ENGINEERING PAPER TUBES TO IMPROVE WINDING PERFORMANCE OF VARIOUS MATERIALS

by

T. D. Gerhardt, Y. P Qiu, C. G. Johnson, and D. E. Rhodes
Sonoco Products Company
USA

ABSTRACT

Over the past 10 years, Sonoco has conducted fundamental, solid mechanics research concerning structural behavior of spirally wound paper tubes. The scope of this program has included experimental, numerical, and analytical mechanics approaches as documented in references (1-7). For recent non-linear finite element research, we have used ABAQUS and developed user-defined material subroutines. These subroutines feature a proprietary 3D constitutive model for paperboard. The model uses non-linear stress-strain properties of Sonoco paperboard measured in 3 principle directions. ***An important research objective is to develop innovative tube designs that enable our customers to improve their winding operations.*** To achieve this objective, we have developed several patented test devices that measure tube properties fundamental to winding applications. Tests to measure core radial stiffness on the inside and outside (E_c) with respect to an external pressure and radial strength have been developed. This paper describes the test methods and presents data to verify mechanics research findings by way of two core applications. These are examples of where cores were engineered using mechanics technology to improve winding capability: (1) development of an extremely high E_c core for winding low friction, coated aluminum, and (2) cores for winding textile yarns based on radial stiffness of inside diameter.

INTRODUCTION

Sonoco produces paper tubes for industrial packaging using a spiral winding process (figure 1). Because paper is an anisotropic material, the spiral winding process yields a generally anisotropic structure. To complicate matters, paper tubes are frequently loaded into the non-linear stress-strain region during use. Over the past

10 years, we have developed several experimental, numerical, and analytical tools to aide in the design of tubes to meet a wide variety of customer requirements.

Experimental mechanics work at Sonoco has two concentrations. The first is to generate material behavior data to compliment the development of constitutive models. The second is to mimic loading conditions tubes are subjected to in the field. The overall goal is to develop a capability to design tubes to meet specific requirements and to test for compliance with those requirements.

A numerical mechanics capability has been developed for situations where testing and analytical models can not provide a reasonable framework for product design or understanding. Problems with complex buckling and contact have been successfully solved. Proprietary constitutive models have been incorporated into ABAQUS to analyze these problems.

Several analytical models have been developed over the years. Both linear and non-linear models have been produced, including a general 3D non-linear paper model. With these models and ABAQUS, many product configurations and loading have been successfully modeled.

The balance of this paper will discuss the application of these technologies and capabilities through two design cases.

CORES FOR WINDING COATED ALUMINUM PRODUCTS

Many researchers have computed internal stresses in web materials wound around paper or metal cores. For example Pfeiffer (8), Yagoda (9), Hakiel (10), and Willett and Poesch (11) have considered rolls constructed by center winding. These are typically nonlinear, one-dimensional formulations in the radial direction of the roll. Roisum (12) presents an excellent review.

In the published winding models, core outside diameter stiffness (E_c) is introduced through a boundary condition. Gerhardt and Qiu (4) published E_c for paper tubes. Data is from measurements with strain gauges on three-inch diameter tubes. Analytical, numerical, and experimental results in this paper show that core stiffness values published in the literature were incorrect.

Bernie Becker of ALCOA presented a paper at the fourth IWEB (13) describing his efforts to solve winding problems associated with two failure modes, "V-buckle" and "sag" collapse (13). Figures 2a and 2b illustrate these failure modes. Becker, using WINDER[1], established an exceptionally high E_c performance requirement needed to solve this problem. Figures 3 and 4 show the effect of increasing tube E_c on radial and tangential stress in the wound on aluminum. As Becker illustrates in figure 9 (13), theoretically, the higher tube stiffness widens the process window for web tension control.

For this winding application, we developed and manufactured an extremely stiff paper tube to the desired E_c level. Tube design was accomplished using a proprietary multi-grade linear-elastic equation to estimate tube deformations under external pressure. With this model, E_c values of various constructions can be calculated. Required inputs to the model include elastic modulus values for the paper grades under consideration, Qiu, et al. (7). Becker describes the results of using the new core in (13).

