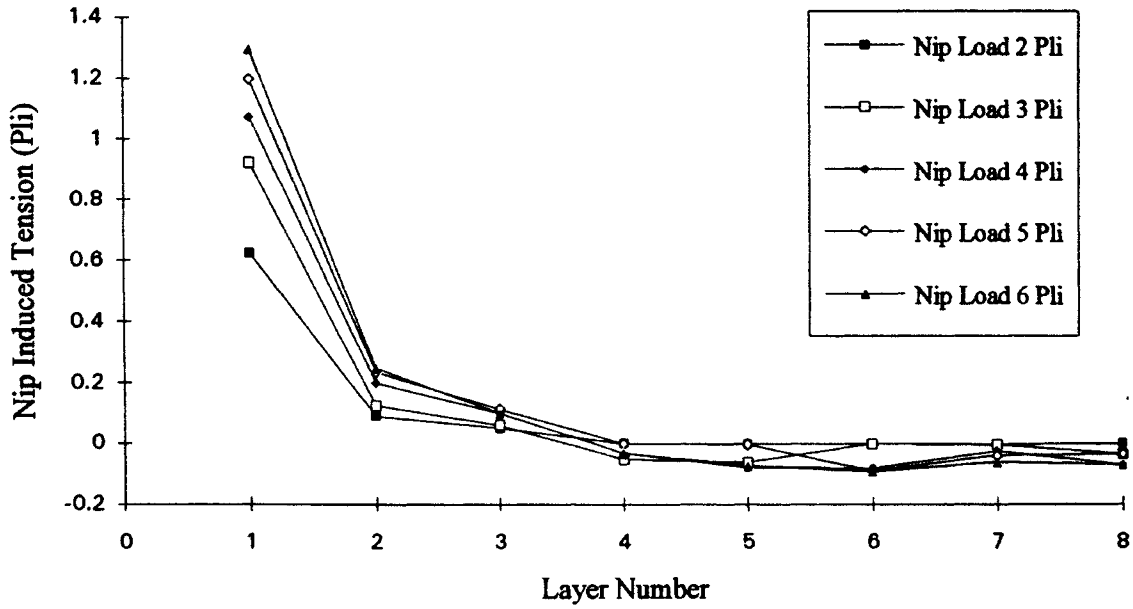


Figure 22 Nip induced tension in the saturated region without simulation of the interlayer pressure

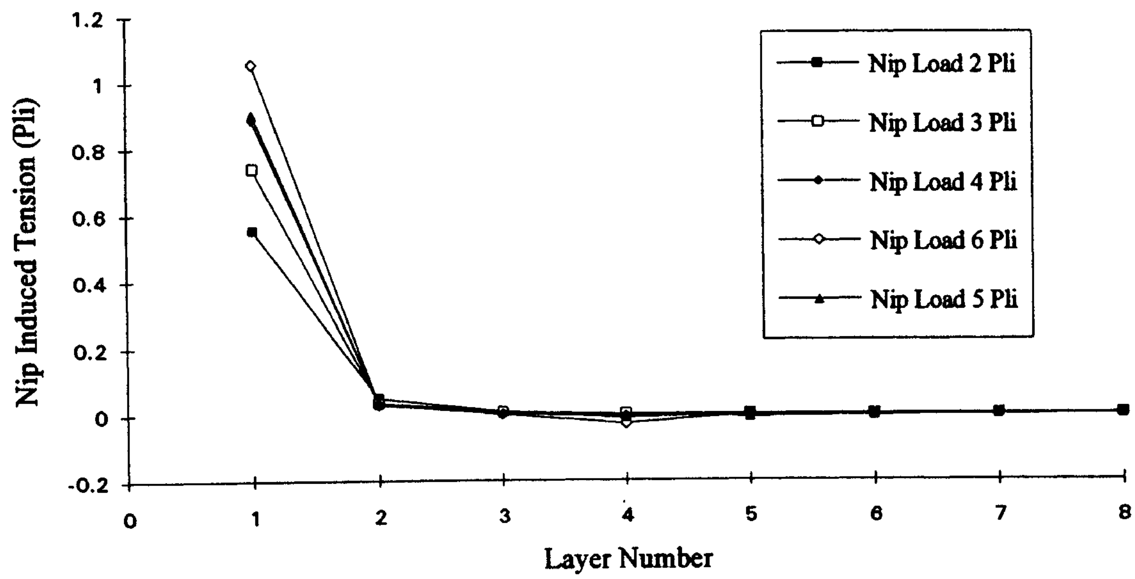


Figure 23 Nip induced tension in the saturated region with simulation of the interlayer pressure

