ONE-DIMENSIONAL DYNAMIC IMPACT MODEL TO PREDICT HARDNESS OF WOUND ROLLS

By

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2009

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, 2013

ONE-DIMENSIONAL DYNAMIC IMPACT MODEL TO

PREDICT HARDNESS OF WOUND ROLLS

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ACKNOWLEDGEMENTS

This thesis is dedicated in loving memory of my beloved uncle, Maddala Madhava Rao.

I would like to take this opportunity to thank each and every individual who has given me the strength and motivation in successfully completing this work.

First and foremost, I would like to express my gratitude to my adviser and mentor Dr. James Keith Good for his unparalleled support and guidance during the course of this work. His invaluable ideas and his patience to discuss ideas with me has not only helped me complete this work but also kindled the passion for research in me. It was an honor to work for him and I believe I've become a better engineer under him.

I would also like to convey my gratitude to my committee member, Dr. Raman Pal Singh and Dr. Sandip Harimkar whose support and insights have greatly helped in making this work a better one.

I would like to thank Mr. Ron Markum from the bottom of my heart for his valuable guidance in conducting experiments during the course of this research work.

I would like to convey my deepest gratitude to Dr. Cagri Mollamahmutoglu for his patience and invaluable support even in the late hours of the day which helped me a lot in this work.

I owe my life to my ever loving parents Mr. Adari Madhu Sudhana Babu and Mrs. Adari Venkata Ramani who stood against all odds to make me into whatever I'm today. Words are not enough to express how thankful I'm to the almighty for giving me such loving parents and my sister, Pooja Adari.

All this would have never been possible if not for the love, motivation and the support given by the love of my life, Gargeyi Baipa who stood by me during every moment during my Master's helping me in every way she can. I would always be in debt to her.

Last but not the least, I would like to thank WHRC for supporting me monetarily here at OSU.

Name: SAGAR ADARI

Date of Degree: JULY, 2013

Title of Study: ONE-DIMENSIONAL DYNAMIC IMPACT MODEL TO PREDICT HARDNESS OF WOUND ROLLS

Major Field: MECHANICAL AND AEROSPACE ENGINEERING

Abstract:

Wound Roll quality measurement plays a crucial role in predicting defects inside a wound roll. The quality of a wound roll is measured in terms of its hardness. A Rho Meter is one such instrument which measures the hardness of a wound roll in arbitrarily chosen unit called Rho. The Rho Meter works on the principle of impact. The peak force exerted by the striker of the Rho Meter onto the surface of the roll is measured by the accelerometer on top of the striker and is converted into arbitrary units called Rhos. The dependence of the Rho hardness of a wound roll on its radial modulus was studied. The moving components of the Rho Meter were modeled. The wound roll was modeled using a pre-existing code (*Roll Compressor*) that can predict the deformation response of a wound roll due to an external contact. These sub models were combined to produce a 1-D dynamic model that could predict the maximum deceleration of the Rho Meter striker which could then be converted to Rho units.

The model made fairly good predictions of the hardness of the wound rolls. These predictions were validated with experimental results obtained by center winding rolls at constant but varied tensions. Also the case of variation in hardness values with variation of pile heights of wound rolls was studied. The deviation of the hardness values predicted by the 1-D code from the experimental values can be corrected by including the factors such as the dynamically varying pressures, radial modulus, shape of the Rho Meter striker and interlayer slippage at the locality of impact. Also by refining the mesh of the *Roll Compressor*, better results can be obtained but requires longer computational times.

ADVISER'S APPROVAL: Dr. James Keith Good

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LIST OF SYMBOLS USED

P – Radial Pressure

E_t – Tangential Modulus

E_c – Elastic Modulus of the core

E_r – Radial Modulus

E_{roll} – Energy absorbed into wound roll due to impact

F - Force of Impact

F_{peak} – Peak Force imparted by the striker on surface of the roll

h - Thickness of the web

K_1, K_2 – Pfeiffer Constants

k_s - Stiffness of the striker of the Rho Meter

m_s - Mass of the striker

Q - Function of displacement of striker

r - Radius of the wound roll

Rho_{max} - Hardness value at the instant of peak force of impact

T_w - Winding Tension

Δt - Increment in time

V - Velocity of the compressive wave

x_{in} - Distance from which the striker is released to impact the surface of the roll

x_{gap} - Distance between the equilibrium position of the striker and the wound roll surface

α - Coefficient of the second order term in the stiffness equation from Roll Compressor

β - Coefficient of the first order term in the stiffness equation from Roll Compressor

ε_r - Radial Strain

δ - Displacement of the striker

δ_{max} - Maximum displacement of the striker

$\Delta\delta$ - Increment in displacement of the striker during the impact process.

ρ - State Dependent density of the web material

ρ_0 - Density of the web material in free state

υ - Poisson's ratio

σ_r - Radial Stress in a wound roll

CHAPTER I

INTRODUCTION

1.1 Description of Web and Web Handling

A *web* is a continuous flexible strip of material. Many objects which we come across in our day to day lives can be filed into the category of webs. For example, rolls of tape, paper towels, plastic films, aluminum foils, newspapers etc. An important characteristic to note about webs is its length to width ratio which is very high and its thickness is relatively very small. Utilizing the flexible nature of webs, many products today are manufactured in the form of wound rolls of webs for ease of handling, storage and transportation to the next process of manufacturing or as a final end product. This process of converting long webs into wound rolls is called *winding*. Figure 1.1 shown below is an illustration depicting a wound roll and winding process

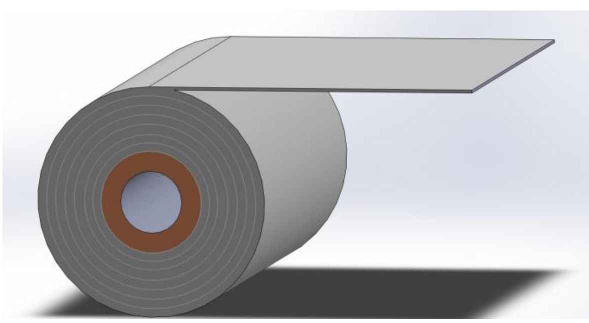


Figure 1.1 : Representation of a wound roll with a central core.

During the process of winding, the web passes through multiple rollers before being finally wound as a roll on a core. Each layer of the material gets added on top of the previously wound layer as time progresses causing pressure in between layers. This pressure keeps changing as the size of the roll keeps increasing. This variation of pressure in between the layers as winding progresses is dependent on the winding parameters such as Tension, Speed, Nip and Torque applied.

The entire process of winding is carried on equipment known as *winders*. Various forms of these winders are available basing on the number of drums. Most commonly used winders are single drum winders and these single drum winders are classified into center winder, center winder with nip roller, surface winder and differential torque winder basing on the application of winding torque.

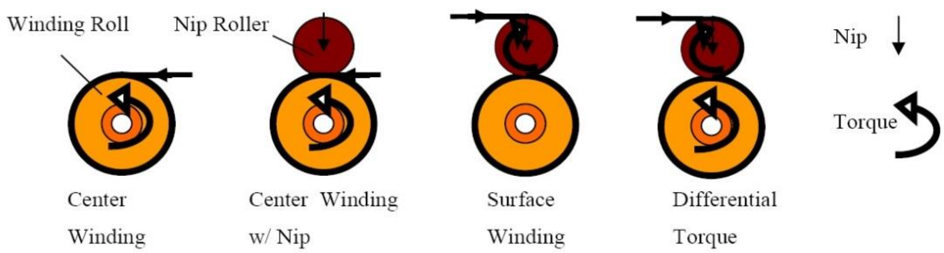


Figure 1.2 : Types of winders.[1]

During the course of this research, we will focus on the simple center winder. In case of a center winder, we do not have additional roller, the nip roller, hence the winding torque necessary for winding is applied at the core region of the roll being wound.

Stresses and displacements are introduced in the structure of the wound roll due to the winding activity. These stresses introduced play a vital role in maintaining the structural integrity of the wound roll and it is the crucial factor in determining the quality of the wound roll. These stresses when left uncontrolled would lead to wound roll defects. Some typically observed roll defects can be seen in the figure below

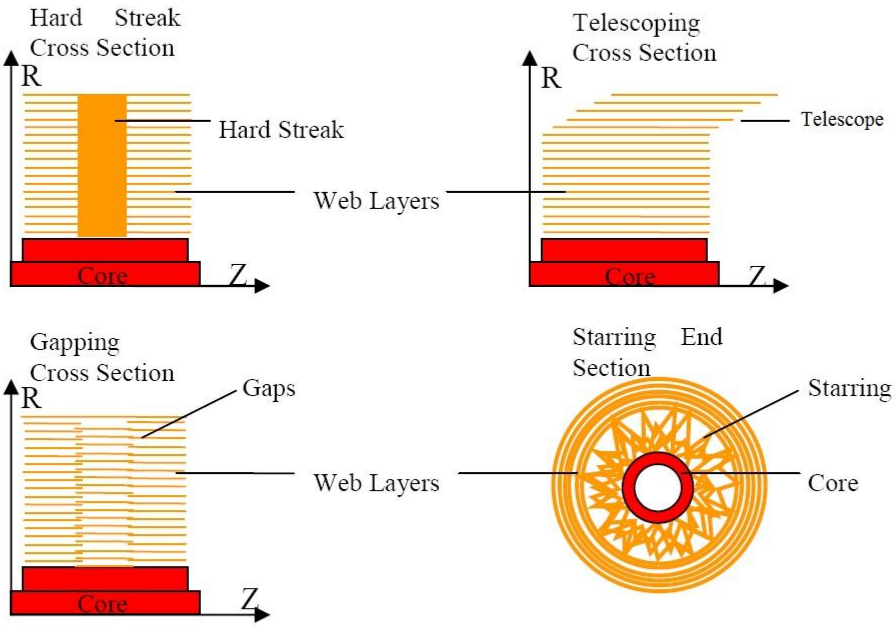


Figure 1.3 : Representation of a few winding defects.[1]

The material properties of the web, the geometry of the web and the winding parameters together can be related to the cause of these defects in wound rolls. So a better understanding of the importance of each of these parameters and how they interact with each other would help in creating good quality rolls by predicting the nature of the stresses and displacements which occur during the process of winding. This understanding of the process can be brought about by the use of computer aided mathematical models. Such models are known as *winding models*. Winding models were first introduced in the late 1950's. The backbone of these models is to solve a second order ordinary differential equation in pressure and radius of the wound roll. This differential equation on solving numerically yields the pressure and stress profiles with respect to the wound roll radius.

1.2 History of Quality Measurement Instruments[2]

Though the winding codes developed help in modeling complex cases, they have not been successful in determining the quality of the wound roll being manufactured at shop floor level. The earliest form of quality measurement device has been a stick or club generally made of hardwood and it was used by the shop floor personnel to strike on the surface of the wound roll. The personnel then observes the sound of the timber and sometimes the vibrations induced in the club handle due to impact. In other words, the personnel is trying to determine the how hard the wound roll is. Though the method of using the club is quick and easy, it posed a problem when it came to quantify the hardness of the roll he tested and also it was difficult to express what he observed.

At this point of time, the Beloit[1] Rho Meter was invented which provided a better means of measuring the hardness of the wound roll. The Rho Meter unlike the rebound testers is an impact tester similar to the club or stick used in early days. The Rho Meter gives a measure of the relative hardness of material and is often considered a reliable source of hardness measurement.

The Rho Meter output is completely different as compared to the winding model's output, which is in terms of pressures and stresses. These engineering units cannot be easily converted into the arbitrary units of hardness read out from the devices on the production floor.

In this study, the objective is to relate the output from the Rho Meter, units of *Rho*, to the outputs of winding models in engineering units of stress. An initial study is made to validate the dependency of hardness on the range of radial modulus values of a wound roll. Later, experiments are carried out to validate the hardness values calculated from a 1-D dynamic impact model. The use of winding models, experimental procedures and the results are discussed in subsequent chapters.

[1] Beloit Manhattan Division, 1910 Lane Blvd. Kalamazoo, Michigan 49003, USA

CHAPTER II

LITERATURE REVIEW

2.1 Review of previous literature

Pfeiffer[3] was one of the earliest to investigate on the radial nonlinearity of the wound roll. He expressed the radial pressure in a compound stack of web as a function of the radial strain as shown in the equation below

$$P = -\sigma_r = K_1(e^{K_2\,\varepsilon_r} - 1) \qquad \{2.1\}$$

Where, K_1 and K_2 called the Pfeiffer's constants and are material specific constants. The values of K_1 and K_2 are found from the stack compression test which will be discussed in subsequent chapters.

He also derived a closed form solution for expressing radial modulus as a function of pressure. The equation below shows the state dependency of the radial modulus on pressure

$$\frac{dP}{d\varepsilon_r} = E_r = K_2(P + K_1) \qquad \{2.2\}$$

Hakiel[4] made one of the most important contributions to wound roll modeling. His model took into consideration the state dependent properties and all the boundary conditions concerning a wound roll. Also he used a polynomial expression in pressure to determine the radial modulus unlike Pfeiffer's exponential equation.

$$E_r = C_0 + C_1 P + C_2 P^2 + C_3 P^3 + \cdots + C_n P^n \qquad \{2.3\}$$

He also devised a second order differential equation to calculate the increments of pressure that are accumulated as a layer of web gets added to the wound roll.

$$r^2 \frac{d^2(\delta P)}{dr^2} + 3r \frac{d(\delta P)}{dr} - \left(\frac{E_t}{E_r} - 1\right) \delta P = 0 \qquad \{2.4\}$$

The above mentioned second order partial differential equation is subjected to two boundary conditions. On the outer surface of the wound roll, the increment in the pressure due to laying the last lap is equated to the circumferential or hoop stress, given as

$$\delta P|_{r=s} = \frac{T_w|_{r=s}}{s}\ h \qquad \{2.5\}$$

The inside boundary is the core. He described the boundary condition at the core as shown in the equation below

$$\left[\frac{d(\delta P)}{dr}\right]|_{(r=1)} = \left[\left(\frac{E_t}{E_c}\right) - 1 + \vartheta\right] \delta P\ |_{(r=1)} \qquad \{2.6\}$$

Hakiel used a numerical solution to solve the differential equation due to the ratio of E_t and E_r not being constant but instead being a numeric function of the radius of the roll. He used the finite difference approach to solve the equations for increment of each lap and calculating the pressure increment. Prior to solving for the increments in pressure, the material properties such as radial modulus was calculated and updated in the model. At the end of winding, the tangential stresses were calculated using the equilibrium equation shown below

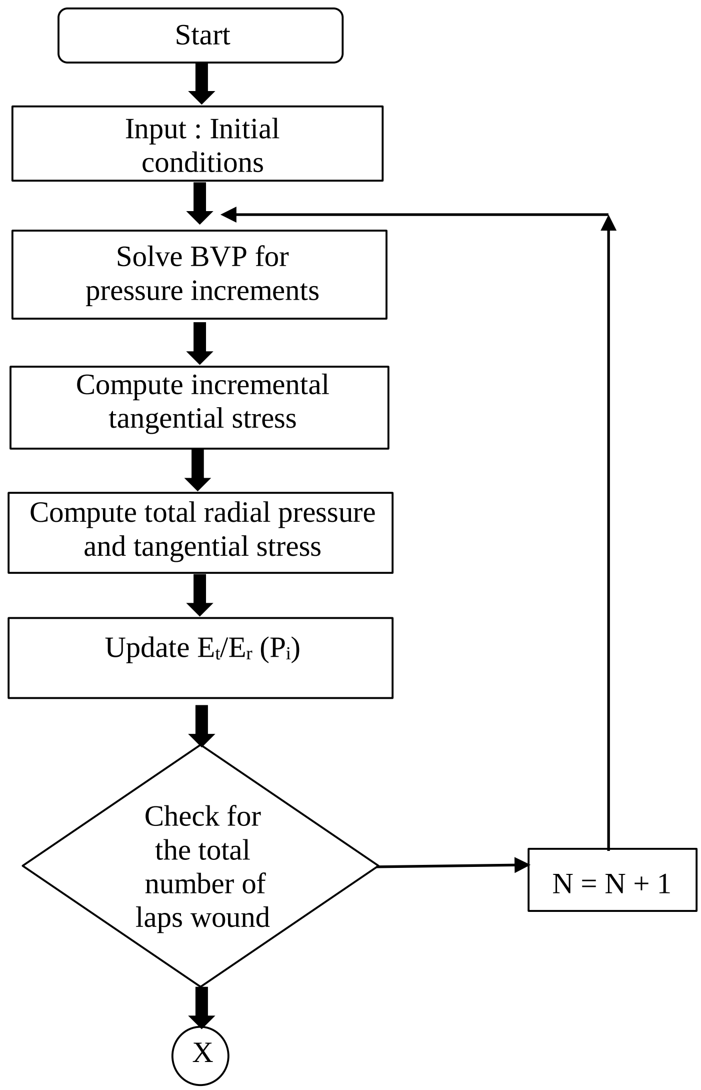
$$\sigma_t = r\frac{d\sigma_r}{dr} + \sigma_r \quad \{2.7\}$$

Dipesh Mistry[5] developed a two-dimensional winding model coupled with a finite element dynamic impact model to convert the outputs like stresses and pressures to units that are used by existing quality measuring devices such as the Rho's measured using a Rho Meter. He studied the variation of roll hardness with respect to roll geometry and winding parameters by means of experimentation. He also studied the relation between the hardness and the peak pressures in a wound roll. He conducted experiments to study the mechanism of the Rho Meter and modeled it into a finite element dynamic impact model. He validated the output from this model with the experimental values.

Mistry found out that the value of hardness of a wound roll increases with increase in the winding tension. He also inferred that the hardness measurements obtained from the Rho Meter will show an increasing trend up to a certain extent with increase in winding tension and beyond that the Rho Meter readings reach an asymptote. He also noted that the hardness readings taken in the machine direction and cross machine direction are similar which implies the geometry of the Rho Meter's striker does not play a crucial role in determining the hardness value.

2.2 A One-Dimensional Winding Model – *WINDaROLL*

The one-dimensional winding model, *WINDaROLL*, hereafter used in this research, is originally developed by Good,J.K. and Roisum,D.R.[6] based on the principles of Hakiel's winding model, which has been discussed previously in this chapter. The following flow chart best explains the working of the WINDaROLL winding model.



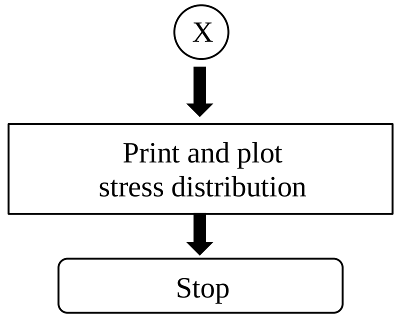


Figure : 2.1 Flow chart showing the algorithm of *WINDaRoll* winding model.