Large diameter tubes, 406.4 mm (16 inch), are used for winding in the metals industry. An issue is that these are too large to test using our patented radial crush testers (14). Thus to verify this design methodology, we developed a test device to directly measure E_c.

[1] WINDER V4.2, A proprietary winding analysis software package developed by the Web Handling Research Center, Oklahoma State University.

E_c Test Device

The large-scale test device is pictured in Figure 5. A tube is initially mounted as shown. The entire section then slides into an extremely large pressure vessel. During the test, air pressure is increased in increments to about 125 psi. During pressurization, the two arms shown rotate and sensors mounted on the ends measure outside diameter deformation. Average outside diameter is measured at several different pressure levels.

Typical data collected is shown in Figure 6. By definition (12), the slope of this line multiplied by tube outside diameter is the E_c value. ***Note the linearity of the pressure - OD change response.*** For this test and the ID stiffness test that follows, we analyze average diameter changes. Data from both tests show a linear response at low pressures.

For OD pressure loading of tubes, the first buckling mode is an oval shape. As discussed in the companion paper, the radial crush tester prohibits this buckling. ***Moreover, when used in the field, the wound material also restrains this buckling mode in the tube.*** Thus, the linear response in Figure 6 is consistent with field loading of these large tubes. Attempts to measure E_c from strain gages at several locations around the tube circumference would be unsuccessful. Tube buckling would be inadvertently interpreted as a non-linear pressure - OD change response.

CORES FOR WINDING TEXTILES

Many paper tubes are used to wind synthetic textile yarns such as polyester, nylon and lycra™, which are produced at high-speeds (up to 7000 m/min). These yarns are wound under tension and most exhibit some recovery after winding. It is not unusual for a 30-pound package of polyester to wind for 16 hours. The winders will generally have a single station that can accommodate three or four packages. A solid steel winding mandrel with extensible elastomer "gripper" rings support and holds the core during winding by the inside diameter. The inside diameter (ID) and the winding mandrel diameter generally differ by one to two millimeters. This set of process conditions drives two primary core requirements. Firstly, a core must have enough radial strength to withstand the pressure of wound yarn over time. Secondly, the core ID stiffness must be sufficient to maintain an ID larger than the winding mandrel.

Deformation in a Paper Tube

Under external pressure loading, deformations in paper tubes are quite different than those found in isotropic or even transversely orthotropic materials. Gerhardt (2) discusses these differences and provides a theoretical framework to estimate deformations in paper tubes. In this paper, data from strain gauge measurements confirms the elasticity solution for load levels less than about 50% of ultimate strength. A typical deformation pattern is illustrated by the dotted lines in Figure 7. Unlike an isotropic tube, radial deformation on the outside diameter greatly exceeds radial deformation on the inside diameter. As described in the paper, this is caused by an extremely low ratio of modulus in the r and q directions, respectively.

ID Stiffness Test Device

To measure ID stiffness, Sonoco developed an accessory for the radial crush tester. This system is a laser-based displacement sensor and associated hardware and software. Figure 8 is a schematic of the basic configuration of the ID measurement system. The laser is rotated as displacement data is acquired. Typical data is shown in Figure 9. Pressure is plotted on the Y axis and inside diameter change, or ID comedown, is plotted on the X axis. Data from 5 replications is shown.

Radial crush strength of this particular tube was about 800 psi. Note that up until about half the failure load, pressure-deformation response is fairly linear. The straight line represents the slope of this linear portion of the curve. We define the ID stiffness of this tube as the slope of this line, or approximately 85,000 (psi/in).

Modulus values have been measured for recycled paperboard in all directions (Qiu, et al., 7). Using these values, tests have confirmed that the elasticity solution (2) provides reliable ID stiffness estimates. We measured tube diameter changes at several textile manufacturing operations. By combining design technology and field measurements, special tubes were designed for specific yarn applications. The issue of creep/moisture content is again important as, for some yarns, winding times can be as long as 18 hours.