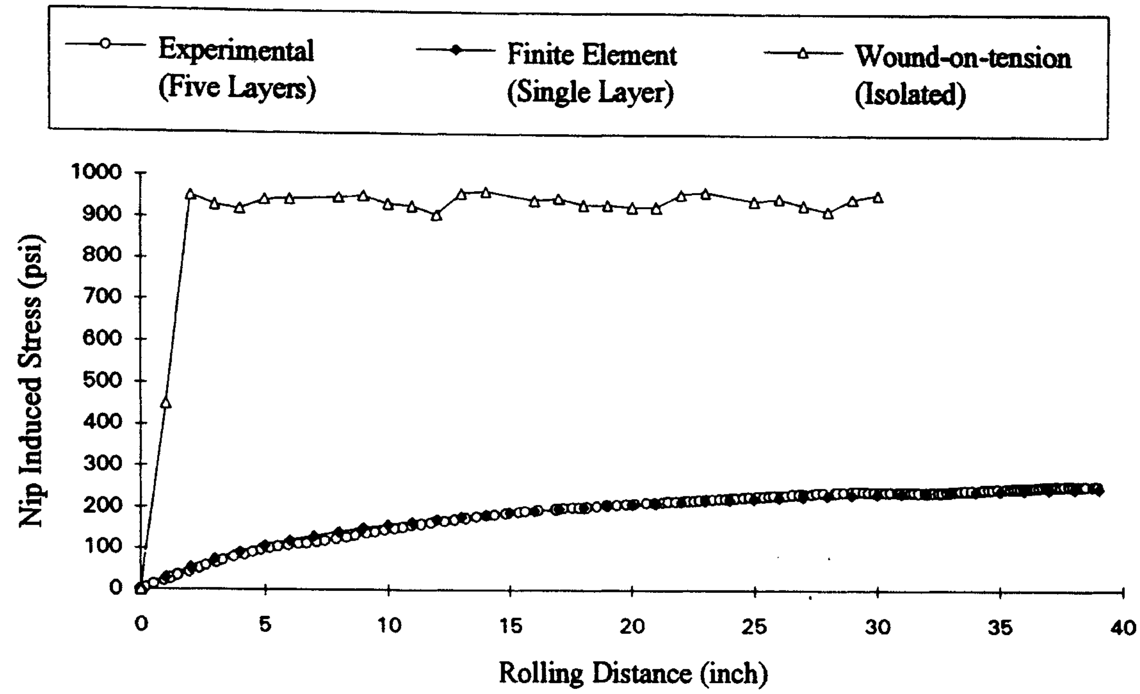


Figure 24. The comparison of the multiple layer experimental result and the single finite element analysis results

In Figure 24, the finite element results represent the wound-on-tension for single layer test and the experimental results represent the wound-on-tension measured by load cell for five layers test. The finite element results are based upon *C*(refer to equation {2}) and no effect of slippage or friction. The experimental results are affected by the slippage and friction. According to Markum's[2] isolated test, the experimental results in Figure 24 would have been brought closed to $\mu * N / h$ which is 952 psi, if the first layer were isolated and the layer number beneath the first were increased to seven layers. In the finite element analyses, the value of C in equation {2} is dependent on the enlongating machine direction strain which is affected by the stiffness of the base material. Since, the stiffness of the base for the first layer in multiple layer test is softer than the regid stiffness used in the finite element analyses, the magnitude of C would be increased with the number of the layers which are involved in the test. Therefore the finite element result will approach the isolated value of the nip induced stress when we are able to model the correct stiffness of multiple underlying layers. The experimental result will also approach the isolated case with additional layers installed beneath the outerlayer.