2.2.1 Input to *WINDaROLL* winding model

The inputs to the winding model should be accurate in order to get a good result which can be validated with an experiment. Before giving the input values to the winding model, first the Center winding option should be selected. Table below illustrates the input parameters that need to be given to the WINDaROLL winding model:

Input	**Components**
Grid Points	Number of grid points in the roll at which the stresses are to be calculated
Winding Conditions	Initial and final winding tensions including the winding taper
Core and Roll Geometry	Inside, Outside diameters of core and Outside diameter of wound roll
Web Material	Web Caliper, Web Width, Tangential Modulus, Pfeiffer’s Constants, Poisson’s ratio of web
Core Properties	Core Material Modulus, Poisson’s ratio of Core, Core Stiffness

Table 2.1 : Table showing the input required for the WINDaROLL winding model.

2.3 Research Objective

Literature review shows that previously attempts have been made to connect the output from winding models to the measurements made in laboratory or shop floor. Those attempts required reasonable mesh densities which took an enormous amount of computation time and also needed modeling of the quarter wound roll instead of the localized area struck by the striker of the Rho Meter. There are two objectives of this research. The first objective will be to study the dependency of roll hardness on the state dependent radial modulus. The second objective is to develop a one-dimensional model as an extension to the wound roll models which predicts the hardness values in Rho’s by utilizing the output’s from the wound roll model in least possible computation time.

CHAPTER III

ROLL QUALITY MEASUREMENT INSTRUMENTS

3.1 Introduction to Roll Quality Measurement Instruments

The Hardness of a wound roll is measurable. As such wound roll quality has been inferred more by hardness measurement than any other method. Hardness measurements are qualitative when estimating roll quality. It is unknown what roll hardness must exist to prevent slippage of rolls during winding or during transportation. It is unknown what roll hardness will permit or prevent roll buckling. Hardness can be very informative when several measurements are made across the roll width. Web or coating thickness variation across the web width will produce a hardness variation. An objective of this research is to couple hardness measurements to winding models to help predict roll defects in the engineering units. A discussion of hardness instruments follows.

3.1.1 Billy Club[6]

The Billy Club is considered one of the oldest and crude means of measuring the hardness of a wound roll. Using this, the operator strikes on the surface of the roll. From the strike the operator gets a feel for the roll basing the sound emitted due to strike. The thicker regions would give a higher pitch as compared to the less thicker regions. However, the use of clubs has many limitations and shortcomings. Some them being, its inability to quantify the measurement and record its value, highly dependent on the skill of the operator using the club, difficult to make relative measurements, it sometimes may damage the surface its striking like removal of coatings applied on surface of the web.

3.1.2 Rho Meter[6]

The Rho Meter was invented by David Pfeiffer in 1965. It was a first of its kind instrument to quantify the value of hardness of the wound roll it is being struck on. It's a hand held impact testing machine which calculates and displays the value of hardness of the wound roll basing on the peak deceleration suffered by the striker by coming in contact with the surface against which it is struck. The Rho Meter consists of a cantilever spring system with the striker attached to the end of the cantilever. This cantilever system guides the striker in vertical motion by accelerating it to a known constant velocity at every strike. After the impact of the striker against the surface, the accelerometer mounted on top of the striker measures the value of the peak deceleration and the internal circuitry of the Rho Meter converts this value of peak deceleration into a unit of hardness called "*Rho"* and displays the output on a digital screen. Shown below is a Rho Meter. However, the Rho Meter too has some limitations. It cannot be used on soft materials such as non-wovens nor for hard materials like footboard, metals etc. Shown in figure 3.1 on the next page is the Rho Meter and its calibration block.

Figure 3.1 : Beloit Rho Meter.[7]

3.1.3 Rho Hammer[8]

The Rho Hammer is a lighter and computerized model of the Rho Meter. It consists of a hammer or striker with a mounted accelerometer, which measures the energy of impact between the striker and the roll and the peak deceleration of the striker. This accelerometer is connected to a combined hand held signal processor and computer which reads the values of hardness on a scale similar to the Rho Meter and also records it. But, similar to the hand held club, the accuracy of reading taken using this instrument depends on how good strike is or rather the skill of the operator using it. It doesn't have good repeatability due to the above mentioned factor. A view of the Rho hammer and its computer can be seen on the next page.

Figure 3.2 Rho Hammer.[9]

3.1.4 Backtender’s Friend[6]

The Backtender’s Friend is hardness profile generator as a function of the roll diameter and its position across the width of the roll. It has a wheel, which is mounted on a carriage and rides on the roll being wound. This wheel has a sensor button on its circumferential periphery which hits the roll once in a complete revolution. The value obtained from the impact is recorded and the carriage moving across the width makes the wheel take readings at each location on the width of the roll. Though useful in many cases, the Backtender’s Friend also has some limitations. The first and foremost being it is expensive and bulky. Due to this it is difficult to handle and maintain. Also its impact may sometimes cause damage to materials which are pressure sensitive. In addition to the above, the Friend also read out readings that are unique to it instead of a fundamental engineering unit.

3.1.5 Schmidt Hammer[6]

The Schmidt Hammer was initially used to measure the hardness of cured concrete. It measured on the principle of measuring the co-efficient of restitution, which is the square root of the ratio of height to which the striker rose to the height from which the striker was dropped. It consists of a spring loaded plunger which is pressed against the surface of the roll leading to the compression of the spring. After sufficient compression, the plunger is made to strike the roll and rebound due to release of the spring. This height of rebound is recorded in a scale designated in "*R*" units. Repeating the procedure across the width of the roll would yield the hardness profile varying across the width of the roll. Figure 3.3 shown below is the Schmidt Hammer.

Figure 3.3 Schmidt Hammer.[10]

3.1.6 ParoTester [5],[6]

Similar to the Schmidt Hammer, the ParoTester infers hardness by measuring coefficient of restitution. The ParoTester measure the impact and rebound velocities and converts it into an instantaneous hardness value. The value is designated in "*L*" units. The ParoTester has many advantages over the Rho Meter and the Schmidt Hammer as its impact energy is much less than both the former testers. This instrument is supposed to be useful for assessing hardness of delicate and sensitive materials. Figure 3.4 is a picture of the ParoTester.

Figure 3.4 : ParoTester.[11]

CHAPTER IV

WINDING EQUIPMENT AND WEB MATERIAL PROPERTIES MEASUREMENT

4.1 Introduction

Throughout this research, experimental validation is done by winding rolls at different and constant tensions. Winding of rolls is carried out on the Web Handling Research Centre small scale winding machine with cantilever rolls. The rolls were wound at a low and constant speed throughout the process of winding to avoid air entrainment, which makes the roll softer. Hardness readings are then taken on the surface of the roll with the help of a Rho Meter. Below is a description of the equipment used during the course of this research.

4.2 Winder Setup

The Small Scale Winder is a center winding machine which consists a number of cantilever rolls on which the web passes during the process of winding. The tension in the web is applied by means of a feedback tension control system. This consists of a magnetic brake at the un-winder and basing on the tension feedback, it controls the speed of the un-winder to create tension in the web travelling on the rollers. The winder is equipped with a web guide which monitors the position of the edge of the web to avoid lateral misalignment during winding. During winding, the speed is maintained at a minimal to avoid air entrainment. Presence of air in between the layers causes the web to float thus making is softer and decreasing its quality. The limitation of this winder is it can only wind rolls in the tension range of 3 lb to 20 lb.

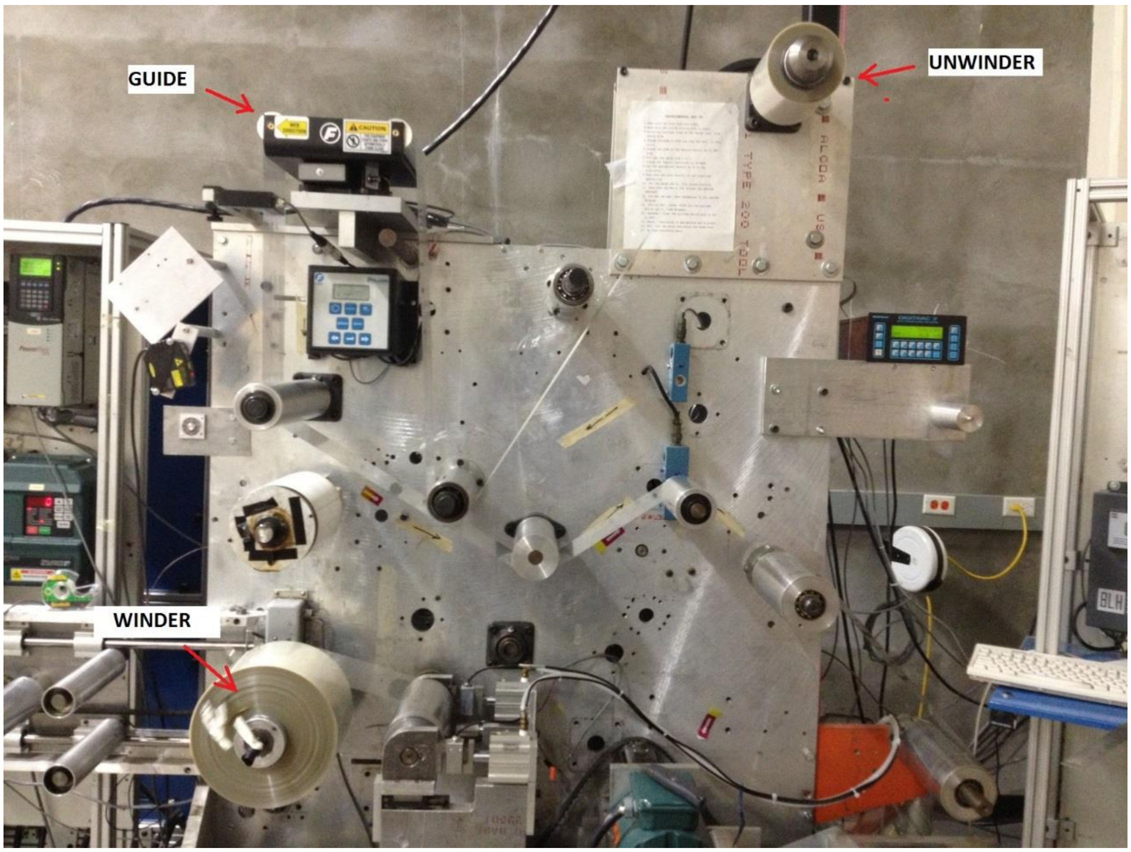


Figure 4.1 : Small scale winding machine at WHRC, Oklahoma State University.

Steel Cores are used during the winding to wind the web upon. These cores had an internal diameter of 3 in and an external diameter of 3.5 in. The rolls were wound until the pile height is 3.5 in. The Rho Meter is then placed on the surface of the roll in a tangential way and the trigger is triggered in a uniform way. The hardness value displayed on the Rho Meter display was recorded manually. In this way, ten readings are taken on the surface of the roll and the average value of hardness is calculated. But, before using the Rho Meter on the wound roll, it is first struck on the calibration block to check if the Rho count given out by the Rho Meter is within the tolerable limits.

4.3 Choice of web materials

The web materials chosen for this research are Dupont-377 and Dupont-S materials. The thickness of both these materials was taken as 92 gauge or 0.000092 inch thick and 6 inch wide. These two materials are very distinct to each other. The Dupont-377 had surface roughness of 2.12 μm and Dupont-S had a surface roughness of 0.221 μm. Below is a picture of the two materials taken into consideration.

Figure 4.2 : Web Materials.

One more important reason for the choice of these materials for the current research is the wide varying nature of their K_2 (Pfeiffer's constant) value due to their surface roughness. Most of the commonly available other web materials fall in the range of K_2's for both these materials thus implying that the following research can be applicable for those materials too.

4.4 Determining Material Properties

In order to get accurate results while modeling, it is important to find the material properties of the web and the core upon which the web is wound. The web characteristics needed are the Pfeiffer's constants, K_1 and K_2 of the web material and its tangential modulus or Machine Direction Modulus (E_t). The Pfeiffer's constants can be measured using the Stack Test and the tangential modulus can be measure using the Stretch Test. Following is a brief description of the tests.

4.4.1 Stack Test

The Stack Test gives us a measure of the radial modulus (E_r) of the web material. The radial modulus is considered as a crucial parameter of the structure of the wound roll. The radial modulus of the wound roll is state dependent on the value of the pressure at a particular location in radial direction. Below is the experimental setup to perform the stack test.

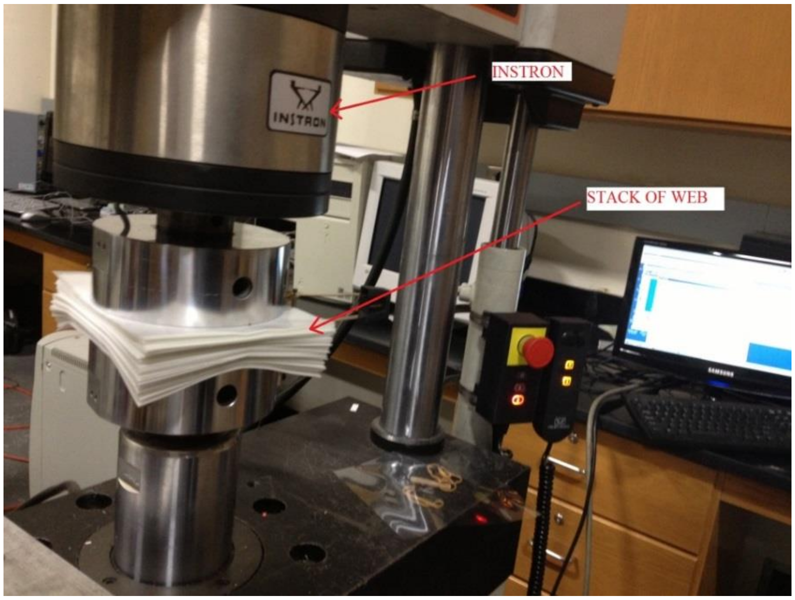
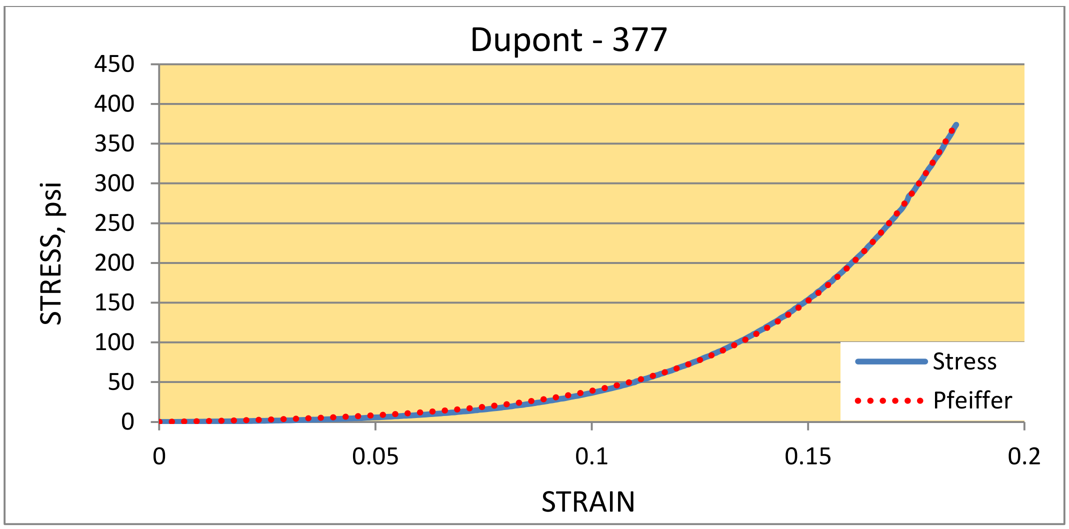


Figure 4.3 : Stack Compression Test on INSTRON.

The Stack Compression Test was done on INSTRON on a stack of the web material of 1 in height. The compression was carried out very slowly, at a rate of 0.06 in/min, to allow any trapped air between the layers to escape. The dynamic values of load and corresponding displacement were recorder in the data logger connected to the INSTRON. The data obtained is the stress values as a function of the strain underwent by the stack of the web as shown in the charts below for Dupont – 377 and Dupont – S respectively.



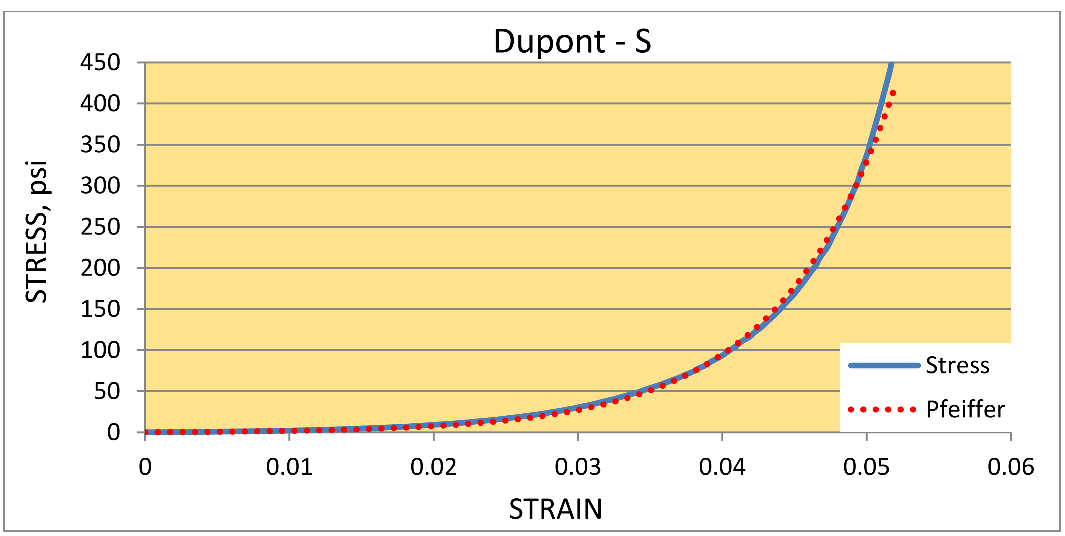


Figure 4.4 : Stress vs. Strain plots of Dupont-377 and Dupont-S.

The blue curve in the charts shown on the previous page represents the stress vs. strain values obtained from the stack test. The green curve is a least square approximation used to fit the curve to the experimental data. It is obtained by using the Pfeiffer's equation described earlier in {2.1}.

$$P = K_1(e^{K_2 \varepsilon} - 1)$$

Optimization the value of K_1 and K_2 is done until a good fit is obtained.

The values of K1 and K2 thus obtained for both the materials are shown in the tabular form below:

Material	K_1	K_2
Dupont -377	3.12	26.05
Dupont - S	0.67	123.88

Table 4.1 : Table showing the Pfeiffer's constants of the web materials chosen.

4.4.2 Stretch Test

The tangential modulus (E_t) or the machine direction modulus of the web is measured by means of the stretch test. The tangential modulus is as important as the radial modulus as these two are the factors that affect the radial stresses in the wound roll governed by the second order ordinary differential equation. Following are the steps of performing the stretch test.

A 50 ft. length of web is taken and is laid on the floor. One end of the web is fixed and below the other end, a blank paper is kept and the datum line is marked on the web. Now load is applied at the free end of the web using a force gauge. At specific intervals of load, the displacement of the datum line is marked on the blank sheet of paper lying below the web. Now the stress strain and strain-displacement relations are used to predict the tangential modulus of that web material. Shown below is a picture of the stretch test.