We derived a proprietary, elasticity solution for multi-grade tubes. Based on this model and experiments, an optimized, multi-grade structure was discovered. As described in Patent 5,505,395 (15), the construction features a weaker grade located in the center of the tube wall.

ID Stiffness: Effect of Moisture Content

The relationship between tube inside diameter stiffness and moisture content is shown in Figure 10. In this study, four different tube types were tested. ID stiffness measurements were conducted at four different moisture content levels. In analysis of the data, a regression curve was determined for each tube type. Each data set was then normalized to yield an ID stiffness of 1.0 at a moisture content of 8.5%. Note the dramatic impact of moisture content on this performance attribute.

SUMMARY

Over the past 10 years, researchers at Sonoco have conducted fundamental, solid mechanics research concerning structural behavior of spirally wound, paper tubes. The scope of this program has included experimental, numerical, and analytical mechanics approaches. As described in this paper, a portion of this research has been published while many details have remained proprietary. This paper describes several test devices and design methods that measure tube property data fundamental to winding applications. Such data verifies mechanics-based design methods developed for various field applications. We also describe field examples where paper tubes were successfully engineered using mechanics technology to improve winding capability. These include a high stiffness tube designed for winding low friction, coated aluminum and tubes designed for winding textile yarns based on stiffness of inside diameter.

ACKNOWLEDGEMENTS

The authors would like to thank Sonoco's senior management for continuous funding of a mechanics research program over the past 13 years. These individuals include Charlie Coker, Peter Browning, Tom Coxe, Harris DeLoach, Trent Hill, Russell King, and Earl Norman. Other individuals that have contributed greatly to the success of this program include Linda Hill, Wim van de Camp, William Blakeney, Bill Miller, Mike Schock, Wayne Honeycutt, and Ray Hayes. Finally, Kathy Tutcher capably typed this manuscript.

REFERENCES

1. Bank, L. C., T. D. Gerhardt, and J. H. Gordis "Dynamic Mechanical Properties of Spirally Wound Paper Tubes." *ASME Journal of Vibration, Stress, and Reliability in Design*, Vol. 111, p. 489-490, 1989.

2. Gerhardt, T. D. "External Pressure Loading of Spiral Paper Tubes: Theory and Experiment."
3. Bank, L. C., E. Cofie, T. D. Gerhardt "A New Test Method for the Determination of the Flexural Modulus of Spirally Wound Paper Tubes." *ASME Journal of Engineering Materials and Technology*, Vol. 114, p. 84-89, 1992.
4. Gerhardt, T. D., Y. P. Qiu "Paper Tube Deformations During Winding Processes." ASME Proceedings: Mechanics of Cellulosic Materials, Anaheim, CA, p. 1-6, Nov. 8-13, 1992.
5. Gerhardt, T. D., J. F. Staples, R. G. Lucas "Vibrational Characteristics of Wound Paper Rolls: Experiment and Theory." *Tappi Journal*, Vol. 76, p. 121-128, 1993. 0
6. Gerhardt, T. D., R. W. Kearns "Radial Crush Takes the Measure of a Core." *Converting*, Vol. 12, No. 2, p. 50-52, 1994.
7. Qiu, Y. P., M. Millan, C. H. Lin, T. D. Gerhardt "Nonlinear Properties of High Strength Paperboards." ASME Proceedings: Mechanics of Cellulosic Materials - 1997, AMD-Vol. 221, MD-Vol. 77, Northwestern University, p. 1-18, June 29 - July 2, 1997.
8. Pfeiffer, J.D., Hamad, W.Y., "How Core Stiffness and Poisson Ratio Affect Energy Balance Roll Structure Formulas.", Presented at the First International Conference on Web Handling, May 17-22, 1991 Oklahoma State University, Stillwater, Oklahoma.
9. Yagoda, H.P., "Resolution of a Core Problem in Wound Rolls." *ASME Journal of Applied Mechanics,* Vol. 47, p 847, 1980.
10. Hakiel, Z., "Nonlinear Model for Wound Roll Stress," *TAPPI Journal*, Vol 70(5), p. 113, 1987.
11. Willett, M.S. and Poesch, "Determining the Stress Distributions in Wound Rolls of Magnetic Tape Using a Nonlinear Finite Difference Approach." *ASME Journal of Applied Mechanics*, Vol 55, p 365, 1988.
12. Roisum, D.R., "The Measurement of Web Stresses During Roll Winding." Ph.D. Thesis, Oklahoma State University, Stillwater, Oklahoma, 351 pgs.
13. Becker, B. J. "A Systems Approach to Reducing Winding Defects at Alcoa-Warrick Operations." Proceedings of the Fourth International Conference on Web Handling, Oklahoma State University, p. 102-114, June 1 – Jun 4, 1997.
14. Rowlands, R.E., Saliklis, E.P., Wise, J.T., Gerhardt, T.D., "Apparatus and Method for Testing Tubular Products.", Patent number 5,339,693, 1994.
15. Qiu, Y.P., Gerhardt, T.D., "Multigrade Paperboard Winding Cores for Yarns and Films Having Enhanced Resistance to Inside Diameter Reduction.", Patent number 5,505,395, 1996.