6.2 Predicting The Wound-on-Tension

An attempt was made to predict the wound-on-tension by means of the band-brake equation which is

$$\frac{T_1}{T_2} = e^{\mu\theta} \tag{6}$$

where T_1: represent the wound-on-tension

T_2: represents the portion of the wound-on-tension measured by the load cell

μ : represents the coefficient of friction

θ : represents the angle of wrap of the web around the test bed.

Figure 25 shows a free body diagram of a sector of the web, which lay on the test bed, and had been rolling from position A to position B by the nip roller. Position A represents the tangent contact position of the web and the test bed, and position B represents the point right behind the immediate contact position of the nip roller and the web. Therefore, T_1 represents the wound-on-tension and T_2 represents the nip induced tension which was measured by the load cell.

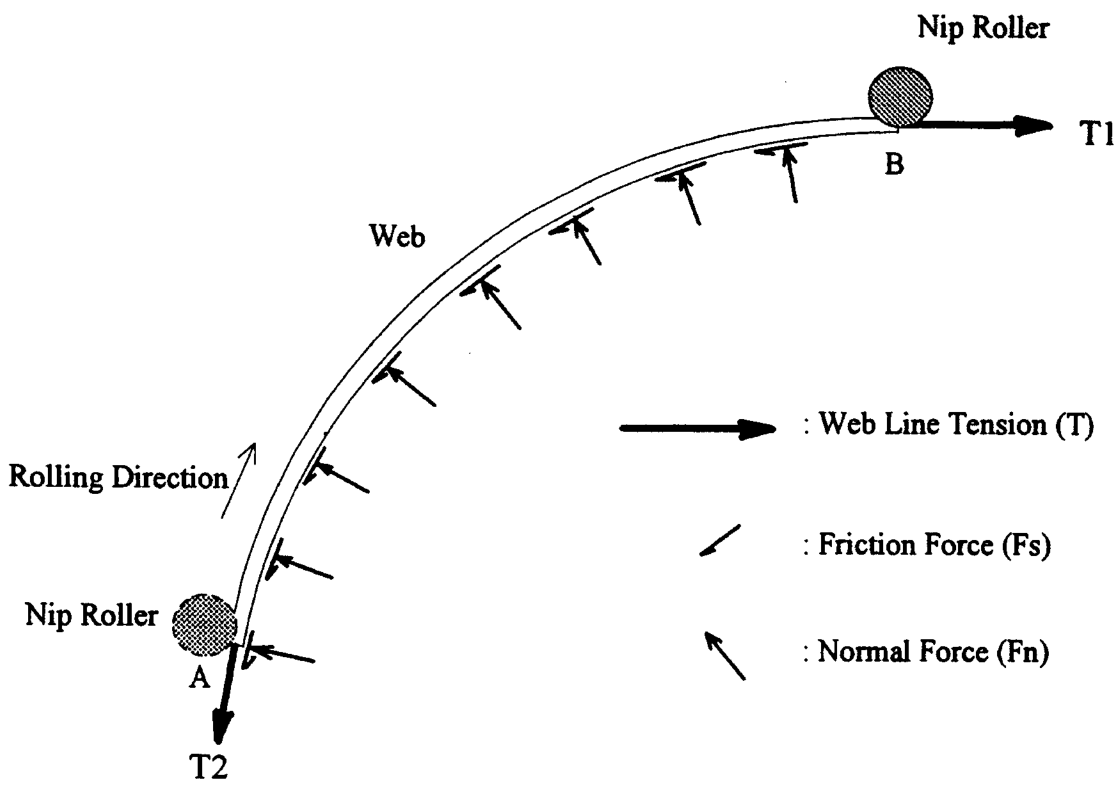


Figure 25. The free body diagram of the web

Macroscopically, according to Markum[2] the experimental results, from a test in which the nip was 4 inches diameter and with a 4 pli nip load, the saturated nip induced tension is 3 pounds after about 25 inches of nip rolling distance. This corresponds to a wrap angle of 5/6 radians. Substituting T_2=3 pounds; μ = 0.354(for news print) and θ = 5/6 radians into the band-brake equation, T_1(wound-on-tension) was found to be 4.03 pounds. But Markum's experimental result showed the wound-on-tension in this test was 9.03 pounds, which is more than two times of the result from band-brake equation.