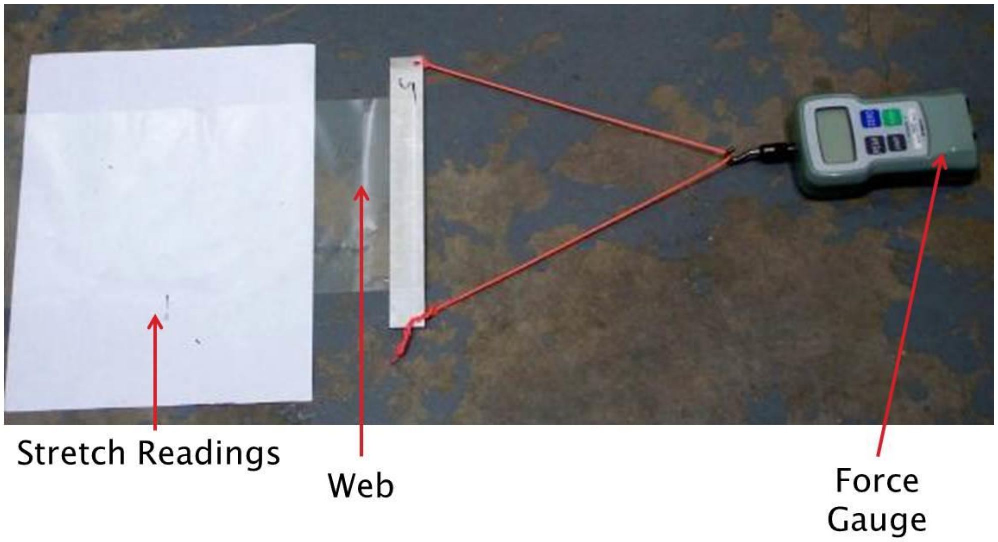
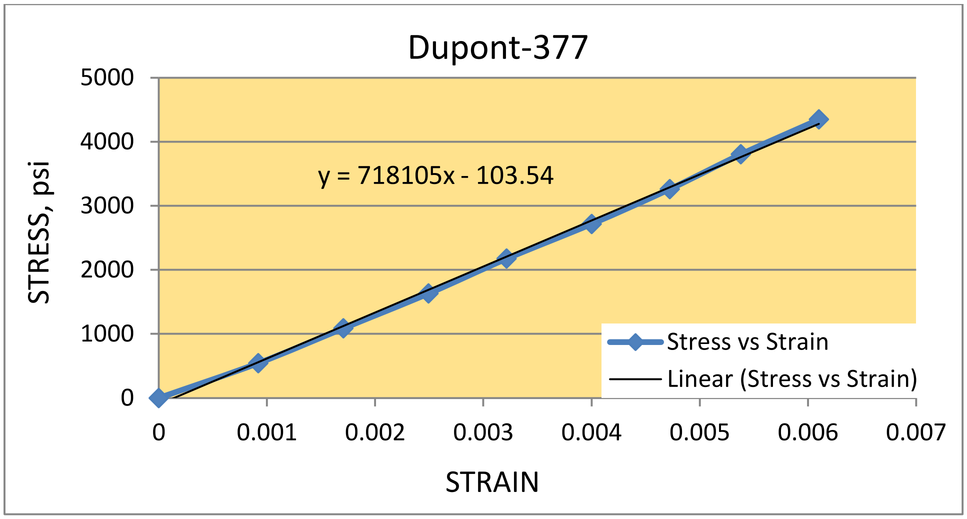


Figure 4.5 : Stretch Test setup.[7]

The strain is calculated from the value of the displacement of the datum line at every corresponding load. Stress calculations are carried out using the load applied and the area of the web. Using these values of stress and strain, plots are plotted and the value of tangential modulus of each material is determined by finding the slope of the stress-strain curve of respective material. Shown in the successive page are the stress-strain curves of Dupont – 377 and Dupont –S materials.



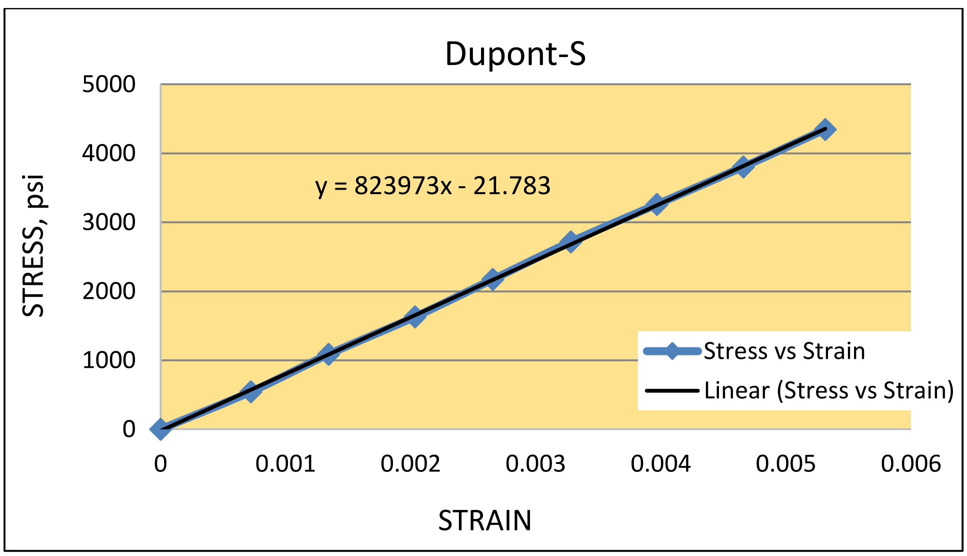


Figure 4.6 : Stress vs. Strain plots obtained from Stretch Test.

After fitting a linear trend line to the stress-strain curve, we get the equation of the line which helps us in determining the slope or tangential modulus of the material. The values observed from above plots are, tangential modulus for Dupont-377 is nearly 718000 psi and for Dupont-S it is 824000 psi.

4.4.3 Summary of material properties used in this research

Material	**Thickness (in)**	**Width (in)**	**K_1**	**K_2**	**Tangential Modulus E_t, psi / in^2**
Dupont-377	0.000092	6	3.12	26.05	718000
Dupont-S	0.000092	6	0.67	123.88	824000

Table 4.2 : Table showing the materials properties of the web materials.

4.5 Pull Tab Tests

The Pull Tab Tests are used to validate the pressures predicted in a wound roll using a winding model. Before the pull tabs are used during the actual winding process, they are calibrated in the INSTRON by compression tests. During the calibration, these pull tabs are placed in between 1 in thick stacks of web material and these stacks are compressed. Periodically, the compression is stopped so that the stack is under a static load. Now, the force required to cause the slippage of the tab is measured using a force gauge as shown in the next page. This helps us in estimating the pressures inside the wound roll for a given force required cause slippage of the tabs which are placed in the wound roll.

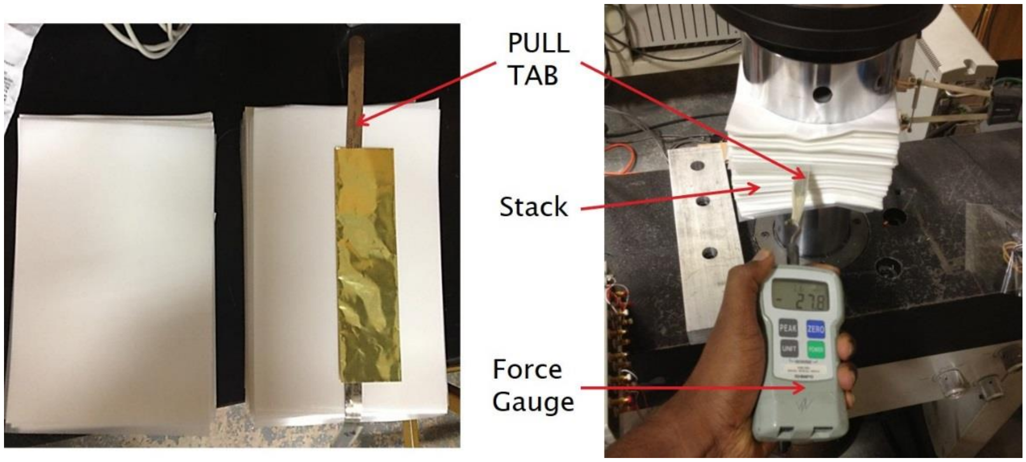


Figure 4.7 : Pull Tab test.

Shown below is the plot which is obtained from the calibration experiment of the pull tabs for Dupont - 377.

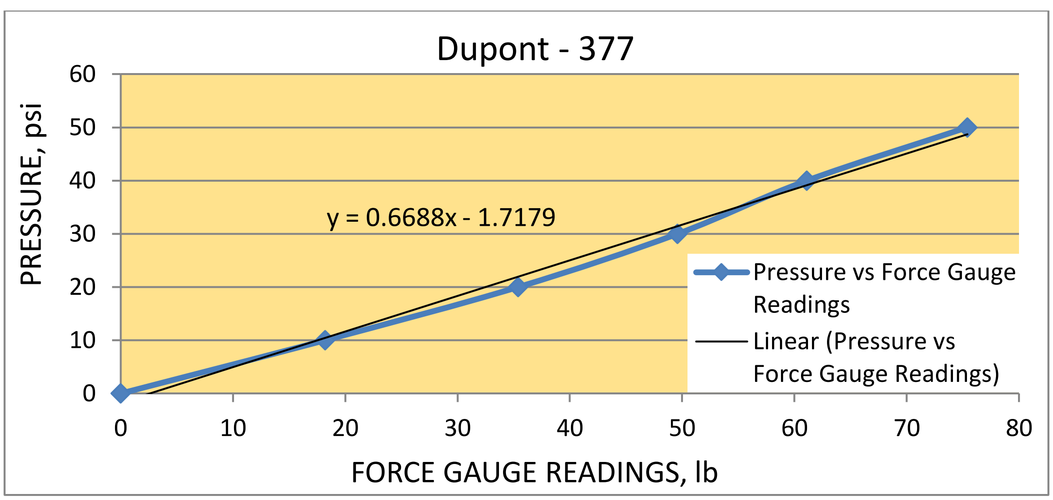


Figure 4.8 : Pressure vs. Force Gauge Readings plot for Dupont – 377.

From the plot above we obtain the equation for calculating the pressures basing on the force gauge reading in a pull tab test. Equation described below is the equation for Dupont – 377.

$$Pressure = 0.6688 * Force\ Gauge\ Readings - 1.7179 \qquad \{4.1\}$$

Similarly on plotting the values obtained from calibration experiment for Dupont – S, we get the following plot:

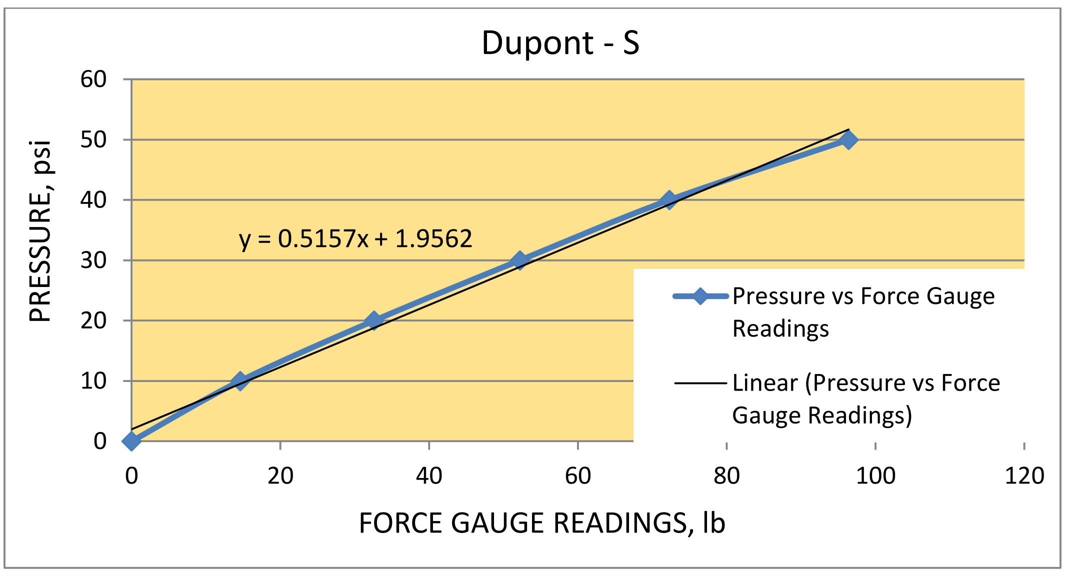


Figure 4.9 : Pressure vs. Force Gauge Readings plot for Dupont – S.

The trendline for the plot would give us the linear equation for the Pressure in a wound roll as a function of the force gauge reading from the pull tab. Shown below is the equation applicable for Dupont – S.

$$Pressure = 0.5157 * Force\ Gauge\ Reading + 1.9562 \qquad \{4.2\}$$

4.6 Roll winding with Pull Tabs

` With all the required values in hand, we now proceed to wind rolls of the two materials with the different and constant winding tensions and perform the pull tab tests on them to determine the inter-layer pressures and then compare them with the output obtained from the 1D winding model. Winding was done at low speeds to minimize air entrainment. The Pull tabs are inserted at specific radii during winding as shown in the figure below:

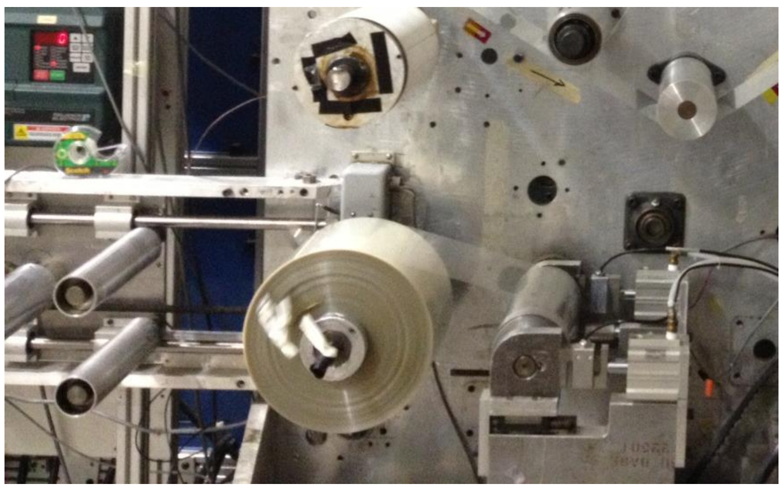


Figure 4.10 : Wound roll with Pull Tabs inserted at specific radii.

After the roll is wound to the required diameter, the winder is stopped. The Pull Tabs in the wound roll were then tested for slippage by pulling them using a force gauge and the corresponding force gauge values and radial locations were recorded. These values are then plugged into equation 4.1 or 4.2 (basing on the material used) to convert the force gauge values into the respective pressure values at each radial location later to be compared with the pressure values obtained from the 1-D winding model.

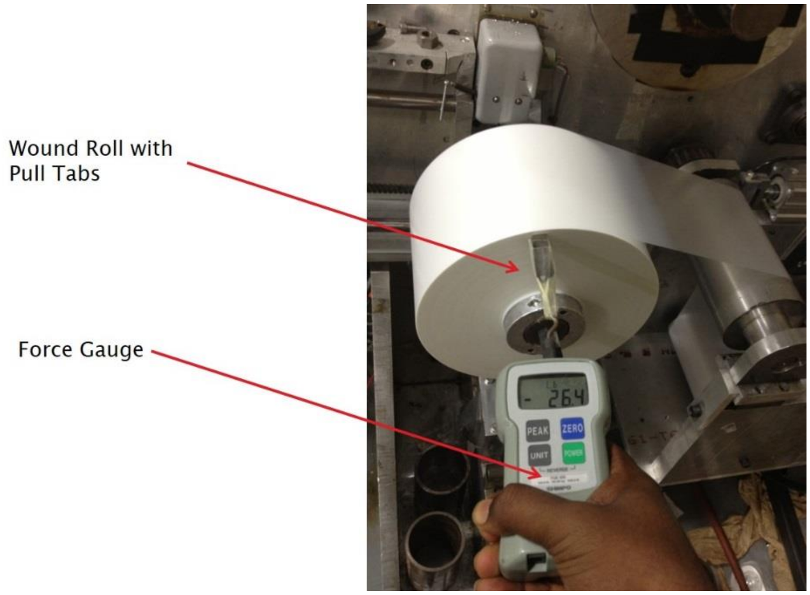


Figure 4.11 : Pull Tab test on a wound roll.

The following table illustrates the values obtained from the pull tab tests on Dupont – 377 roll:

Winding Tension, (lb)	Radius, (in)	Force Gauge Reading, (lb)	Pressure Experiment, (psi)	Pressure Model, (psi)
3	1.75	32.9	20.3	17
	2.5	22.9	13.6	10.16
	3.5	21.4	12.6	10.14
	4.25	21	12.3	10.13
	5	20.3	11.9	9.06

Table 4.3 : Force gauge readings obtained from Pull Tab test on Dupont-377.

Plotting the values obtained on a chart would help us in better understanding of the comparison between the experimental and model values. Plot shown in the successive page shows the comparison:

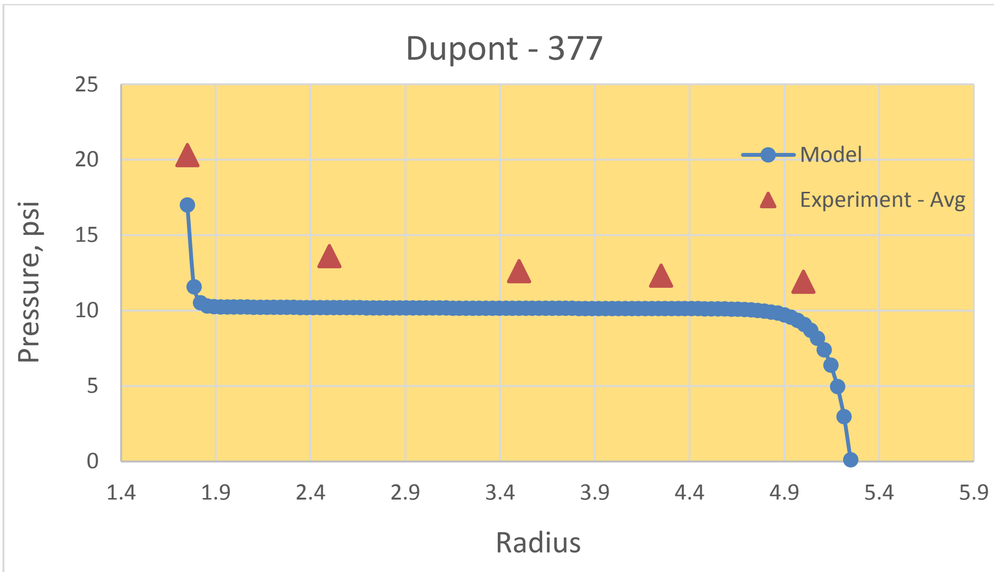


Figure 4.12 : Pressure vs. Radius plot showing the comparison between experimental and model values for 92 gage DUPONT 377 wound at 3 lb tension.