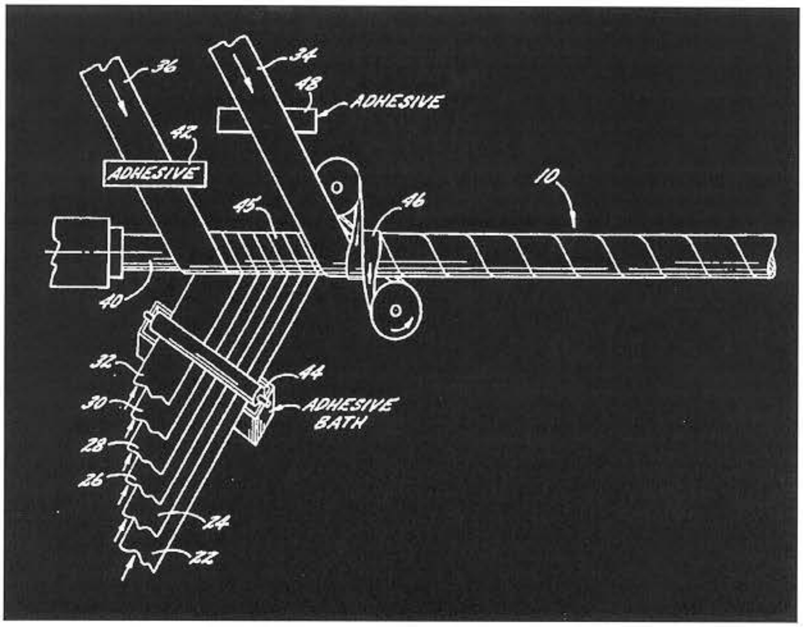

Figure 1. Schematic of paper tube winding

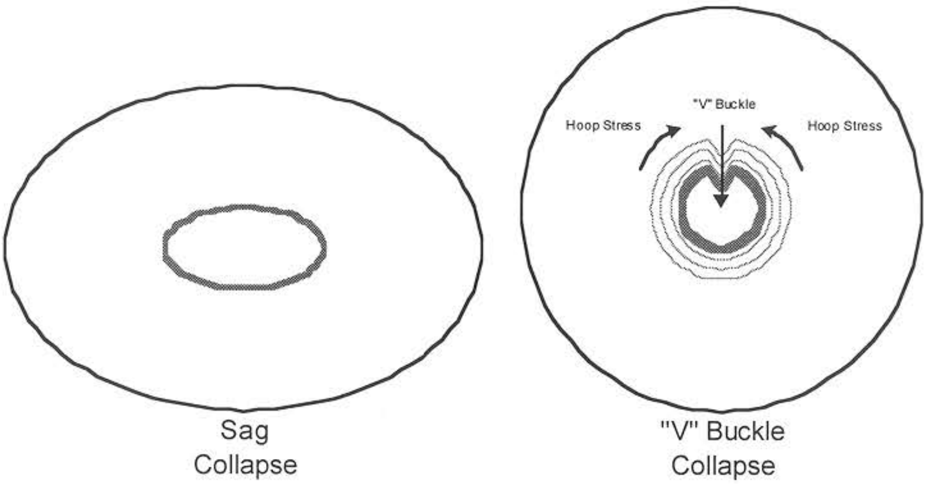

Figure 2a & b. Sag Collapse and "V-buckle".