On the other hand, microscopically, according to the results from finite element analysis, the friction force between the web and the test bed decreases very fast along the sector behind the immediate contact position of the web and the nip roller. Figure 26 shows a comparison of the results from finite element analysis and band-brake equation.

Since the simulated rolling distance in finite element analysis was only about 0.02 inch, the magnitude of the tension shown in Figure 26 is very small.

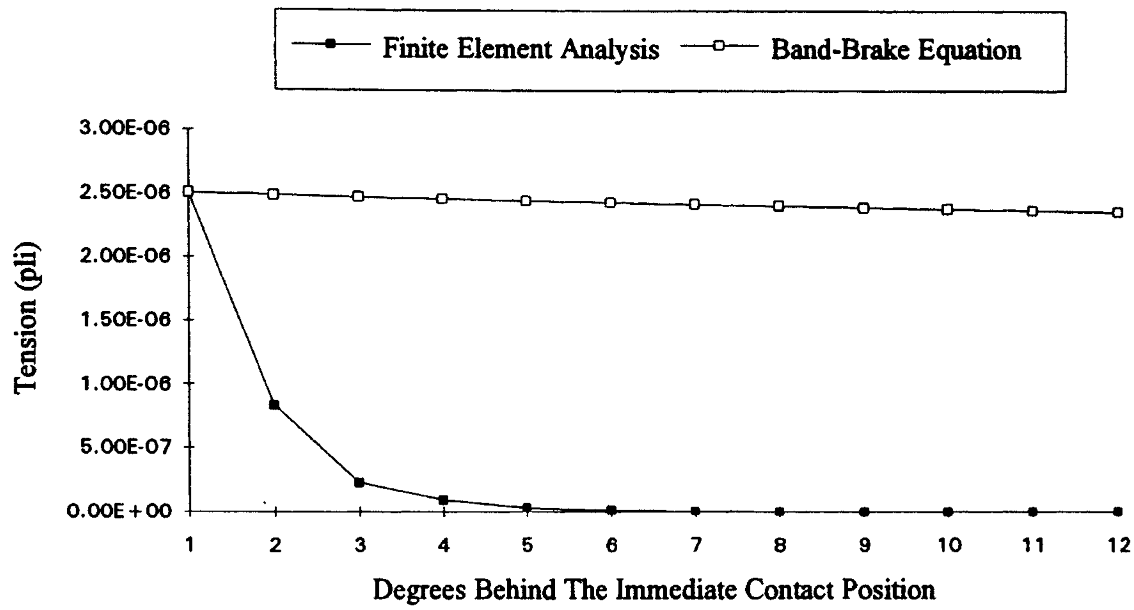


Figure 26. The comparison of tension decrease along the contact arc between the finite element result and band-brake equation

From this figure, according to the band-brake equation the tension behind the immediate contact position decreases very slowly compared to the finite element analysis result. The finite element analysis results showed however that the friction force decreased nearly to zero within 6 degrees of the sector angle(i.e. 3 inches), which means the slippage between the web and the test bed occurred only over a very short distance right behind the current nip roll position.

The friction coefficient for light weight coated paper which was used in these analyses as repored in Figure 26 is shown in Table II.

TABLE II

Coefficient of friction for light weight coated paper

Pass	Kinetic	Static
1	0.23	0.39
2	0.24	0.41
3	0.24	0.39
4	0.24	0.44
5	0.25	0.39
6	0.25	0.40
7	0.23	0.39
8	0.23	0.38
9	0.24	0.36
10	0.23	0.40
Average	0.238	0.395

Therefore, from the macroscopic and microscopic viewpoint, it was obvious that the band-brake equation can not be use to predict the wound-on-tension in the case of center winding with an undriven lay-on roll.