We notice from the plot above that the pressure values from the winding model compare reasonably well with the experimental average values. But nevertheless a difference is observed. This might be due to the variation of web thickness. The material is said to be of 92 gage or 0.00092 inch but since it's a material with higher roughness values, the thickness is expected to vary due to the asperities on the web. This variation in thickness leads to variation in value of winding tension in terms of psi from the lb value which is used as an input to the winding model. Now let us perform the same operation as done above on Dupont–S material but using the equation 4.2, while calculating the pressure values form force gauge values, to check the comparison between the pressure values obtained from experiment and 1-D winding model. Table below displays the pressure values from both the sources:

Winding Tension, (lb)	Radius, (in)	Force Gauge Reading, (lb)	Pressure Experiment, (psi)	Pressure Model, (psi)
3	2.495	57.8	31.8	26.9
	3	55.6	30.6	26.7
	3.7	52.7	29.1	26.6
	4.695	45.5	25.4	20
	5	33.8	19.4	15.1

Table 4.4 : Force gauge readings obtained from Pull Tab test on Dupont-S.

Plot shown below is the pictorial representation of the data shown in the table above

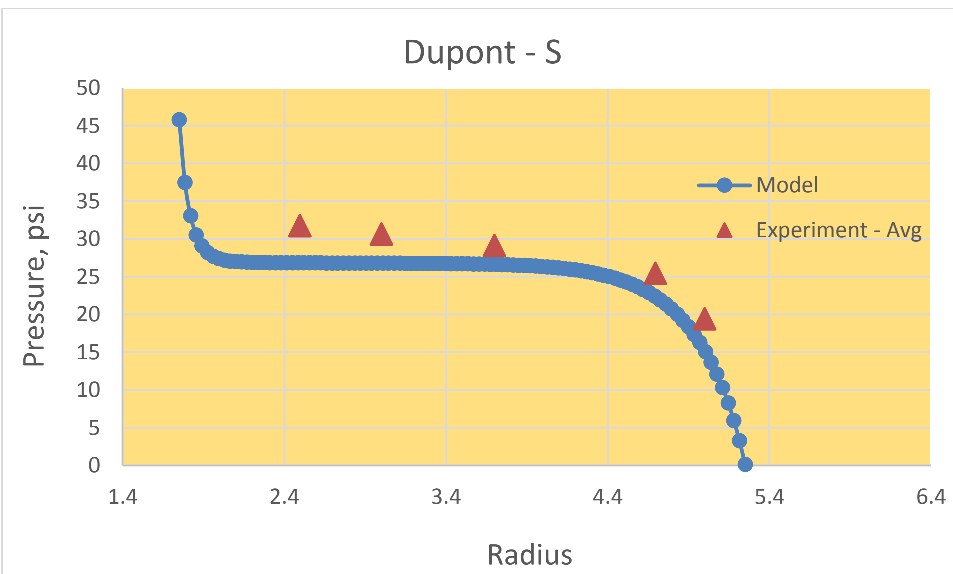


Figure 4.13 : Pressure vs. Radius plot showing the comparison between experimental and model values for 92 gage DUPONT-S wound at 3 lb tension.

From the plot above we notice that the pressure values from the 1-D winding model compare well with the experimental average values even for the Dupont – S material. From the results of both the cases we can infer that the values obtained from the 1-D model, *WINDaROLL*, can be further used to predict the values of inter-layer pressures quite accurately.

CHAPTER V

DEPENDENCE OF HARDNESS ON THE RADIAL MODULUS OF A WOUND ROLL

5.1 Introduction

As mentioned earlier, the first objective of this research is to test the dependence of hardness on the radial modulus of the wound roll. This study was carried using two different web materials, namely, Dupont-377 and Dupont-S. The roadmap to achieving this objective was to find the right winding tensions for the respective web materials in such a way that their wound rolls had nearly same radial modulus values on the outside. This was studied with the aid of the values obtained from the various tests to measure the material properties and which are mentioned in the previous chapter. These material property values were used as input to the 1-D winding model, *WINDaROLL* along with the values concerning the winding conditions. The output from the winding model was then used to establish the experimental parameters. The above mentioned approach will be discussed in detail in the sections below.

5.2 Input to *WINDaROLL*

As stated previously in the literature review, the *WINDaROLL* is a one dimensional winding model which would predict the radial pressure distribution in a wound roll basing on the input winding parameters and the material properties of the web and the core. The figure shown in the subsequent page is the interface of the *WINDaROLL*.

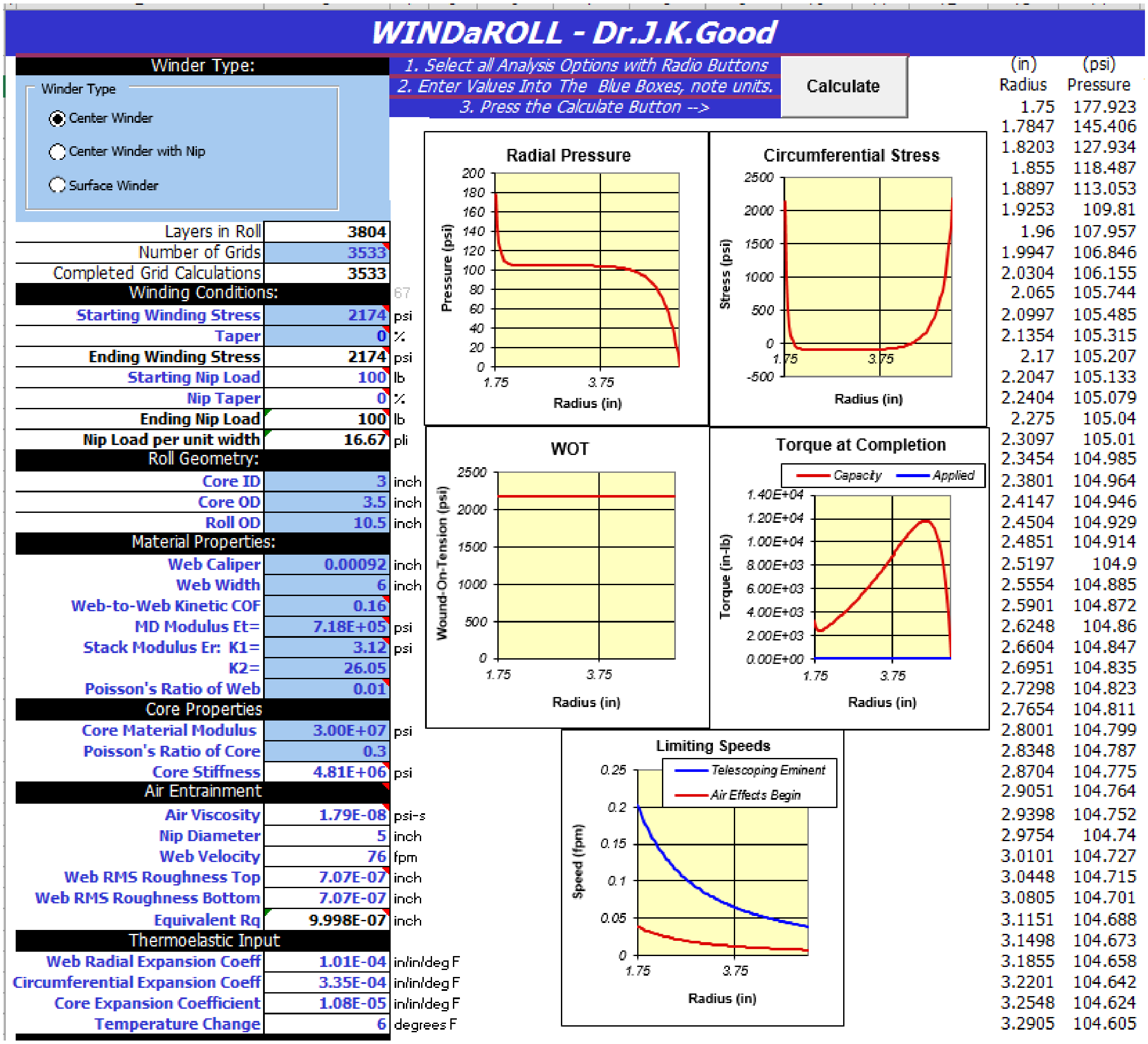


Figure 5.1 : Input sheet of *WINDaROLL*

The input to the above code is given beginning from the winding conditions section where the initial winding stress and the final winding stress are specified. These values of stress are calculated using the equation shown in the next page.

$$Winding\ Stress = \frac{Winding\ Tension\ (lbf)}{(Web\ Width * Web\ Thickness)} \qquad \{5.1\}$$

As the experimentation is performed on a web which is 6 inches wide and 0.00092 inches thick, the winding stress is calculated using these numerical values and then is used as input to the *WINDaROLL*. Since we are using Center Winding, it is not necessary to input any Nip Load values. Next, we need to specify the values of the roll dimensions in the Roll Geometry section. Here the inside and outside diameters of the core and also the final diameter of the roll are specified. In the Material Properties section, the Pfeiffer's constants and the Machine Direction values obtained from the Stack Test and the Stretch Test respectively should be used. Since the experimentation is carried on Dupont-377 and Dupont-S web material of 92 gauge, the Web Caliper is 0.00092 in. Reasonable values are used in the fields of Web to Web Kinetic Coefficient of Friction and Poisson's ratio of the web. In the next section, the Core Properties need to be specified. Since a steel core is used, the properties of steel are specified while filling out these fields. Further sections requires the values needed for calculation of effects of Air Entrainment and Thermoelastic Input but these are not taken into consideration as the winder is run at a very low speed of 40 rpm during the experimentation. On executing the code with the above inputs, the winding model gives the radial distribution of pressures inside the wound roll as shown in the figure on the next page.

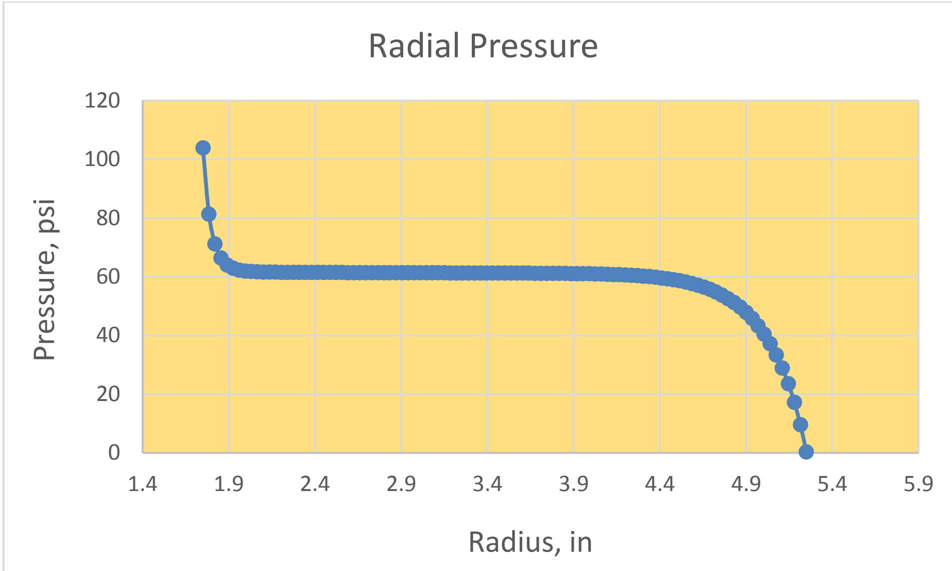


Figure 5.2 : Sample Pressure profile of a wound roll (Dupont – 377), 92 gage wound at 9lb.

The procedure mentioned above is performed on the two web materials chosen and the pressure values obtained from the winding model are converted into radial modulus values at each radial location using the equation 2.2 :

$$E_r = K_2(P + K_1)$$

Where, K_1 and K_2 are the Pfeiffer constants of the respective web materials measured from Stack Compression Test. Now, the radial modulus values are compared for both the rolls. If the radial modulus values are not close to each other, then the winding tension values are varied and then winding model is run again until a good convergence between the radial modulus values is obtained. This procedure can be better explained using the flow chart shown on the next page.

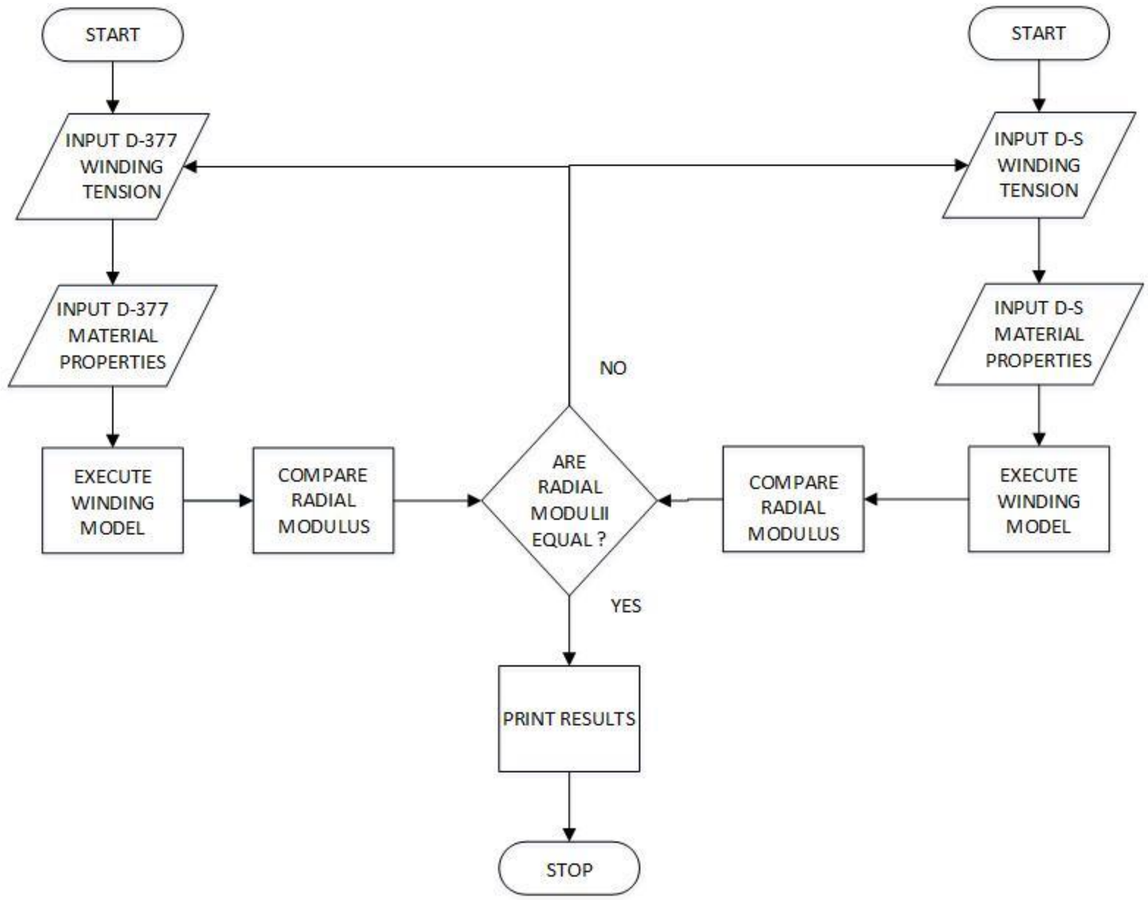


Figure 5.3 : Flow chart to obtain winding tensions for Dupont-377 and Dupont-S with the criterion of equal radial modulus.

The above algorithm is repeated on both the web materials until satisfactory results are obtained in terms of the radial modulus. Shown on the next page are the list of successful input values to the *WINDaROLL* for the Dupont -377 and Dupont-S web materials to have same radial modulus on the outer surface of the wound roll.

PROPERTIES	Dupont-377	Dupont-S
TENSION	13.45 lb.	3 lb.
MD MODULUS	718100 psi	824000 psi
CORE ID	3 in	3 in
CORE OD	3.5 in	3.5 in
ROLL OD	10.5 in	10.5 in
K_1	3.12	0.67
K_2	26.05	123.88
WEB CALIPER	0.00092	0.00092

Table 5.1 : Input parameters to *WINDaROLL.*

After a number of iterations using the 1-D winding model, it was found that the values of outer radial modulus for the Dupont-377 and Dupont-S wound rolls converged well when the winding tension of Dupont-377 is 13.45 lb and for the Dupont-S is 3 lb. Though other pairs of winding tensions were found, the above mentioned values were chosen due the limitation of the winder in the laboratory.

5.3 Output from *WINDaROLL*

The chart in next page shows the distribution of pressure in radial direction for the wound rolls of different materials when wound at the above mentioned respective tensions.

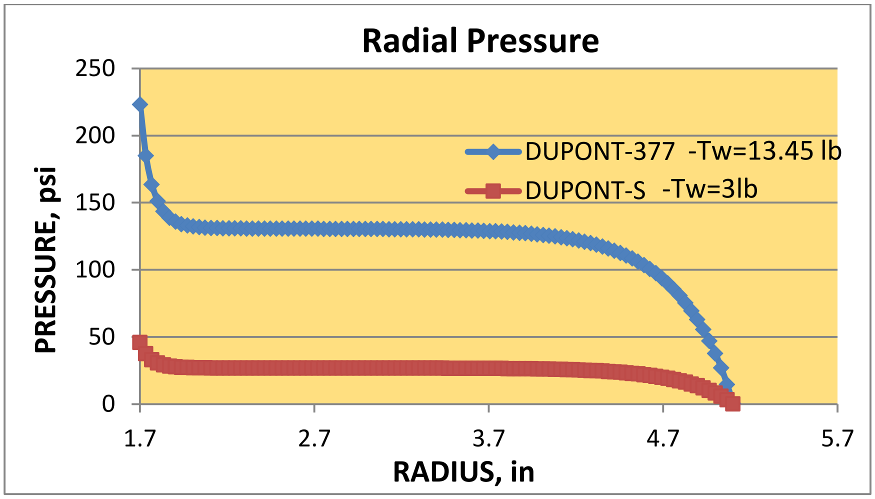


Figure 5.4: Pressure profiles for Dupont-377 and Dupont-S when wound at their respective winding tensions of 13.45 lb and 3 lb respectively.

We notice a drastic difference in the radial distribution of pressures for both the wound rolls due to the difference in their Pfeiffer constants. But as seen from the work of Mistry[5], the hardness measurement is considered as a local measurement but there is no estimate as to how local the measurement is made with respect to the outer surface of the wound roll. The following section will discuss the same.

5.4 Estimation of affected region of a wound roll during hardness measurement.

In order to estimate the region of the wound roll affected or playing part during the process of hardness measurement, a wave propagation model is constructed. This wave propagation model helps in determining how local the hardness measurement is. In this model, the propagation of the compression wave into the roll due the strike of the striker on the surface of the roll is studied. In this model, the depth travelled by the wave is studied at the instant the hardness reading has been measured by the Rho Meter. The figure shown on the next page describes the concept in a better way.