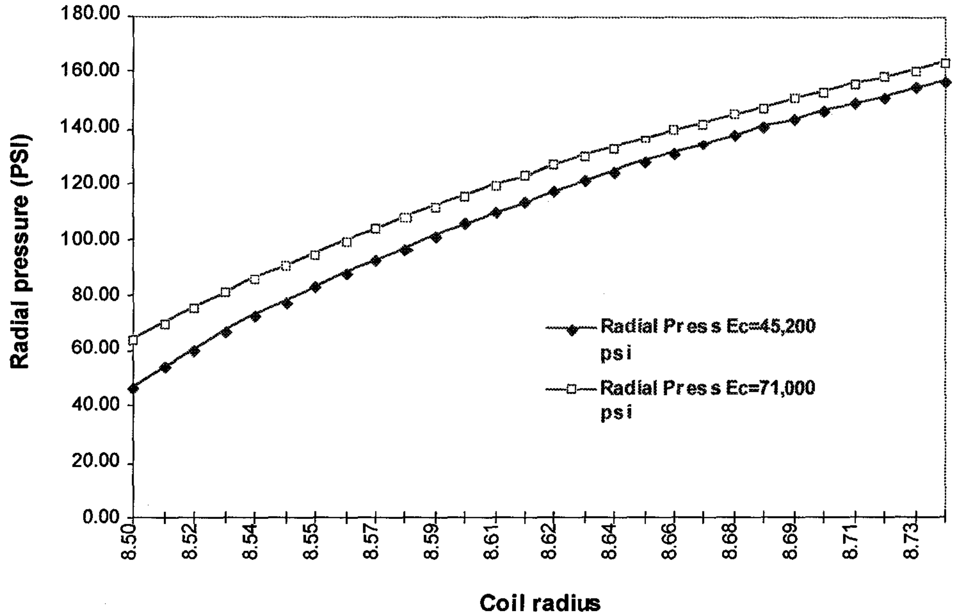

Figure3. Radial Pressure at the coil inside diameter for cores with different E_c Values. [13]

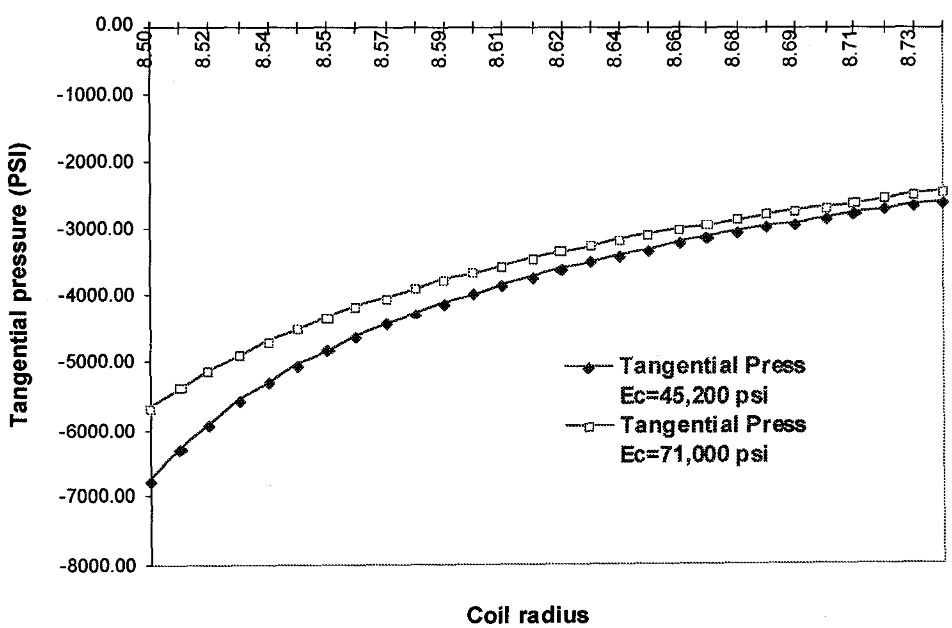

Figure 4. Tangential stress at the at the inside diameter for cores with different stiffness values. [13]