CHAPTER 7

CONCLUSIONS AND FUTURE WORK

Conclusions

The results in this research and Markum's[2] show that the nip induced stress was saturated after a rolling distance of about 25 inches. Prabhakar's[4] results on a flat test bed indicated that more than 100 inches of rolling distance was required for portray the nip induced stress to reach the saturated level, thus the results from circular test bed more accurately the real wound roll. Using the equation {2} derived by Good et al[1], the finite element result does not work very well with the experimental results(refer to Figure 24). This was due to the fact that the value of C in equation {2} is dependent on the stiffness of the base beneath the first layer. It is necessary to study the value of C as a function of the number of the layer beneath the nip roller in the multiple layers test and with the correct value of C expression {2} should be applicable.

The wound-on-tension was not predictable from the band-brake equation for the following reasons:

1. The band-brake equation was derived with kinetic boundary conditions at each end of the band. The nip mechanics is such that a displacement is enforced by the nip which is a kinematics boundary condition.
2. The band-brake equation was used in the case which the slippage occurred over the whole contact surface between the contact bodies. However, in this research, the slippage only occurred over part of the contact surface between the web and the test bed.

Future Work

In this research study, the simulated nip rolling distance in computer compared to the experimental nip rolling distance is very tiny(0.1 inch VS 40 inches). It would be beneficial to pursue the analyses to the point at which the nip induced stress saturates(about 25 inches in this research) to study the profile of slippage between the outerlayer and the wound roll.

In the experimental setup, an attempt could be made to install a measuring system (load cell) which can be attached to nip roller and measure the tension of the web right behind the nip roller while the nip roller is rolling. This concept is an extension of the wound-in-tension and wound-off-tension winding system developed by Pfeiffer[3]. Therefore, the nip induced tension and the wound-on-tension could be monitored simultaneously and the relationship between the nip induced tension and wound-on-tension could be thoroughly studied.

REFERENCES

1. Good, J.K., Wu, Z., and Fikes, M.W.R., "The Internal Stresses in wound rolls with the presence of a nip roller". Submitted for review to the Journal of Applied mechanics, May 1990.
2. Markum, R.E., "Theoretical and Experimental Studies on Nip Mechanics." MS. Thesis, Department of Mechanical and Aerospace Engineering, Oklahoma State University, July 1992.
3. Pfeiffer, J.D., "Mechanics of Rolling on Paper webs". TAPPI Journal, Vol. 51, No. 8, August 1968, pp. 77A-85A,.
4. Prabhakar, M., "Study of The Effect of Nip Diameter on The Rate of Nip Induced Tension." MS. Thesis, Department of Mechanical and Aerospace Engineering, Oklahoma State University, May 1994.
5. Radzimovsky, E.I., "Stress distribution and strength condition of two rolling cylinders pressed together". Univ. Ill. Engr. Expt. Station, Bulletin 408, 1953, pp. 1-40.
6. Roisum, D.R., "The Measurement of Web Stresses During Roll Winding." Ph.D. Thesis, Department of Mechanical and Aerospace Engineering, Oklahoma State University, May 1990.
7. Shigley, Joseph.E., and Mitchell, Larry.D., Mechanical Engineering Design, Fourth Edition, McGraw-Hill Book Company, New York, 1983, pp. 340 - 342.
8. Vaidyanathan Nandakumar, "An Investigation of the Nip Induced Tension Mechanism Using Photo elasticity." MS Report, Department of Mechanical and Aerospace Engineering, Oklahoma State University, May 1989.
9. Wu, Z., "An Investigation of the Effect of Nip Mechanics upon Wound Roll Stresses." Ph.D. Thesis, Department of Mechanical and Aerospace Engineering, Oklahoma State University, July 1990.