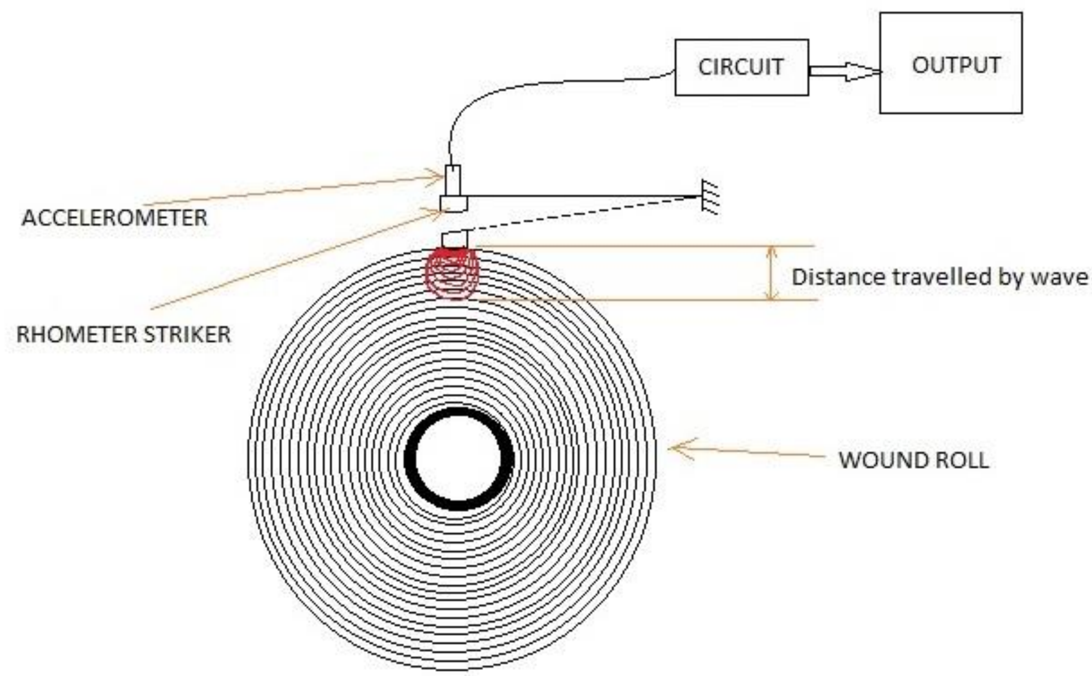


Figure 5.5 : Figure showing the depth of wave travel at the instant of hardness measurement using a Rho Meter.

In order to estimate the depth of travel of the wave, its velocity through each layer should be calculated. Following equations describe the calculation of the wave travel velocity inside the wound roll starting from its surface.

The velocity of a compression wave is given as

$$V = \sqrt{\frac{E_r}{\rho}} \qquad \{5.2\}$$

But from equation 2.1,

$$P = -\sigma_r = K_1(e^{K_2\,\varepsilon_r} - 1)$$

This can be re-written as

$$K_1\, e^{K_2\, \varepsilon_r} = P + K_1 \tag{5.3}$$

$$\frac{dP}{d\varepsilon_r} = E_r = K_1 K_2\, e^{K_2\, \varepsilon_r} \tag{5.4}$$

Using equation 5.3 in equation 5.4,

$$E_r = K_2(P + K_1) \tag{5.5}$$

Now we need to find the expression for the state dependent density, ρ. We know that the state dependent density is given by

$$\rho = \frac{\rho_0}{386}(1 - \epsilon_r) \tag{5.6}$$

Where ρ_0 is the mass density in reference state. The radial strain term can be expressed in terms of the Pfeiffer constants and the Radial Pressure using the equation 5.3.

$$\ln\left(\frac{P + K_1}{K_1}\right) = \ln(\, e^{K_2\, \varepsilon_r}\,) \tag{5.7}$$

$$K_2 \varepsilon_r = \ln\left(\frac{P + K_1}{K_1}\right) \tag{5.8}$$

$$\varepsilon_r = \frac{1}{K_2} \ln\left(\frac{P + K_1}{K_1}\right) \tag{5.9}$$

Substituting equation 5.5 and 5.6 in equation 5.2, we get

$$V = \sqrt{\frac{K_2(P + K_1)}{\frac{\rho_0}{386}(1 - \epsilon_r)}} \tag{5.10}$$

Using equation 5.9 in the above equation, 5.10, we get,

$$V = \sqrt{\frac{K_2(P + K_1)}{\frac{\rho_0}{386}\left(1 - \frac{1}{K_2}\ln\left(\frac{P + K_1}{K_1}\right)\right)}} \qquad \{5.11\}$$

With the help of the equation 5.11, we calculate the wave travel through each layer of the wound roll starting from the surface and observe what layer the wave has reached by the time the reading is taken. An Excel/VBA code is developed using the equations above to calculate the distance travelled by the wave. The interface of the Wave Propagation model is shown in the picture shown on the next page:

Wave Propagation

Radius	Pressure	Er	Velocity of wave	Distance Travelled	Time of Travel	Wave Travel Time
in	psi	psi	in/sec	in	sec	
5.25	0.381002	91.20111	991.0715797	0.00092	9.28288E-07	9.28288E-07
5.24908	0.381136	91.20459	991.0912156	0.00092	9.2827E-07	1.85656E-06
5.24816	0.381069	91.20285	991.0813969	0.00092	9.28279E-07	2.78484E-06
5.24724	0.759401	101.0584	1045.327041	0.00092	8.80107E-07	3.66494E-06
5.24632	1.135085	110.845	1096.736667	0.00092	8.38852E-07	4.5038E-06
5.2454	1.508201	120.5646	1145.683304	0.00092	8.03014E-07	5.30681E-06
5.244479	1.87882	130.2193	1192.463858	0.00092	7.71512E-07	6.07832E-06
5.243559	2.247008	139.8106	1237.319314	0.00092	7.43543E-07	6.82187E-06
5.242639	2.612827	149.3401	1280.448518	0.00092	7.18498E-07	7.54036E-06
5.241719	2.97633	158.8094	1322.017862	0.00092	6.95906E-07	8.23627E-06
5.240799	3.337571	168.2197	1362.168287	0.00092	6.75394E-07	8.91166E-06
5.239879	3.696598	177.5724	1401.020439	0.00092	6.56664E-07	9.56833E-06
5.238959	4.053455	186.8685	1438.678566	0.00092	6.39476E-07	1.02078E-05
5.238039	4.408186	196.1092	1475.233488	0.00092	6.2363E-07	1.08314E-05
5.237119	4.760829	205.2956	1510.764915	0.00092	6.08963E-07	1.14404E-05
5.236199	5.111425	214.4286	1545.343271	0.00092	5.95337E-07	1.20357E-05
5.235279	5.460008	223.5092	1579.031151	0.00092	5.82636E-07	1.26184E-05
5.234359	5.806612	232.5382	1611.884493	0.00092	5.70761E-07	1.31891E-05
5.233438	6.151271	241.5166	1643.953535	0.00092	5.59627E-07	1.37488E-05
5.232518	6.494015	250.4451	1675.283602	0.00092	5.49161E-07	1.42979E-05
5.231598	6.834875	259.3245	1705.915756	0.00092	5.393E-07	1.48372E-05
5.230678	7.173878	268.1555	1735.887341	0.00092	5.29988E-07	1.53672E-05
5.229758	7.511052	276.9389	1765.232441	0.00092	5.21178E-07	1.58884E-05
5.228838	7.846424	285.6753	1793.982268	0.00092	5.12826E-07	1.64012E-05
5.227918	8.180018	294.3655	1822.165492	0.00092	5.04894E-07	1.69061E-05
5.226998	8.511859	303.0099	1849.808521	0.00092	4.97349E-07	1.74035E-05
5.226078	8.841971	311.6094	1876.935749	0.00092	4.90161E-07	1.78936E-05

Layer reached by wave	2026
Radius Reached	**3.61317**

RUN CLEAR

Force of impact	180	lbf
Impulse	0.06	lbf-sec
Del t/2	0.00033	sec
K1	3.12	
K2	26.05	

Figure 5.6 : Interface of the Excel/VBA code to calculate the depth of wave travel.

The Excel/VBA code for the Wave Propagation model can be found in the Appendix A. The input to the Wave Propagation model is the output of the *WINDaROLL* which gives the pressure profile in the radial direction (pressures inside the wound roll at a specific radial distance). Using these pressure values at each layer and the Pfeiffer constants of that material, the velocity of the wave through that layer is calculated using the equation 5.11. The time of travel through each layer is then calculated using the value of the velocity obtained and the cumulative value of this time is recorded simultaneously. But, in order to know the depth of travel of the wave, there should be a terminating criteria. This terminating criteria value is the time taken by the striker from the time of its contact with the surface of the roll to the instant of maximum imparting maximum force. This can be better understood using the curve below.

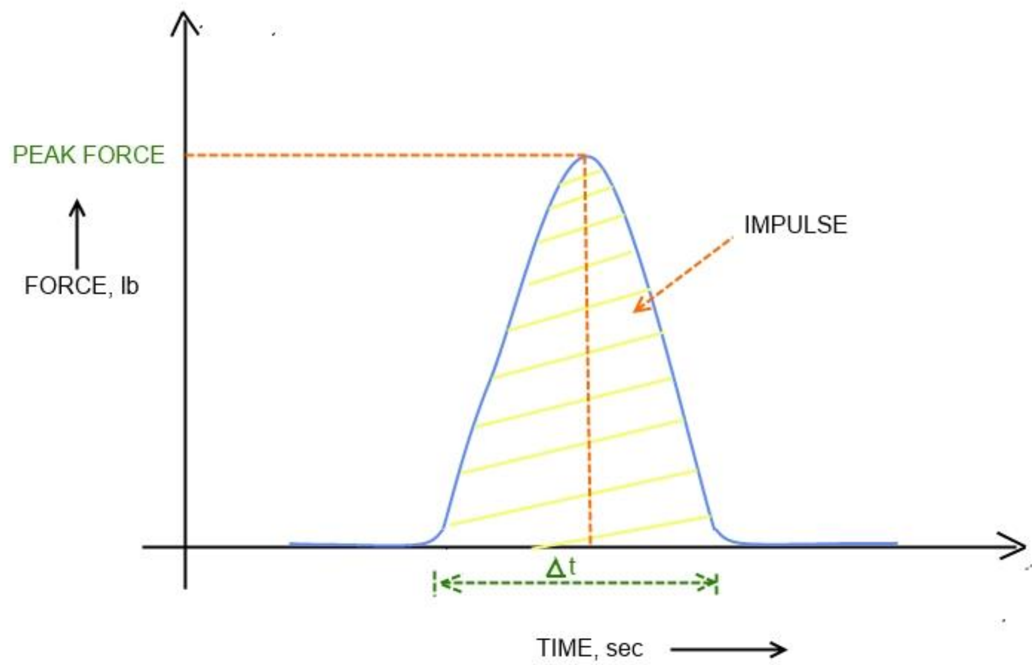


Figure 5.7 : Representation of the Force vs. Time plot during the impact of the striker with the surface of the wound roll.

From the figure shown on the previous page, it can be observed that the peak value of force occurs at a time which is half of the time required for the total contact phenomenon. This value of $\Delta t/2$ can be obtained from the value of the impulse exerted by the striker. It has been mentioned in the manual of the Rho Meter that the striker, on an average, imparts an impulse of 0.06 lb-sec. Equations below describe the criterion for the termination of the wave propagation algorithm.

$$Impulse = Area\ under\ the\ Force - Time\ curve = \frac{1}{2} * \ Peak\ Force * \Delta t \qquad \{5.12\}$$

$$0.06 = \frac{1}{2} * F_{peak} * \Delta t \qquad \{5.13\}$$

$$\frac{\Delta t}{2} = \frac{0.06}{F_{peak}} \qquad \{5.14\}$$

The value of the F_{peak} mentioned in the equation above can be found from the Energy method algorithm (discussed in section 6.2.1).

After obtaining the value of Δt/2 , it is used as a criterion for terminating the calculation of the depth of the wave travel into the wound roll and distance travelled by the wave is displayed out as output.

Table shown below distance travelled by the compressive wave in the wound rolls wound at their respective winding tensions

Material	**Winding Tension (lb)**	**Distance Travelled by Wave from the outer surface (in)**
Dupont-377	13.45	0.56
Dupont-S	3	1.52

Table 5.2 : Table showing the distance travelled by the wave by the time the hardness measurement is made by the Rho Meter.

Observing the values of the distance travelled by the wave in to the wound roll from the outer surface, we notice that they are just a few inches away from the outer surface. This proves the premise that the hardness measurement made by the Rho Meter is a local measurement of hardness.

5.5 Comparison of Radial Modulus

As it is observed from the results of the previous section that the hardness measurement is a local measurement, the radial modulii of the wound rolls of the two materials are compared until a certain depth from the outer surface of the wound roll. The chart shown below is the comparison between the radial modulus values of the two wound rolls of the two different materials after wound at the tensions of 13.45 lb and 3 lb respectively.

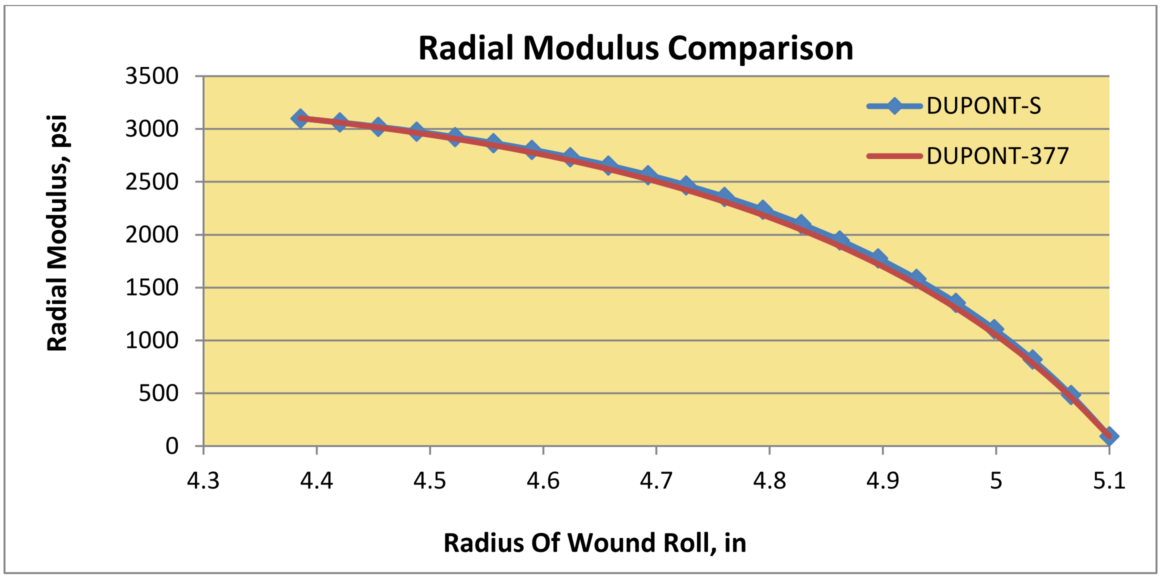


Figure 5.8 : Radial Modulus of Dupont–377 and Dupont-S when wound at their respective tensions of 13.45 lb and 3 lb.

5.6 Experimental Validation

The values of tensions for the wound rolls of each material obtained from the study above are used to center wind the rolls on the small scale winder in the Winding Laboratory of the Web Handling Research Center. They were wound at a constant speed of 40 rpm to minimize air entrainment effects. After the desired outer diameter of the roll is attained, the winding is stopped and the hardness of the rolls are measured using the Rho Meter. Pictures shown below represent the hardness readings from the Rho Meter after striking each roll of different material.

Dupont - 377

Dupont - S

Figure 5.9 : Comparison between the hardness readings of the wound rolls of the two materials.

We notice from the pictures above that the hardness values of both the rolls are nearly equal thus implying that the hardness of the wound rolls depends on the radial modulus of it. Furthermore, experiments were also carried to make a comparison of hardness values when two rolls are wound at same winding tensions. Chart on the next page shows the comparison between the radial modulus of the Dupont-377 wound at 13.45lb and Dupont-S at 3 lb and Dupont-377 at 3 lb winding tension.

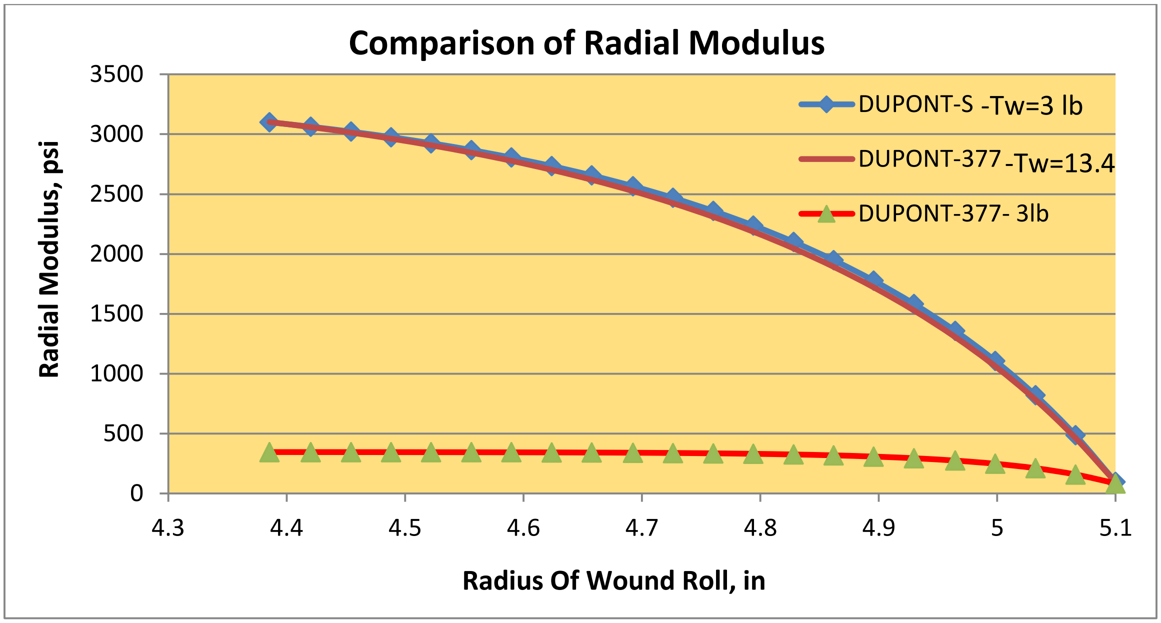


Figure 5.10: Comparison of radial modulus when Dupont-377 winding tension is equal to 3lb.

Table below shows the comparison in hardness values of rolls of different materials wound with same winding tension

MATERIAL	TENSION, lb	HARDNESS	STANDARD DEVIATION
DUPONT-S	3	61	1.8408
DUPONT-377	13.45	58	1.8529
DUPONT-377	3	27	1.8

Table 5.3: Hardness values of the wound rolls of respective material.

5.7 Conclusion

Basing on the results obtained, the first objective was successfully achieved by proving that the hardness measurement of a wound roll also depends on the radial modulus of it apart from the winding tension and the pile height which was previously proven by Mistry[5]. Also, it was proven with the wave model that the hardness measurement made by the Rho Meter is a localized measure and is dependent on the outer layers of the wound roll.