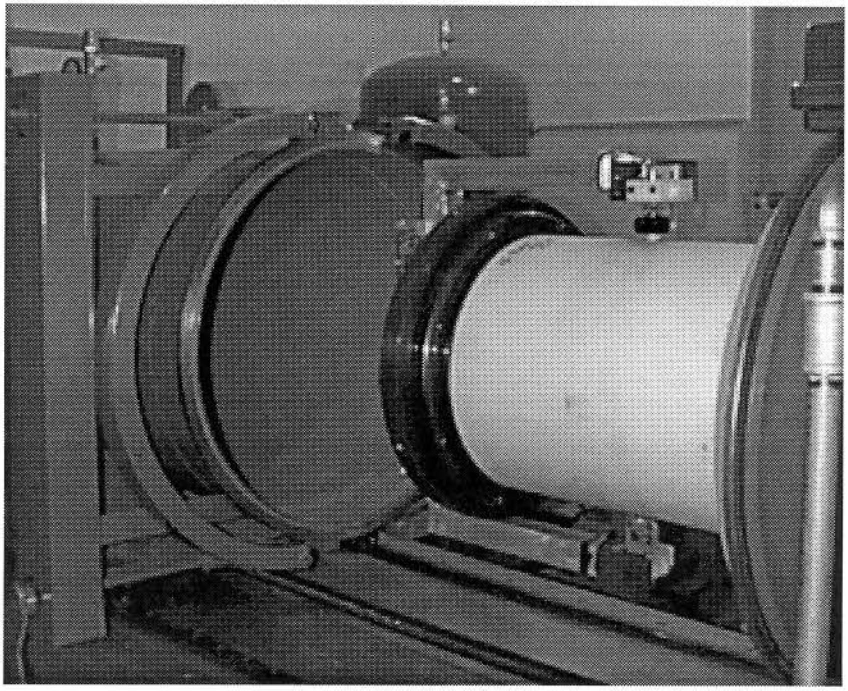

Figure 5. E_c measurement device.

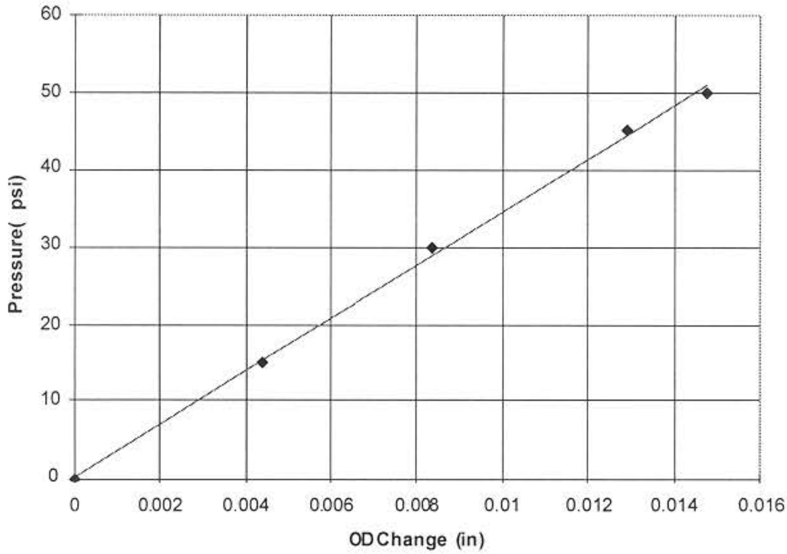

Figure 6. Typical E_c test results.