APPENDIX I

Basic Code for Data Acquisition of Circular Test Bed

```
20 DIM V4(250), D(250)
30 REM*******************DEFINE FILE NAME**************************
40 PRINT " ENTER THE ROLLER DIA (Inch)"
50 INPUT R$
80 PRINT " ENTER A LETTER FOR MATERIAL "
90  INPUT M$
100 PRINT " ENTER THE NIP WEIGHT (lbf) "
110 INPUT T$
120 PRINT " ENTER THE RUN NUMBER "
130 INPUT U$
140 P$ = "A:":
150 F$ = P$ + R$ + M$ + T$ + U$ + ".DAT"
160 PRINT " THE FILE NAME IS: "; F$
170 CALL KDINIT
180 OPEN "O", #1, F$
190 VOLTS(0) = 0: DISP1(0) = 0: V1(0) = 0: V2(0) = 5
200 REM****************LOAD SCALING CONSTANTS********************
210 OPEN "I", #2, "CONST.CHE"
220 INPUT #2, OF4, SF4
230 REM************READ LOAD CELLS INITIAL VOLTAGE***************
240 CALL FGREAD'("S4","NONE",VOLTS(),"C.AIM8.D","NT")
250 REM******************FORCE TRANSLATION************************
260 V04 = ((VOLTS(0) - OF4) * SF4) / 100
270 REM ****READ DISPLACEMENT TRANSDUCER INITIAL VOLTAGE*****
280 CALL FGREAD'("DISP","NONE",DISP1(),"C.VOLTS","NT")
290 DIS1 = DISP1(0)
300 REM***************DISPLACEMENT TRANSLATION******************
310 DIS = 4.03325 * DISP1(0) - 2.091394
320 PRINT USING "PRETENSION IN THE TOP SHEET IS :###.#####"; V04
330 PRINT #1, "THE DEAD WEIGHT IS", DW
340 PRINT #1, USING "PRETENSION IN THE TOP SHEET IS:###.#####"; V04
350 PRINT USING "STARTING POSITION IS :###.##INCHES"; DIS
360 PRINT #1, USING "STARTING POSITION IS :###.##INCHES"; DIS
370 PRINT "ADJUST NIP WEIGHT"
380 INPUT NW
390 PRINT #1, "THE NIP WEIGHT IS", NW
400 REM*****************SET DC MOTOR SPEED************************
```

```
410 PRINT "ENTER THE MOTOR INPUT VOLTAGE( -3V = 1/4 RPM -
    -4V = 2 RPM)"
415 INPUT MIV
420 IF MIV < -4 OR MIV > 4 THEN 810
430 PRINT #1, "THE MOTOR INPUT VOLTAGE IS", MIV
440 v(0) = MIV
450 REM ********PRINT OUT THE DISPLACEMENT AND TENSION**********
460 PRINT #1, "NIP POSITION", "TENSION"
470 PRINT "START MOTOR"
480 INPUT YES$
490 PLAY "<<A"
495 REM********VOLTAGE  OUTPUT TO  START  THE DC MOTOR**********
500 CALL FGWRITE'("ACH1,V1(),"C.VLOTS","NT")
510 CALL FGWRITE'("ACH0,V1(),"C.VLOTS","NT")
520 FOR X = 0 TO 250
530 VOLTS(0) = 0
540 CALL FGREAD'("S4","NONE",VOLTS(),"C.AIM8.D","NT")
550 VA4 = ((VOLTS(0) - OF4) * SF4) / 100
560 CALL FGREAD'("DISP","NONE",DISP1(),"C.VOLTS","NT")
570 D = 4.03325 * DISP1(0) - 2.091349
580 PRINT USING "###.## ###.#####"; D; VA4
590 PRINT #1, USING "###.## ###.#####"; D; VA4
600 PRINT "DO YOU WANT TO TAKE MORE EXP. DATA? S=STOP"
610 INPUT E$
620 IF LEN(E$) <> 0 THEN GOTO 520
630 NEXT X
635 REM********VOLTAGE OUTPUT TO STOP THE DC MOTOR*************
640 CALL FGWRITE'("ACH1,V2(),"C.VLOTS","NT")
650 CALL FGWRITE'("ACH0,V1(),"C.VLOTS","NT")
660 PRINT "FINISH"
670 END
```