CHAPTER VI

ONE DIMENSIONAL ENERGY MODEL TO PREDICT HARDNESS OF WOUND ROLLS

6.1 Introduction

As discussed earlier, the second objective of this research is to develop an inexpensive and computationally faster method to predict the hardness of a wound. For this purpose, the mechanism of the Rho Meter was studied as well as the impact phenomenon of the striker on the roll before integrating them into a 1-D model. The following sections would describe in detail the study, approach and experimental validations of the results obtained from the model developed as well.

6.2 Mechanism of the Rho Meter and Impact Phenomenon

The mechanism and the working of the internal parts of the Rho Meter need to be well understood for replicating it into a mathematical model. As discussed previously in section 3.1.2, the Rho Meter consists of a cantilever spring system with an end mass and an accelerometer on top of it as shown in the figure in the next page.

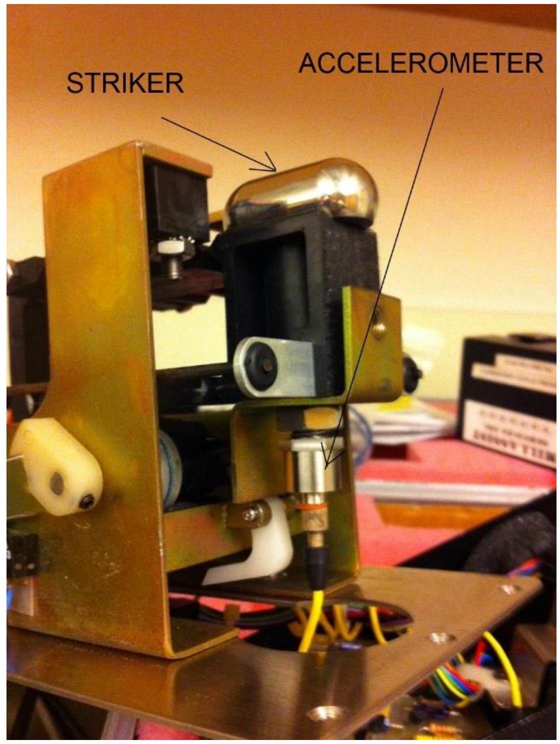


Figure 6.1 : Striker and Accelerometer of the Rho Meter.

This striker which is travelling at a known velocity and acceleration on striking the surface of the roll is subjected to a sudden deceleration. This deceleration is measured by the accelerometer mounted on the top of the striker and converts into Rho's and displays it on the digital display. This mechanism was modeled into a spring mass system and the roll which is struck using the Rho Meter is also modeled into a spring mass system as shown on the next page:

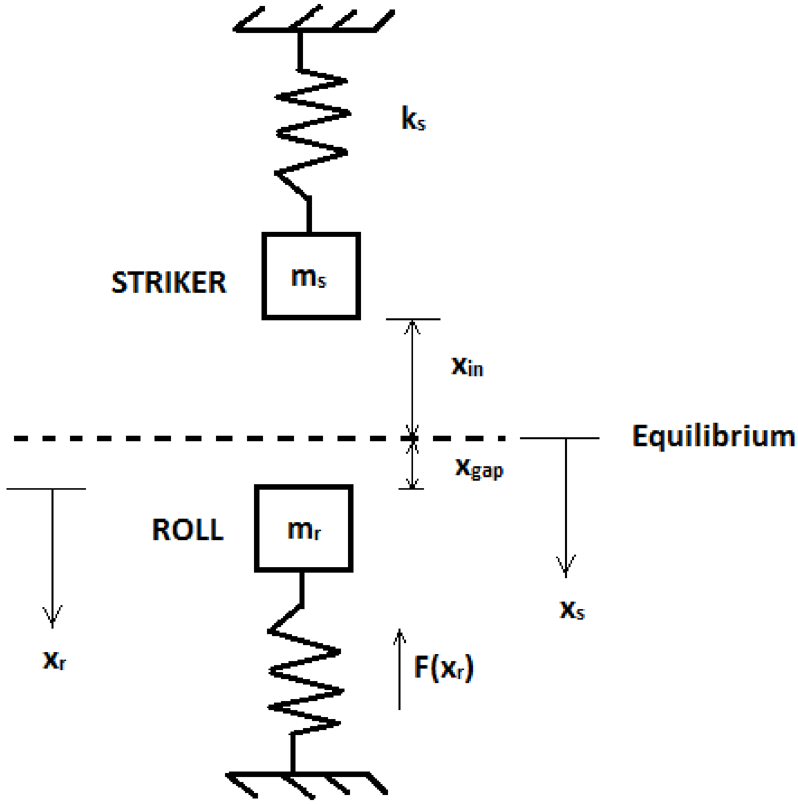


Figure 6.2 : 1-D Dynamic Impact model.

In the 1-D model shown on the previous page, the x_{in} or the initial displacement and x_{gap} or the gap between the equilibrium position of striker and the wound roll is measured using a vernier calipers and the value of the stiffness of the striker mechanism are recorded as shown in table 6.1 :

Property	Value
k_s	16 lb/in
x_{in}	0.3125 in
x_{gap}	0.0938 in

Table 6.1: Rho Meter parameters for the 1-D Model.

6.2.1 Energy Method (1-D Hardness Predictor)

The impact of the striker with the surface of the wound roll will be studied using the Law of Conservation of Energy. According to this principle, the total energy before a process and after the process should always remain constant. Thus, the following expression can be stated:

$$\textit{Elastic Energy Stored in the Striker Spring at its initial extreme position} =$$
$$\textit{Elastic Energy of the Striker after maximum displacement into the roll} +$$
$$\textit{Elastic Energy absorbed into the Wound Roll during the maximum displacement of striker.}$$

{6.1}

Writing the above expression in mathematical equation form, we get,

$$\frac{1}{2}\, k_s\, x^2{}_{in} = \frac{1}{2}\, k_s\, (\, x_{gap} + \delta\,)^2 + E_{roll}\, [\delta] \qquad \{6.2\}$$

But, the elastic energy absorbed into the wound roll during the impact is given as,

$$E_{roll}\, [\delta] = \int_0^{\delta_{max}} F[\delta]\, d\delta \qquad \{6.3\}$$

Where, *F[δ]* can be considered as a second order polynomial of the deflection, δ as

$$F[\delta] = \alpha\delta^2 + \beta\delta \qquad \{6.4\}$$

The above equation is the generalized form obtained by fitting a second order polynomial through the data obtained from compression tests on a wound roll. This compression test data can be obtained from the *ROLL COMPRESSOR* code. The working of the *ROLL COMPRESSOR* code will discussed in the next section.

Once, the values for α and β are obtained by extracting them from the roll compressor code (which will be discussed in the next section), the value of maximum displacement of the striker into the roll, δ_{max} can be calculated by solving the integral in the previous page, which would give an equation similar to

$$E_{roll}\,[\delta] = \frac{\alpha\delta^3}{3} + \frac{\beta\delta^2}{2} \qquad \{6.5\}$$

Once the value of δ reaches the value of δ_{max} (which will be discussed in later sections), the value of hardness can be calculated using the equation

$$Rho_{max} = \frac{F[\delta_{max}]}{3.76 * G * m_s} \qquad \{6.6\}$$

Where, 3.76 is the conversion factor arbitrarily chosen by the Pfeiffer when he created the Rho unit to convert acceleration value to the units of hardness, Rho's.

6.2.2 Roll Compressor

The *Roll Compressor* code predicts the spring stiffness between a wound roll and a rigid contact surface was developed by Cagri Mollamahmutoglu [12]. This code will allow the computation of the α and β spring coefficients in the expression 6.4.

The spring stiffness between a wound roll and a contact surface is dependent on how the roll is wound. In figure 5.7, the variation of in the radial modulus of the Dupont-377 material for two winding tensions was shown. Since the winding tension affects the radial modulus, it must also affect the contact stiffness.

The *Roll Compressor* code has several components, the first of which is a winding model similar to the *WINDaROLL* code previously described. This establishes the radial modulus of the wound roll as a function of radius. Then a plane strain model of a wound roll in the R-θ plane is created. Each element has an initial radial modulus due to winding.

Then a contact analysis is begun where the perimeter nodes of the wound roll are brought successively into contact as shown in figure 6.3.

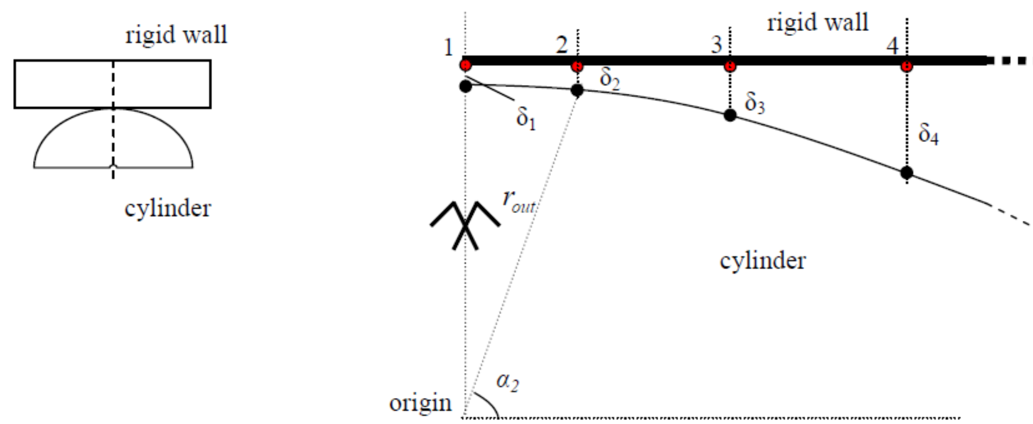


Figure 6.3 : Geometry of the Node to Node contact of a Rigid Wall and Wound Roll [1].

At the completion of the program, the loads are known where we are required to bring each successive node into contact. A least squares routine is then used to determine α and β in the expression 6.4.

In the figure 6.4 shown on the next page, the input interface for the roll compressor code is shown. Inputs are shown for the Dupont-377 web wound at a tension of 12 lb. In this case, the wound roll is brought into contact with a flat rigid surface.

The interface for the *Roll Compressor* is shown in the figure below

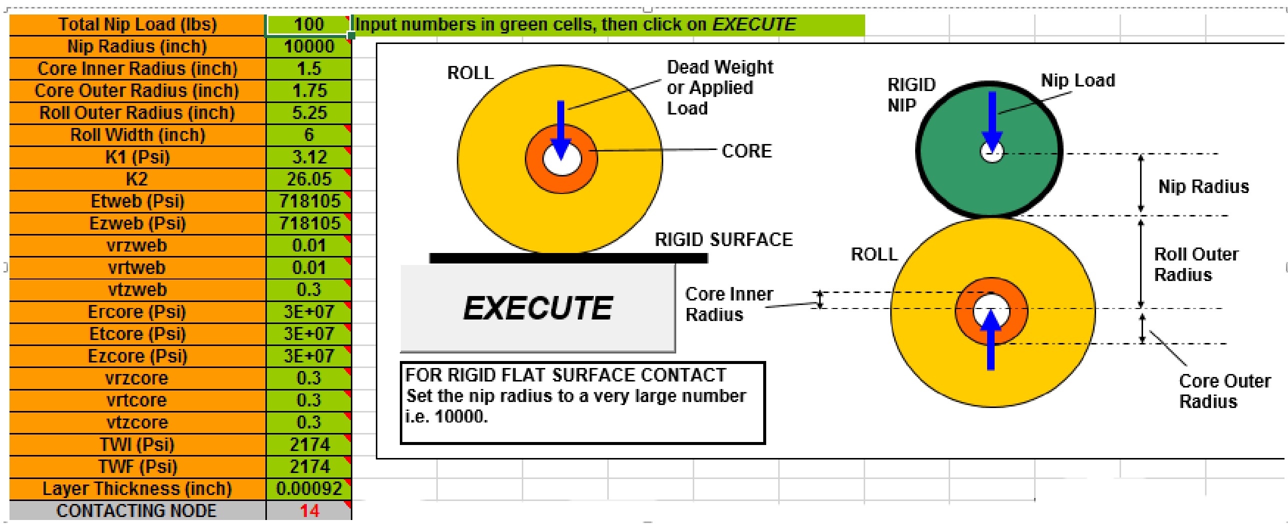


Figure 6.4 : Input interface of the *Roll Compressor.*

In figure 6.5 below, the loads that are required to bring the successive nodes on the wound roll into contact with the flat surface are shown charted against the associated radial deformations of the wound roll. The data has been curve fit and α and β are shown in the legend.

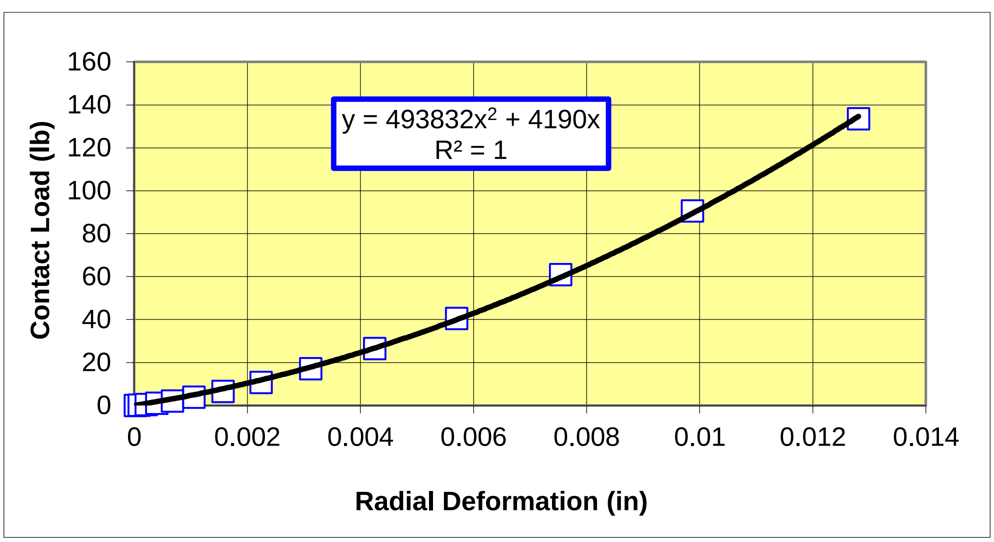


Figure 6.5 : Output from the *Roll Compressor* code.

The Excel/VBA code for the extraction of the α and β values is shown in the Appendix - B.

These values of α and β are used as input for the energy method algorithm shown in the next section.

6.2.3 Solving for maximum displacement of striker into the roll (δ_{max})

From the Energy Conservation equation discussed in section 6.2.1, we start our solution for obtaining the value of δ_{max}. Consider the equation {6.2}, when $\delta=\delta_{max}$,

$$\frac{1}{2}\, k_s\, {x^2}_{in} = \frac{1}{2}\, k_s\, (\, x_{gap} + \delta_{max}\,)^2 + E_{roll}\, [\, \delta_{max}] \qquad \{6.16\}$$

The above equation can be re-written as

$$\frac{1}{2}\, k_s\, (\, x_{gap} + \delta_{max}\,)^2 + E_{roll}\, [\, \delta_{max}] - \frac{1}{2}\, k_s\, {x^2}_{in} = 0 \qquad \{6.17\}$$

The expression on the left hand side of the above equation can be written as a function of δ_{max} , Q, as the values of x_{gap} and x_{in} are always constant. So,

$$Q\, [\, \delta_{max}\,] = 0 \qquad \{6.18\}$$

But,

$$Q\, [\delta] \neq 0 \qquad \{6.19\}$$

So, the difference between δ_{max} and δ can written in equation form as:

$$\delta_{max} = \delta + \Delta\delta \qquad \{6.20\}$$

Substituting the above equation into equation number {6.18} and solving for $\Delta\delta$, we get

$$Q\, [\, \delta + \Delta\delta\,] = 0 \qquad \{6.21\}$$

By Taylor Series expansion we get,

$$Q\,[\,\delta\,] + \frac{dQ}{d\delta}\,.\,\Delta\delta = 0 \quad \{6.22\}$$

$$\Delta\delta = \frac{-Q\,[\,\delta\,]}{(\frac{dQ}{d\delta})} \quad \{6.23\}$$

But, by using equation {6.17} the value of $\frac{dQ}{d\delta}$ can be found as

$$\frac{dQ}{d\delta} = \alpha\delta^2 + \beta\delta + k_s(x_{gap} + \delta) \quad \{6.24\}$$

Using equations {6.17} and {6.24}, Δδ can be written as

$$\Delta\delta = \frac{-(\frac{1}{2}\,k_s\,(\,x_{gap} + \,\delta\,)^2 - \frac{1}{2}\,k_s\,x^2{}_{in} + \frac{\alpha\delta^3}{3} + \frac{\beta\delta^2}{2})}{\alpha\delta^2 + \beta\delta + k_s(x_{gap} + \delta)} \quad \{6.25\}$$

The values of x_{in} and x_{gap} were measured as 0.3125 in and 0.09375 in respectively and the value of k_s was measured by Mistry [5], see Table 6.1.

We start the solution procedure by assuming an initial value for δ. With the aid of above mentioned equations, we calculate the value of the increment for the next step, Δδ. This increment is added to the current value of δ to proceed to the next iteration. But before proceeding to the next iteration, the relative error is calculated using the equation below:

$$Relative\ error = \left|\frac{\Delta\delta}{\delta_{i+1}}\right| \quad \{6.26\}$$

Where, *i* denotes the current step.