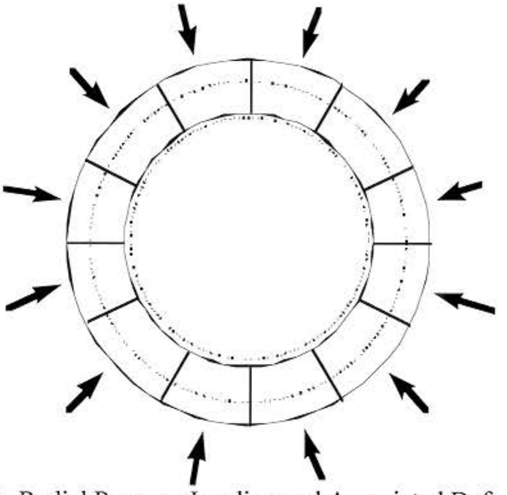

Figure 7. Radial Pressure Loading and Associated Deformation.

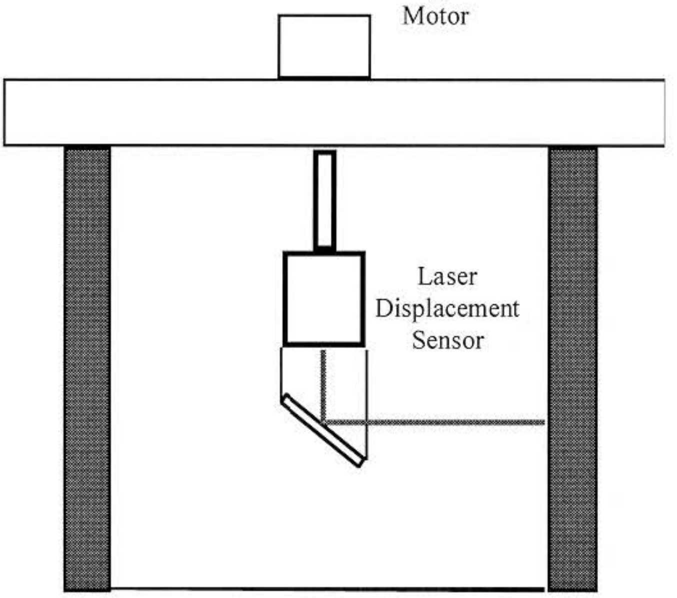

Figure 8. ID Measurement System.

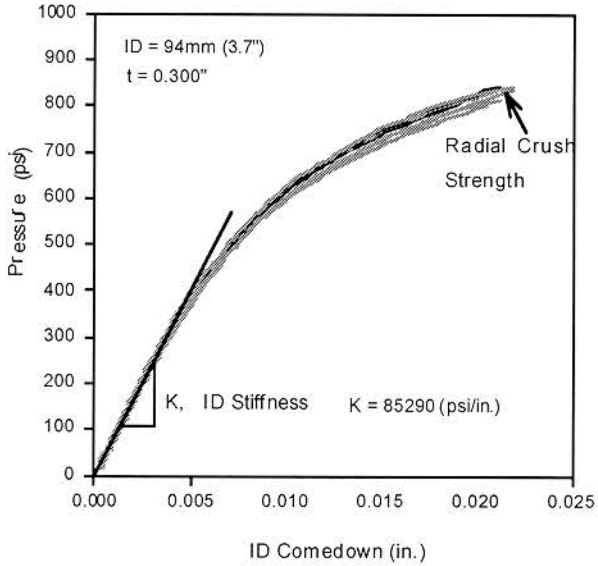

Figure 9. Applied Radial Pressure vs. ID

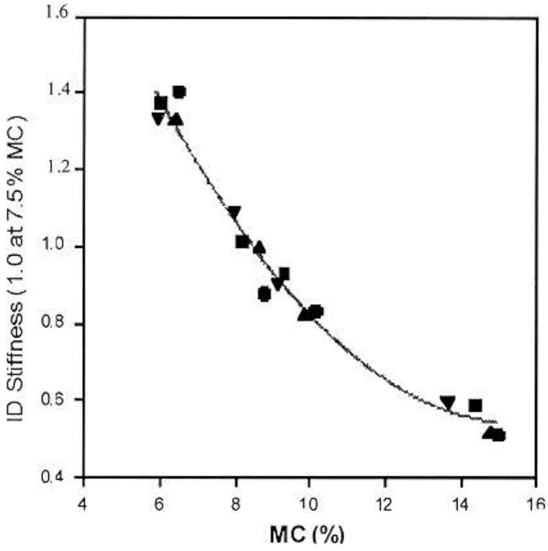

Figure 10. ID Stiffness vs. Core Moisture Content.