APPENDIX II

Finite Element (ANSYS) Code for Analysis

```
/PREP7
/TITLE, A single layer of circular model with 5 inches diameter and 8 pli load.
KYPOST,0
KAN,0
KAY,6,1
ET,1,42,0,1,2,,0,0
ET,2,12,0,0,1,0,,1
R,1,0
R,2,0,5E13,,3,5E9
MP,EX,1,1000000
MP,NUXY,1,0.01
MP,MU,2,0.26
CSYS,1
N,1,30,89.7933
N,101,30,90
FILL,1,101
NGEN,11,101,1,101,1,0.0002
CSYS,0
N,1120,-0.24,30
N,1159,-9.5,30
FILL,1120,1159
NGEN,11,40,1120,1159,1,,0.0002
CSYS,1
N,1600,30,89.7933
N,1700,30,90
FILL,1600,1700
TYPE,1
REAL,1
E,1,102,103,2
EGEN,100,1,1
E,102,203,204,103
Egen,100,1,101
E,203,304,305,204
EGEN,100,1,201
E,304,405,406,305
EGEN,100,1,301
E,405,506,507,406
EGEN,100,1,401
E,506,607,608,507
```

```
EGEN,100,1,501
E,607,708,709,608
EGEN,100,1,601
E,708,809,810,709
EGEN,100,1,701
E,809,910,911,810
EGEN,100,1,801
E,910,1011,1012,911
EGEN,100,1,901
CSYS,0
E,1120,1160,1161,1121
EGEN,39,1,1001
E,1160,1200,1201,1161
EGEN,39,1,1040
E,1200,1240,1241,1201
EGEN,39,1,1080
E,1240,1280,1281,1241
EGEN,39,1,1120
E,1280,1320,1321,1281
EGEN,39,1,1160
E,1320,1360,1361,1321
EGEN,39,1,1200
E,1360,1400,1401,1361
EGEN,39,1,1240
E,1400,1440,1441,1401
EGEN,39,1,1280
E,1440,1480,1481,1441
EGEN,39,1,1320
E,1480,1520,1521,1481
EGEN,39,1,1360
E,101,202,1160,1120
E,202,303,1200,1160
E,303,404,1240,1200
E,404,505,1280,1240
E,505,606,1320,1280
E,606,707,1360,1320
E,707,808,1400,1360
E,808,909,1440,1400
E,909,1010,1480,1440
E,1010,1111,1520,1480
CSYS,1
TYPE,2
REAL,2
MAT,2
E,1,1600
```

```
EGEN,101,1,1401
D,1600,ALL,0,,1700,1
D,1159,ALL,0,,1559,40
D,1120,UY,0,,1158,1
ITER,-1
*create,load
ep,958,2,(0.4581*arg1)
ep,957,2,(0.7454*arg1)
ep,956,2,(0.8958*arg1)
ep,955,2,(0.9751*arg1)
ep,954,2,(arg1)
ep,953,2,(0.9751*arg1)
ep,952,2,(0.8958*arg1)
ep,951,2,(0.7454*arg1)
ep,950,2,(0.4581*arg1)
lwrite
*end
*use,load,(1073.7)
*create,load
ep,958,2,0.0
ep,957,2,(0.4581*arg1)
ep,956,2,(0.7454*arg1)
ep,955,2,(0.8958*arg1)
ep,954,2,(0.9751*arg1)
ep,953,2,(arg1)
ep,952,2,(0.9751*arg1)
ep,951,2,(0.8958*arg1)
ep,950,2,(0.7454*arg1)
ep,949,2,(0.4581*arg1)
lwrite
*end
*use,load,(1073.7)
*create,load
ep,957,2,0.0
ep,956,2,(0.4581*arg1)
ep,955,2,(0.7454*arg1)
ep,954,2,(0.8958*arg1)
ep,953,2,(0.9751*arg1)
ep,952,2,(arg1)
ep,951,2,(0.9751*arg1)
ep,950,2,(0.8958*arg1)
ep,949,2,(0.7454*arg1)
ep,948,2,(0.4581*arg1)
lwrite
*end
```

```
*use,load,(1073.7)
*create,load
ep,956,2,0.0
ep,955,2,(0.4581*arg1)
ep,954,2,(0.7454*arg1)
ep,953,2,(0.8958*arg1)
ep,952,2,(0.9751*arg1)
ep,951,2,(arg1)
ep,950,2,(0.9751*arg1)