The solution procedure can be better understood using the flow chart shown in the next page:

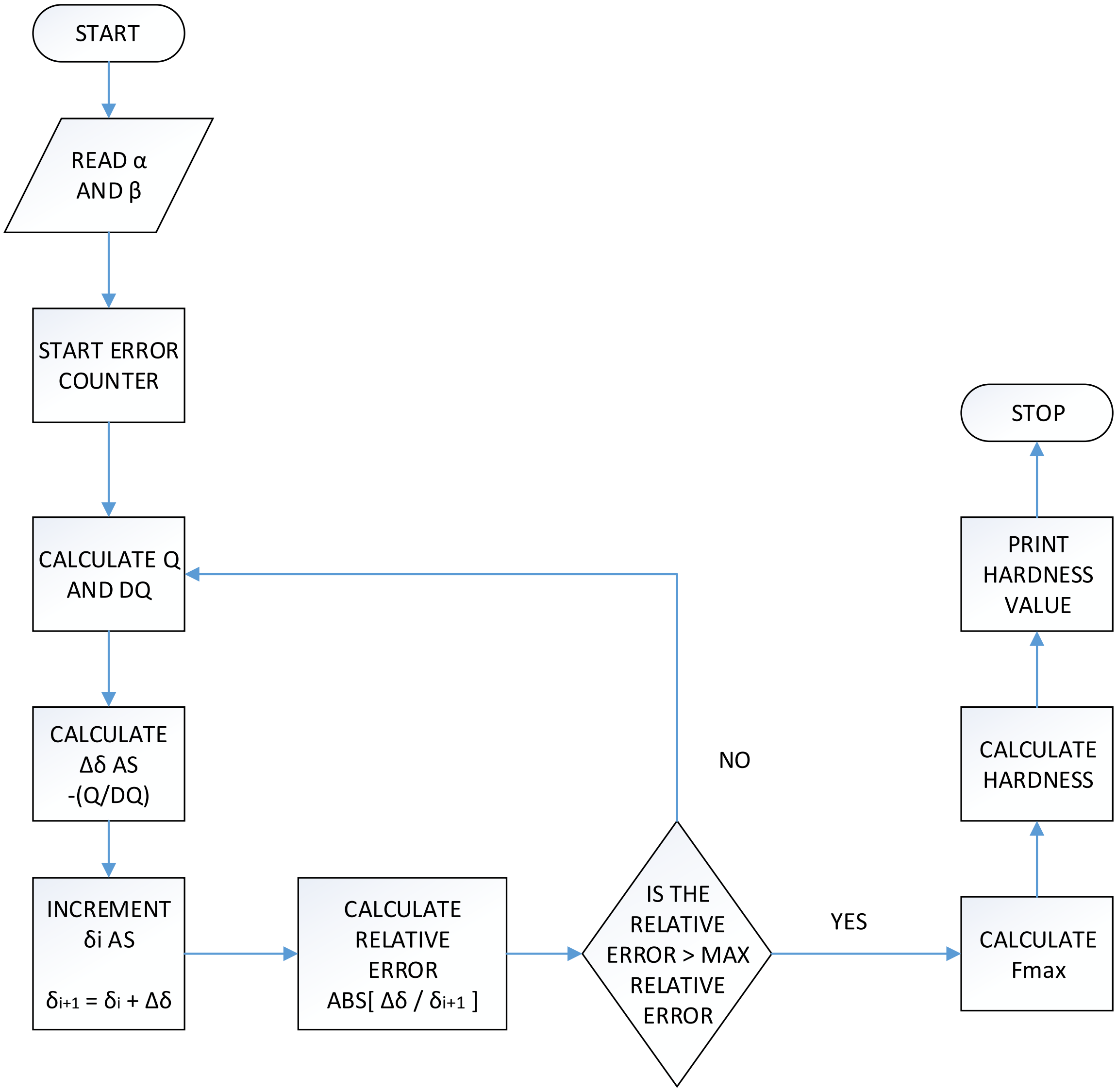


Figure 6.6 : Flow chart explaining the working of the 1-D Hardness Predictor Algorithm.

CHAPTER VII

RESULTS AND DISCUSSION

7.1 Introduction

The results obtained from the 1-D Hardness predictor code must validated for its correctness, for this purpose, experiments were conducted on the Dupont -377 and Dupont –S materials. Wound rolls of these materials are wound at constant and varied tensions to a specific outer diameter and their hardness was measured using the Rho Meter and the comparisons were made with the results from the 1-D Hardness Predictor Code. The following sections will discuss the above mentioned process in detail.

7.2 Experimental Setup

Experiments were conducted on the small scale winder in the Winding Laboratory of the Web Handling Research Center. Rolls with an outside diameter of 10.5 in were center wound on this winder at a constant low speed of 40 rpm to minimize air entrainment effects also it was made sure that no wrinkles were formed during winding. Figure 7.1 on the next page shows the setup of the winder and the direction of flow of web

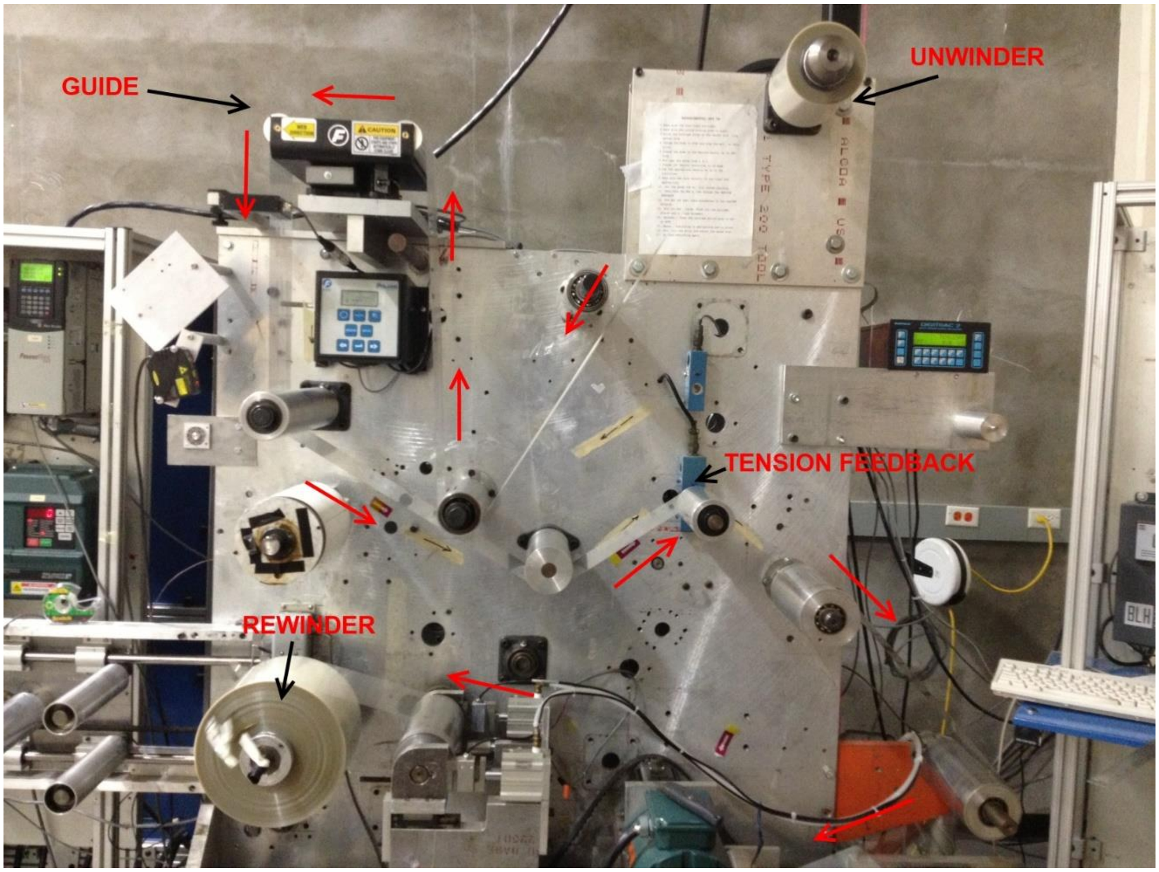


Figure 7.1 : Center Winder Setup.

Dupont – 377 material was wound at tensions of 6 lb, 12 lb and 18 lb whereas the Dupont – S material was wound at 6 lb, 7.5 lb and 9 lb. The winding tensions were not increased beyond 18 lb for Dupont -377 and 10.5 lb for Dupont – S due to the limitations of the winder. The Winding Tension profiles through Time are shown in Figure 7.2. There were 3 rolls wound for each case, these charts are demonstrative of all the cases wound:

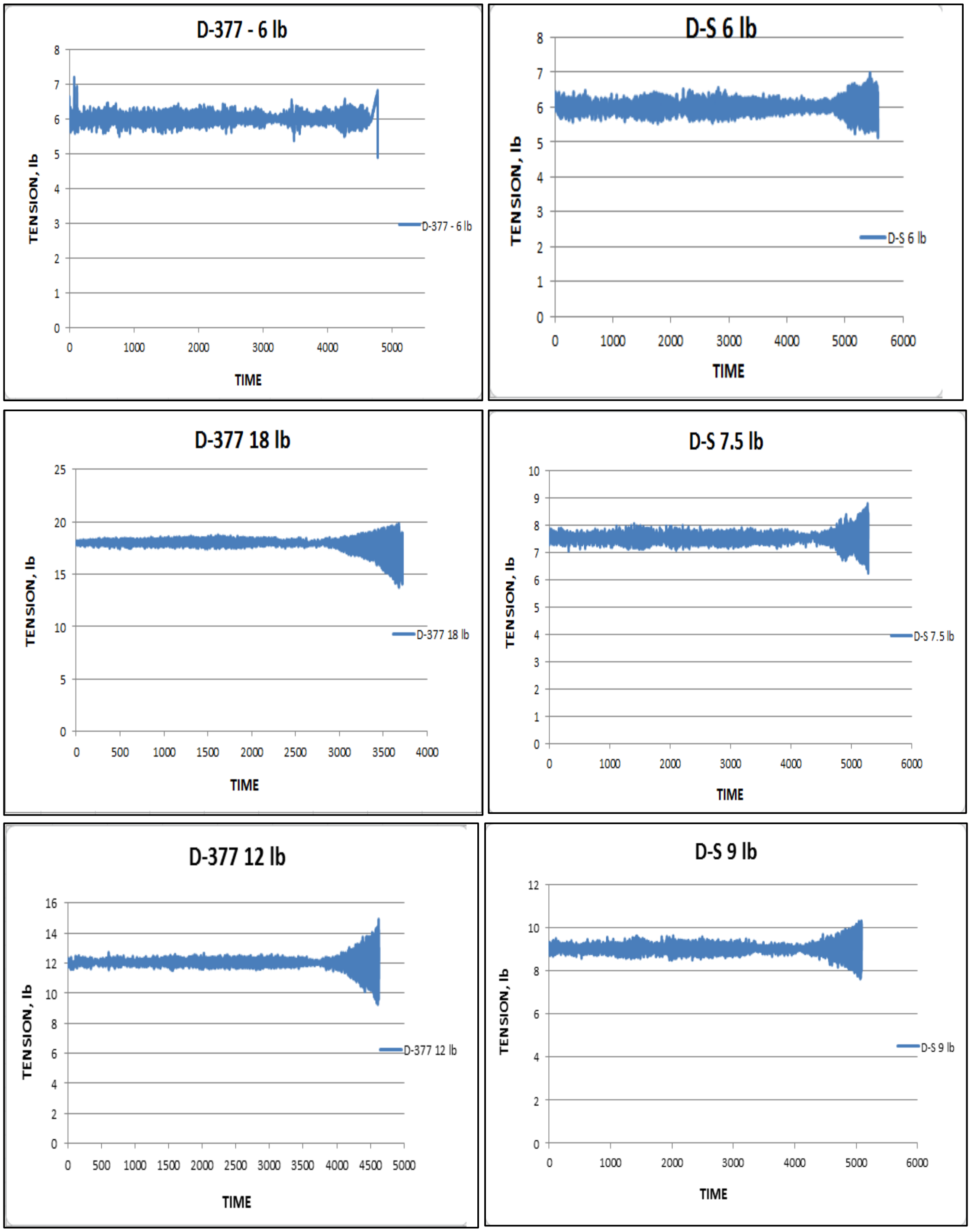
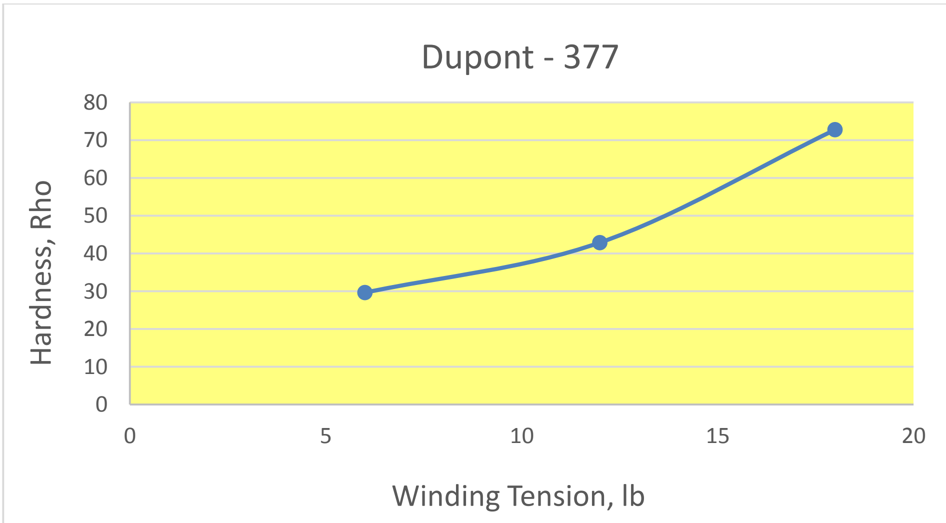


Figure 7.2 : Tension vs. Time plots during winding the rolls of the two materials.

In Figure 7.2, we see that the tension remains nearly constant throughout the process of winding the rolls using different tensions. After obtaining these wound rolls wound at the tensions mentioned previously, hardness readings for these rolls are measured using Rho Meter. The plots shown below are the average experimental hardness values taken from three trials of winding rolls at respective winding tensions and with average of readings from ten strikes of Rho Meter in each trial:



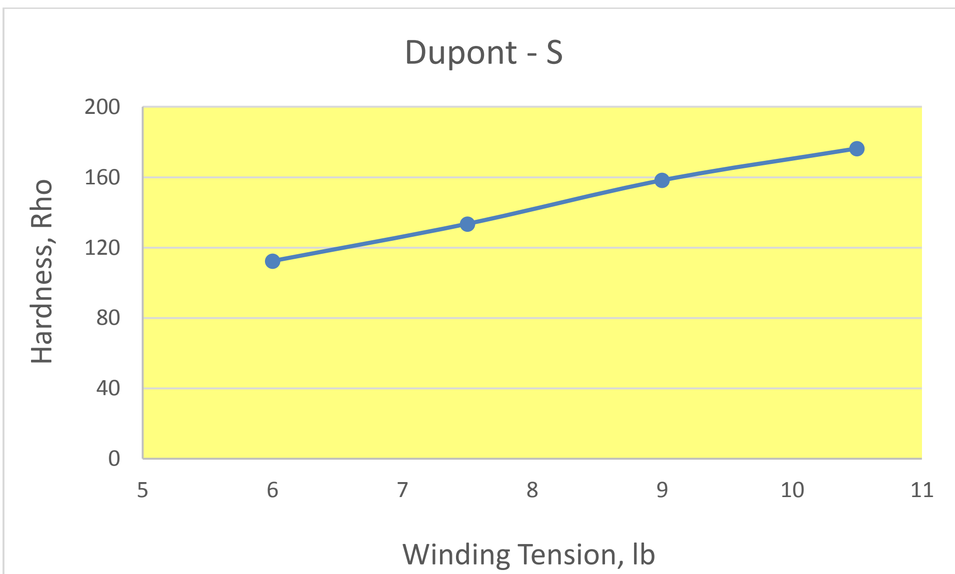


Figure 7.3 : Plots showing the experimental hardness values of the rolls of each material.

7.3 Input to 1-D Hardness Predictor Code

The Hardness Predictor Code was integrated with the *Roll Compressor* code for convenience of α and β extraction from the output of the *Roll Compressor* code and to use it back as input to the Hardness Predictor Code. This Excel/VBA code can be found in the Appendix-B. So the interface of the Hardness Predictor Code looks similar to the interface of the *Roll Compressor* code as shown in figure 6.4. The input to the Code is explained in the table shown below:

Input Parameter	Input Value	Remarks
Total Nip Load (lbs)	930	Based on the striker force
Nip Radius (inch)	10000	10000 for a rigid surface condition
Core Inner Radius (inch)	1.5	
Core Outer Radius (inch)	1.75	
Roll Outer Radius (inch)	5.25	
Roll Width (inch)	6	
K1 (Psi)	0.67	Pfeiffer's Constants
K2	123.88	
Etweb (Psi)	823973	Modulii of the Web
Ezweb (Psi)	823973	
vrzweb	0.01	Poisson's ratio of the Web
vrtweb	0.01	
vtzweb	0.3	
Ercore (Psi)	30000000	Modulii of Steel Core
Etcore (Psi)	30000000	
Ezcore (Psi)	30000000	
vrzcore	0.3	Poisson's ratio of the Steel Core
vrtcore	0.3	
vtzcore	0.3	
TWI (Psi)	1630	Initial Winding Stress
TWF (Psi)	1630	Final Winding Stress
Layer Thickness (inch)	0.00092	
CONTACTING NODE	**12**	

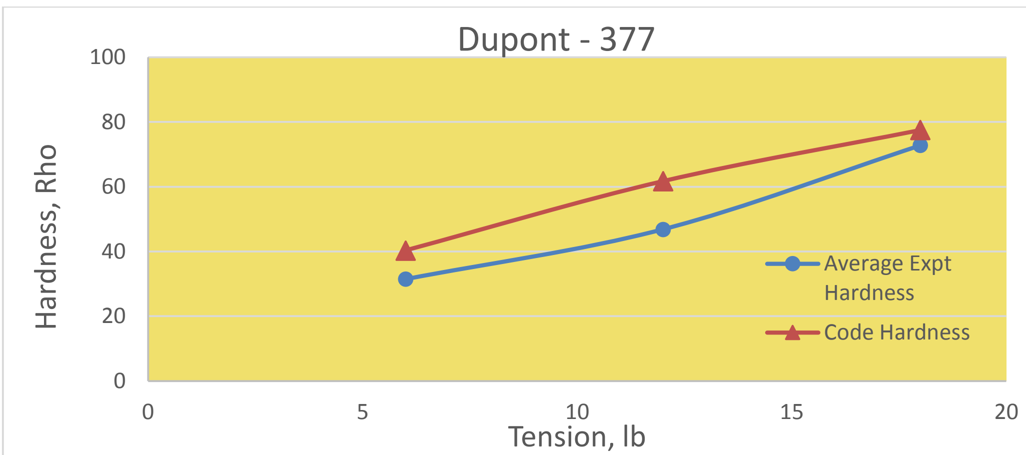
Hardness of Wound Roll	**149.06242**	Output Predicting Hardness Value
Max Striker Force on Roll Surface	**932.220528**	Striker Force To be used as Input Nip Load

Figure 7.4 : Input and Output interface of the *Roll Compressor* with the Hardness Predictor module integrated.

As seen in the table above, all the necessary winding conditions, geometric conditions, web material properties, core material properties and loading conditions should be mentioned for each winding condition to obtain the hardness of the wound roll of that specific material.

7.4 Comparison of Experimental and 1-D Hardness Predictor Code results

The hardness values obtained from the code were compared with experimental hardness values for their validity. The comparison shown in the plots below consist of data points which are the mean result of 3 windings and 10 strikes from Rho Meter per roll. The standard error was then formed from the 30 data points as well.