T. D. Gerhardt, Y.P. Qiu, C.G. Johnson and D.E. Rhodes
Engineering Paper Tubes to Improve Winding Performance
6/8/99 Session 2 10:45 - 11:10 a.m.

Question - Neil Michael, Kimberly Clark
Interesting work. Royce refers to core modulus that possibly can be optimized for particular applications. Do you feel like you can develop a core that has a high internal modulus and low external modulus?

Answer – Chuck Johnson, Sonoco
Sure.

Questions:
Has that been typically done? Is that something that is common practice?

Answer – Chuck Johnson, Sonoco
Again we have tools that are designed for a variety of requirements. Papers have limitations in terms of properties however; we can use these properties to achieve the desired property. We have a couple of patents that are referenced between the two papers that address some of these issues. I know there is a high stiffness design that is patented and you can reference that.

Questions – Semion Stoylar, Tidland Corporation
We are working on differential rewinding. I'm wondering if you are doing research for differential winding for slitters?

Answer – Chuck Johnson, Sonoco
Differential winding?

Comment:
When you have differential distribution of the tension of the slitting, you allow the core ID to act like a clutch.

Answer – Chuck Johnson, Sonoco
We work hard not to have the core slip on the shaft. We consider this a bad situation. You want to purposely have the core slip? Many people here are familiar with the problem where the inside of the core basically gets chewed up by the winding equipment and unwinding equipment. Do we know how to address that problem? Not to my knowledge but contact David or me, about a particular requirement like that.

Questions - Eric Markenstern, Penn State University
I was curious about your experiments on the large diameter tubes. How did you get the pressure on the inside of the tube to be different from the outside of the tube?

Answer – Chuck Johnson, Sonoco
The inside of the tube is open to the atmosphere.

Questions - Gary Homan, Westvaco
In your schematic where you demonstrate how these tubes are manufactured, there is the use of a lot of adhesive. How do you deal with the potential of very high moisture levels inside your product? How do you deal with the inside stiffness and external stiffness versus moisture content?

Answer – Chuck Johnson, Sonoco
All the adhesives are water based. Our testing is performed at standard temperature and humidity conditions, with tubes at equilibrium. We make sure, through the design of the tube and through conditioning processes that the moisture levels and stiffness of the products are suitable for the customer.

Questions - Keith Good, Oklahoma State University
I've done some similar external pressure tests and I guess I was wondering how do you prevent air from permeating the core? Do you somehow prevent air from migrating through the tube and changing the moisture content of the tube?

Answer – Chuck Johnson, Sonoco
The air is dried before it goes into the test chamber.

Questions - Keith Good, Oklahoma State University
But if it is being pumped through the core is it drying out the core?

Answer – Chuck Johnson, Sonoco
We don't know for sure. The tests are performed in a small amount of time, which doesn't allow a lot of time for drying to take place.

Questions - Keith Good, Oklahoma State University
We saw a lot of leakage through the points where the plies cross one another, and we usually had to bag it, or something to prevent the airflow.

Answer – Chuck Johnson, Sonoco
Part of it is these are quite heavy wall tubes, 500-wall 700-wall tube thick, and we've got the end sealed. The custom designed seals prevent a lot of air transmission. We can easily test for this effect.

Questions:
A lot of operations are shaftless today in continuous film winding as well as other web winding. One of the problems that we experience is the actual strength of the core, where it meets the chuck or expanding elements and transmits that type of torque. What work is planned in this area to develop prediction limits?

Answer – Chuck Johnson, Sonoco
We've done some cursory work in that area. We've done those kinds of calculations for people to see what those shear loads would be for instance, in E-stop situations. In terms of actually designing the tube to meet the need of particular shear strength like that, we haven't really done it.

Comment:
I think that would be really helpful to the industry to be able to have some standards in this area. It would reduce a lot of problems that we're currently experiencing.