ep,949,2,(0.8958*arg1)
ep,948,2,(0.7454*arg1)
ep,947,2,(0.4581*arg1)
lwrite
*end
*use,load,(1073.7)
*create,load
ep,955,2,0.0
ep,954,2,(0.4581*arg1)
ep,953,2,(0.7454*arg1)
ep,952,2,(0.8958*arg1)
ep,951,2,(0.9751*arg1)
ep,950,2,(arg1)
ep,949,2,(0.9751*arg1)
ep,948,2,(0.8958*arg1)
ep,947,2,(0.7454*arg1)
ep,946,2,(0.4581*arg1)
lwrite
*end
*use,load,(1073.7)
*create,load
ep,954,2,0.0
ep,953,2,(0.4581*arg1)
ep,952,2,(0.7454*arg1)
ep,951,2,(0.8958*arg1)
ep,950,2,(0.9751*arg1)
ep,949,2,(arg1)
ep,948,2,(0.9751*arg1)
ep,947,2,(0.8958*arg1)
ep,946,2,(0.7454*arg1)
ep,945,2,(0.4581*arg1)
lwrite
*end
*use,load,(1073.7)
*create,load
ep,953,2,0.0
```

```
ep,952,2,(0.4581*arg1)
ep,951,2,(0.7454*arg1)
ep,950,2,(0.8958*arg1)
ep,949,2,(0.9751*arg1)
ep,948,2,(arg1)
ep,947,2,(0.9751*arg1)
ep,946,2,(0.8958*arg1)
ep,945,2,(0.7454*arg1)
ep,944,2,(0.4581*arg1)
lwrite
*end
*use,load,(1073.7)
*create,load
ep,952,2,0.0
ep,951,2,(0.4581*arg1)
ep,950,2,(0.7454*arg1)
ep,949,2,(0.8958*arg1)
ep,948,2,(0.9751*arg1)
ep,947,2,(arg1)
ep,946,2,(0.9751*arg1)
ep,945,2,(0.8958*arg1)
ep,944,2,(0.7454*arg1)
ep,943,2,(0.4581*arg1)
lwrite
*end
*use,load,(1073.7)
*create,load
ep,951,2,0.0
ep,950,2,(0.4581*arg1)
ep,949,2,(0.7454*arg1)
ep,948,2,(0.8958*arg1)
ep,947,2,(0.9751*arg1)
ep,946,2,(arg1)
ep,945,2,(0.9751*arg1)
ep,944,2,(0.8958*arg1)
ep,943,2,(0.7454*arg1)
ep,942,2,(0.4581*arg1)
lwrite
*end
*use,load,(1073.7)
*create,load
ep,950,2,0.0
ep,949,2,(0.4581*arg1)
ep,948,2,(0.7454*arg1)
ep,947,2,(0.8958*arg1)
```

```
ep,946,2,(0.9751*arg1)
ep,945,2,(arg1)
ep,944,2,(0.9751*arg1)
ep,943,2,(0.8958*arg1)
ep,942,2,(0.7454*arg1)
ep,941,2,(0.4581*arg1)
lwrite
*end
*use,load,(1073.7)
AFWRITE,,1,0
FINISH
```

VITA

Chihyih Cheng

Candidate for the Degree of

Master of Science

Thesis : THE EFFECT OF THE ZONE OF SLIPPAGE BEHIND A NIP ROLL UPON WOUND-ON-TENSION

Major Field: Mechanical Engineering.

Biographical:

Personal Data: Born in Changhwa, Taiwan, On Octorber 1, 1965, the son of S.B.Cheng and M.Chen

Education: Graduated from Oriental Institute of Technology, Pan-Chiao, Taiwan, in June 1985; received Bachelor of Engineering in mechanical Engineering degree in 1990 from National Taiwan Institute of Technology, Taiwan; Completed the requirements for the Master of Science degree at Oklahoma State University in July 1994.

Professional Experience: Assistant Engineer, CTCI Cooperation Company, Taipei, Taiwan, 1990; Teaching Assistant, Oriental Institute of Technology, Pan-Chiao, Taiwan, 1991.