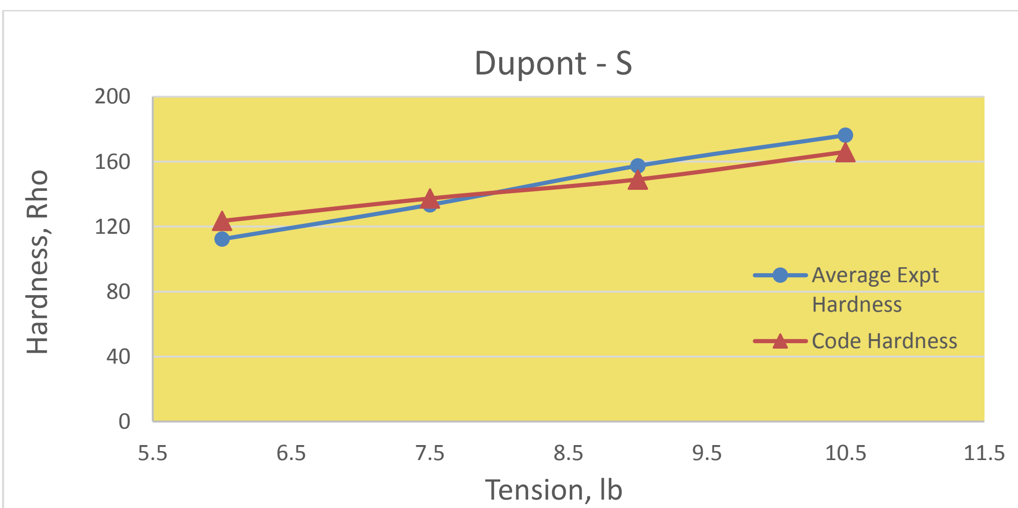


Figure 7.5 : Plots showing the comparison between the experimental average hardness values and the hardness values obtained from the Hardness Predictor code.

DUPONT - 377

Tension (lb)	Alpha	Beta	Hardness-Code (Rho)	Expt. Avg. Hardness (Rho)	Standard Deviation of Expt. Results	% Difference
6	75012.71	4524.24	40.3	31.46	1.98	28.09
12	279535.71	7288.84	60	46.86	0.8	31.71
18	704252.93	7376.83	77.56	72.8	1.23	6.5

Table 7.1: Alpha and Beta values for Dupont-377 from the *Roll Compressor Code* and hardness values from Hardness Predictor Code and experimental average values.

DUPONT - S

Tension (lb)	Alpha	Beta	Hardness-Code (Rho)	Expt. Avg. Hardness (Rho)	Standard Deviation of Expt. Results	% Difference
6	2894363.40	11927.37	123.9	112.33	1.02	10.02
7.5	3960550.09	14026.45	138.02	133.46	0.93	2.92
9	5045766.62	16034.36	148.8	158.23	0.51	5.79
10.5	6929935.87	13219.37	166	176.3	0.87	5.8

Table 7.2: Alpha and Beta values for Dupont-S from the *Roll Compressor Code* and hardness values from Hardness Predictor Code and experimental average values.

We notice from the plots shown on the previous page that the results from the 1-D Hardness Predictor Code compare reasonably well with the experimental values. The experimental results showed good consistency with a standard deviation varying between 0 and 2 which is very minute given the scale of hardness. The minor deviations seen in the plots can be due to many reasons on the roll modeling side. The impact of the striker on the surface of the roll causes development of high compressive stresses at the region of impact. These high stresses cause the change in the pressure values at that region which in turn cause the variation of radial modulus, but the code does not model the roll pressures with such consideration. Also the Pfeiffer constants used namely, K_1 and K_2 , which were calculated from the INSTRON stack compression test were performed at lower compression stresses as compared to the stresses generated at the impact region during the instant of striker impact, hence the values of K_1 and K_2 used also change at the region of impact. Also, the impact on the surface of the roll would cause slippage of layers in machine direction but this was not taken into account during the development of the 1-D Hardness Predictor model. Slightly, better results can be obtained using higher mesh resolutions but it would lead to increase in computation time thus defeating its objective of low computation time. However, these values are reasonably good to give an idea of the quality of the wound roll about to be wound using the set of winding parameters.

7.5 Study of Hardness variation with variation in wound roll pile height.

Apart from studying wound rolls of 10.5 in. outer diameter for hardness variation, the effect of hardness variation with variation of pile height while keeping the winding tension constant was also studied. For this study, the experimental setup was similar to the one used for winding the regular 10.5 in. rolls with an exception that the rolls were now being wound until a specific diameter is obtained while winding at a constant winding tension and the hardness measurements, as always, were made using the Rho Meter.

For this study, rolls were wound with an increment of 0.5 in. pile height each time with the winding tension being constant at 12 lb and the hardness values at that specific diameter were measured using the Rho Meter and were recorded as shown in the plot shown on the next page :

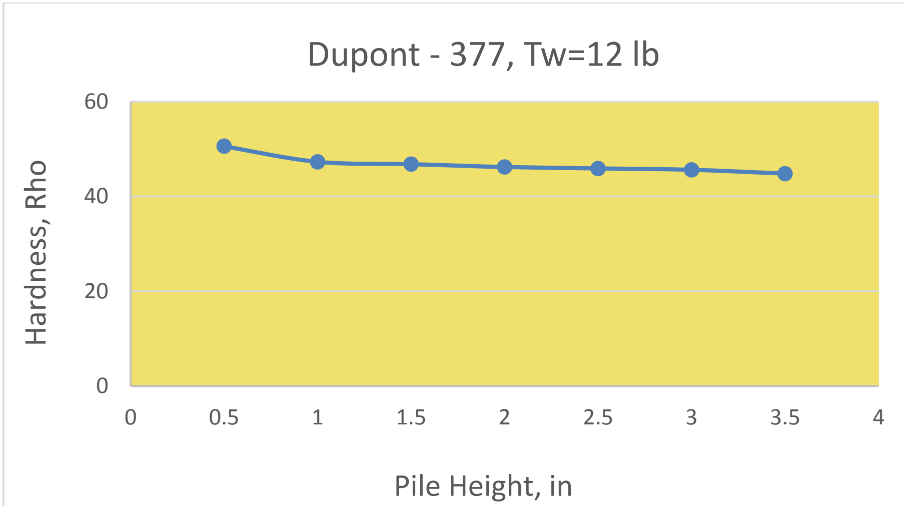


Figure 7.6 : Plot showing hardness variation with increase in pile height of a roll.

7.6 Comparison of experimental hardness values due to pile height variations with hardness values from the 1-D Hardness Predictor Code.

The average hardness values obtained due to the pile height variations were also compared with the hardness values predicted by the 1-D Hardness Predictor Code. The case of the Dupont-377 wound at 12 lb was chosen because maximum difference was observed between the average experimental values and the values predicted by the Hardness Predictor Code, as seen in the previous section. The comparisons are shown in the chart on the next page:

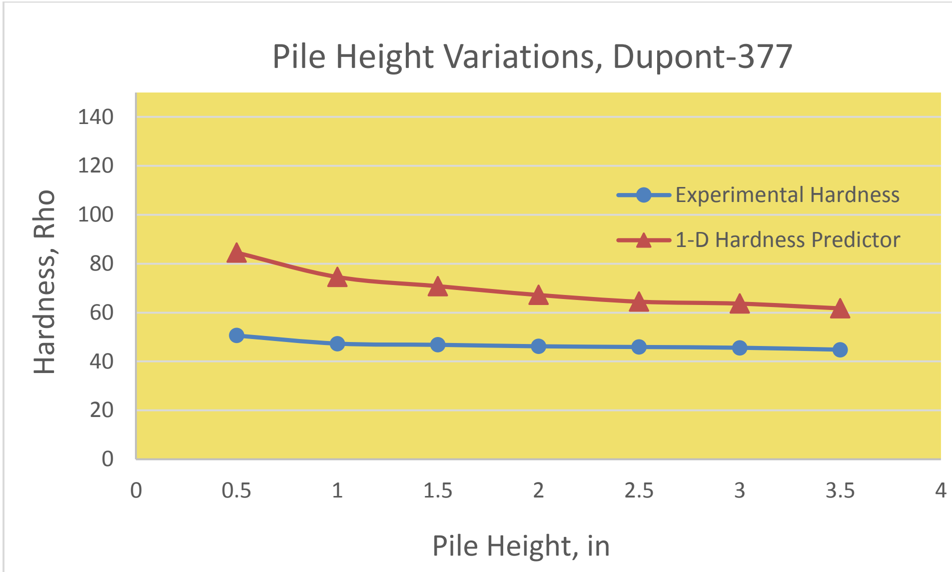


Figure 7.7 : Plot showing the comparison between the experimentally obtained hardness values and the values obtained from the code for varying pile height for Dupont-377 wound at 12 lb of winding tension.

We notice from the plot above that the hardness values of various pile heights from the 1-D Hardness Predictor code are at an offset to the hardness values though they follow the same trend. The explanation about the various factors mentioned at the end of section 7.4 holds valid here as well. Considering the factors of varying Pfeiffer constants, varying pressures, varying radial modulus and the layer slippage factor would help in getting better and more accurate results from the 1-D model.

CHAPTER VIII

CONCLUSIONS AND FUTURE WORK

8.1 Conclusion

The objectives of this research were to study the dependence of hardness of a wound roll on its radial modulus and to develop a computationally efficient 1-D Dynamic Impact Model to predict the hardness of a wound roll using the output from a winding model which is in engineering units. The following conclusions can be drawn from the results obtained during this study:

- The dependence of the hardness of the wound roll on the radial modulus of the outer surface of the wound roll was studied. The hardness values of the rolls with nearly same radial modulus was approximately equal.
- A one-dimensional model was developed which showed promising results in comparison with the experimental values. For the two web materials wound and studied, the values from the model had an average error of 15.13% and the errors ranged in the values of 2% to 32%. Also, higher errors for the cases of Dupont-377 as compared to the hardness values of Dupont-S can be attributed to the thickness variation of Dupont-377 due to higher surface roughness values and more number of asperities on the surface. This variation in thickness value results in a different winding tension values in terms of psi, which is used as an input to the winding model.

- A wave velocity model was studied to prove that hardness measurement made by the Rho Meter is a local measure.

8.2 Future Work

The one-dimensional model is reasonable good for predicting the quality of the wound roll in least computational time possible but the values predicted might not be accurately equal to the values measured using a Rho Meter due to many factors which were not considered during the development of the one-dimensional model which needed further study.

The model can be made to produce more accurate results by studying the localized region affecting the hardness readings measured using the Rho Meter. This can be done by making the model to include the dynamically varying pressures and thus the E_r values at the impact region of the striker and the wound roll surface. These high pressures also influence the values of K_1 and K_2 which were actually measured on the INSTRON during the stack compression test at compression pressures much less than the pressures at the impact region. Also, considering the inter-layer slippage due to the pressure exerted by the striker at the impact region would help in obtaining more accurate results from the 1-D model. Accuracy in measurement of the web thickness and state dependent modulus would also help in improving the accuracy of the Rho hardness values predicted by the model.

By conducting more experiments, as done in this study, using different web materials and different winding conditions and on comparing the results with the results from the one-dimensional model would give further confidence in the model. This model can also be utilized for further development to replicate the working of quality measurement devices which work on the principle of impact.

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APPENDIX - A

'****** WAVE VELOCITY MODEL ******

```
Private Sub vel()

Dim rad_mod(10000), webdens, wav_vel(10000), nu, lambda(10000), mu(10000) As Double
Dim no_layers As Integer
Dim RHO_o, strain(10000) As Double

'***** READ IN THE MATERIAL PROPERTIES

no_layers = Cells(5, 1)
nu = 0.01
webdens = 0.00013
RHO_o = 0.036
kone = Cells(6, 15)
ktwo = Cells(7, 15)

'***** CALCULATE THE VALUE OF RADIAL STRAIN, WAVE VELOCITY AND TIME THROUGH EACH LAYER

For i = 1 To no_layers
```

```
    strain(i) = Log(((Cells(4 + i, 3) + kone) / kone)) / ktwo
    wav_vel(i) = (Cells(4 + i, 4) / ((RHO_o / 386) * (1 - strain(i)))) ^ 0.5
    Cells(4 + i, 5) = wav_vel(i)
    Cells(4 + i, 6) = 0.00092
    Cells(4 + i, 7) = Cells(4 + i, 6) / Cells(4 + i, 5)

Next i

'MsgBox lambda(1)
'MsgBox mu(1)

End Sub
Private Sub wavetime()

Dim i As Integer
Dim n As Integer
Dim delt As Double

n = Cells(5, 1)
delt = Cells(5, 15)

'***** CALCULATE THE CUMULATIVE TIME AND DISPLAY THE OUTPUT

For i = 1 To n
```

```
    Cells(i + 4, 8) = Cells(i + 3, 8) + Cells(i + 4, 7)
    If Cells(i + 4, 8) > delt Then
        MsgBox ("The wave reached layer no.   " & (Cells(i + 4, 1)))
        Cells(5, 11) = Cells(i + 4, 1)
        Cells(6, 11) = Cells(i + 4, 2)
        Exit For
    End If

Next i

End Sub

Private Sub CommandButton1_Click()

Call vel
Call wavetime

End Sub

Private Sub CommandButton2_Click()
Range(Cells(5, 5), Cells(4000, 8)).ClearContents
End Sub
```

APPENDIX - B

'****** 1-D IMPACT MODEL CODE AS A MODULE INTEGRATED WITH ROLL COMPRESSOR CODE [1]******

```
Sub resultsCOMPRESSOR()

'VARIABLES FOR ALPHA, BETA EXTRACTION AND FOR HARDNESS CALCULATIONS

Dim disp2, disp3, disp4, load_disp1, load_disp2, disp2tot, disp3tot, disp4tot, load_disp1tot, load_disp2tot As Double

Dim ks, xin, xgap, xmax, delx, Fmax, alpha, beta, rel_error, max_rel_error As Double

Dim Q, DQ, Hardness As Double

'****************************************************************************

Worksheets("LOAD vs DEFORMATION").Activate

Worksheets("LOAD vs DEFORMATION").Cells.ClearContents

'****************************************************************************

For q1 = 1 To CN

    'READ INPUT FROM THE OUTPUT OF THE COMPRESSOR CODE
```

```
    Range(Cells(q1 + 3, 5), Cells(q1 + 3, 5)) = TLOAD(q1)

    Range(Cells(q1 + 3, 4), Cells(q1 + 3, 4)) = TDISP(q1)


    'CALCULATE PARAMETERS FOR ALPHA, BETA EXTRACTION


    disp2 = (TDISP(q1)) ^ 2

    Range(Cells(q1 + 3, 7), Cells(q1 + 3, 7)) = disp2

    disp2tot = disp2tot + disp2

    disp3 = (TDISP(q1)) ^ 3

    Range(Cells(q1 + 3, 8), Cells(q1 + 3, 8)) = disp3

    disp3tot = disp3tot + disp3

    disp4 = (TDISP(q1)) ^ 4

    Range(Cells(q1 + 3, 9), Cells(q1 + 3, 9)) = disp4

    disp4tot = disp4tot + disp4

    load_disp1 = TLOAD(q1) * TDISP(q1)

    Range(Cells(q1 + 3, 10), Cells(q1 + 3, 10)) = load_disp1

    load_disp1tot = load_disp1tot + load_disp1

    load_disp2 = TLOAD(q1) * disp2

    Range(Cells(q1 + 3, 11), Cells(q1 + 3, 11)) = load_disp2

    load_disp2tot = load_disp2tot + load_disp2


Next


Range(Cells(3, 4), Cells(3, 4)) = "DISPLACEMENT"

Range(Cells(3, 5), Cells(3, 5)) = "LOAD"

Range(Cells(3, 7), Cells(3, 7)) = "DISPLACEMENT_2"
```

```
Range(Cells(3, 8), Cells(3, 8)) = "DISPLACEMENT_3"

Range(Cells(3, 9), Cells(3, 9)) = "DISPLACEMENT_4"

Range(Cells(3, 10), Cells(3, 10)) = "LOAD*DISPLACEMENT"

Range(Cells(3, 11), Cells(3, 11)) = "LOAD*DISPLACEMENT_2"

Range(Cells(3, 11), Cells(3, 11)) = "LOAD*DISPLACEMENT_2"


'CALCULATE THE SUM OF SQUARES, CUBES AND QUADS OF DISPLACEMENT


Range(Cells(CN + 5, 7), Cells(CN + 5, 7)) = disp2tot

Range(Cells(CN + 5, 8), Cells(CN + 5, 8)) = disp3tot

Range(Cells(CN + 5, 9), Cells(CN + 5, 9)) = disp4tot

Range(Cells(CN + 5, 10), Cells(CN + 5, 10)) = load_disp1tot

Range(Cells(CN + 5, 11), Cells(CN + 5, 11)) = load_disp2tot


'BUILD LHS MATRIX


Range(Cells(CN + 8, 9), Cells(CN + 8, 9)) = disp4tot

Range(Cells(CN + 8, 10), Cells(CN + 8, 10)) = disp3tot

Range(Cells(CN + 9, 9), Cells(CN + 9, 9)) = disp3tot

Range(Cells(CN + 9, 10), Cells(CN + 9, 10)) = disp2tot


'BUILD RHS MATRIX


Range(Cells(CN + 9, 12), Cells(CN + 9, 12)) = load_disp1tot

Range(Cells(CN + 8, 12), Cells(CN + 8, 12)) = load_disp2tot
```

```
Dim matrix1(), matrix2(), ansmatrix() As Variant

'SOLVE MATRICES TO EXTRACT VALUES OF ALPHA, BETA

matrix1 = Range(Cells(CN + 8, 9), Cells(CN + 9, 10))

matrix2 = Range(Cells(CN + 8, 12), Cells(CN + 9, 12))

ansmatrix = ThisWorkbook.Application.WorksheetFunction.MMult((ThisWorkbook.Application.WorksheetFunction.MInverse(matrix1)), matrix2)

'PRINT VALUES OF ALPHA AND BETA

Range(Cells(CN + 11, 11), Cells(CN + 12, 11)) = ansmatrix

Range(Cells(CN + 11, 10), Cells(CN + 11, 10)) = "ALPHA"

Range(Cells(CN + 12, 10), Cells(CN + 12, 10)) = "BETA"

'****************HARDNESS CALCULATION**********************

'INPUT VALUES OF RHOMETER STRIKER

ks = 16 * RWIDTH

xin = 10 / 32

xgap = 3 / 32

'READ VALUES OF ALPHA AND BETA FROM PREVIOUS ALGORITHM

alpha = Range(Cells(CN + 11, 11), Cells(CN + 11, 11))
```

```
beta = Range(Cells(CN + 12, 11), Cells(CN + 12, 11))

rel_error = 1
max_rel_error = 0.001
xmax = xgap / 3

'START ITERATIONS FOR CALCULATING THE MAXIMUM DISPLACEMENT OF STRIKER

Do While rel_error > max_rel_error

   Q = (alpha / 3) * xmax ^ 3 + 0.5 * beta * xmax ^ 2 + 0.5 * ks * ((xgap + xmax) ^ 2 - xin ^ 2)
   DQ = alpha * xmax ^ 2 + beta * xmax + ks * (xgap + xmax)

   delx = -Q / DQ

   xmax = xmax + delx
   rel_error = Abs(delx / xmax)
Loop

'CALCULATE MAXIMUM FORCE EXERTED BY THE STRIKER ON THE SURFACE OF THE ROLL

Fmax = alpha * xmax ^ 2 + beta * xmax

'********CALCULATE THE VALUE OF HARDNESS************
Hardness = Fmax / (386.08858 * (0.000718 * RWIDTH) * 3.76)
```

VITA

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Master of Science

Thesis: ONE-DIMENSIONAL DYNAMIC IMPACT MODEL TO PREDICT HARDNESS OF WOUND ROLLS.

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