

INVESTIGATION OF THE EFFECT OF VOIDS
ON THE STABILITY OF WEBS.

By

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2006

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
December, 2007

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Acknowledgements

First and foremost I offer my sincere gratitude to my advisor Dr.J.K.Good for his guidance throughout my master's career. His unlimited patience with me is greatly appreciated. He has offered invaluable guidance in my research endeavors. I could not wish for a better, friendlier supervisor. As a productive researcher, he will always be a role model for me through out my career.

Secondly, I would like to thank my committee members Dr.C.E.Price and Dr.H.B.Lu for their advice and assistance. It has been a great experience being their student. Dr.Price has imparted great knowledge about materials and their properties. The analytical skill acquired by me through Dr.Lu's courses is marvelous. I would like to extend my gratitude to Ron Markum for his invaluable help in the lab, both with my equipment setup and experiments. In addition, I thank the WHRC sponsors for making my research possible.

Finally, I would like to extend my sincere gratitude to my parents B.L.Gurudatha Mallya and Radha Mallya and my sister Sushma Mallya for their continued support during my research at Oklahoma State University.

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Nomenclature

CMD,MD	Cross Machine Direction, Machine Direction
d	Diameter
E	Young's Modulus
F_{CMD}	Force in the Cross Machine Direction
$F_{friction}$	Friction force
$F_{wrinkle}$	Force required to sustain a wrinkle
FE	Finite Elements
FEA	Finite Element Analysis
h,t	Thickness of the web
L	proximity of the void from the tip of the wrinkle
r	roller radius
T, Tw	Web line tension
W	CMD separation between the wrinkles
w	Width of the web
X,Y,Z	Co-ordinate directions
σ_y	Normal Stress
$\sigma_{y,cr}$	Critical compressive stress
σ_1, σ_2	Principal stresses
ϵ_1, ϵ_2	Principal strains

ν	Poisson's Ratio
μ	Coefficient of Friction
λ	Ratio of principal strains

CHAPTER I

Introduction

Wrinkling in Web Handling

A web is a continuous flexible material such as paper, plastic film, and thin metal sheets. The web undergoes several processes such as printing, coating, drying, slitting, or laminating, which add value to the web prior to conversion into the final product. The transportation of webs through web processes is known as web handling.

During the processing of these webs, there are possibilities of wrinkles being generated, which may result in immediate loss of quality, value and productivity. Wrinkling, typically causes permanent damage to the web. It can have devastating effects on the quality of a downstream winding roll. The formation of troughs in the free span may adversely affect processes such as printing and coating, due to non planar geometry in the web span. Whether the web breaks or is damaged permanently, the end result is often wasted web and costly downtime of the web line. The objective of web handling is to reduce the loss of quality and to avoid wastage. Prediction of wrinkles and protecting the webs from wrinkling is an important engineering problem in the web handling industry.

Wrinkling consists of crests and troughs, which are out of plane deformations of the web as it travels through the free span. A wrinkle formed on a roller is illustrated in Figure 1. There are three types of wrinkles that might be formed in a web, namely, machine direction [MD] wrinkles, cross machine direction [CMD] wrinkles and shear wrinkles.

(i)MD wrinkles are due to the presence of compressive forces in the CMD.

(ii)Lateral shear forces due to misaligned rollers, imperfect rollers causes shear wrinkles in the web.

Shear wrinkles or diagonal wrinkles often result from misaligned or tapered rollers [1, 2]. One of the two regime behaviors can be responsible for a wrinkle based on the previous research in this area.

Regime 1: These are diagonal wrinkles, caused in the presence of a net lateral force or a shear force, due to a tapered roller or a misaligned roller. These are independent of web velocities and assume there is no loss of traction due to air entrainment. Web enters normal to the roller.

Regime 2: Wrinkles are dependent on web velocities and traction between the web and roller. There is loss of traction and the web slips laterally. The web may violate the normal entry rule as discussed by Lorig [3].

(iii)CMD wrinkles [1] are generated during the winding or unwinding processes due to interlayer slippage which may be the result of air entrainment.

The focus of this research is on the first type of wrinkles, the MD wrinkles, which result from CMD compressive forces. The research will help determine, how the CMD compressive forces arise.

In order to reduce the process time of the web, the velocity has to be as high as possible. Higher velocities may cause air entrainment between the web and the roller, resulting in loss of traction. This may cause lateral movement of the web leading to shear wrinkles. Using a roller with higher coefficient of friction might improve the traction between the web and the roller, but may cause the out-of-plane deformations in the web span to travel across the roller as a wrinkle. Very low tension can result in collapse or telescoping of a wound roll. Increasing web tension will increase the amount of compressive CMD stress the web can withstand prior to formation of troughs. Troughs are out-of-plane instabilities that occur in free spans between web rollers. Thus, we see that web velocities and web line tension are important parameters when considering wrinkling. They are also amongst the few parameters that a web line operator can control. Thus, the knowledge of how tension, velocity and friction interact to create and sustain wrinkles is important.

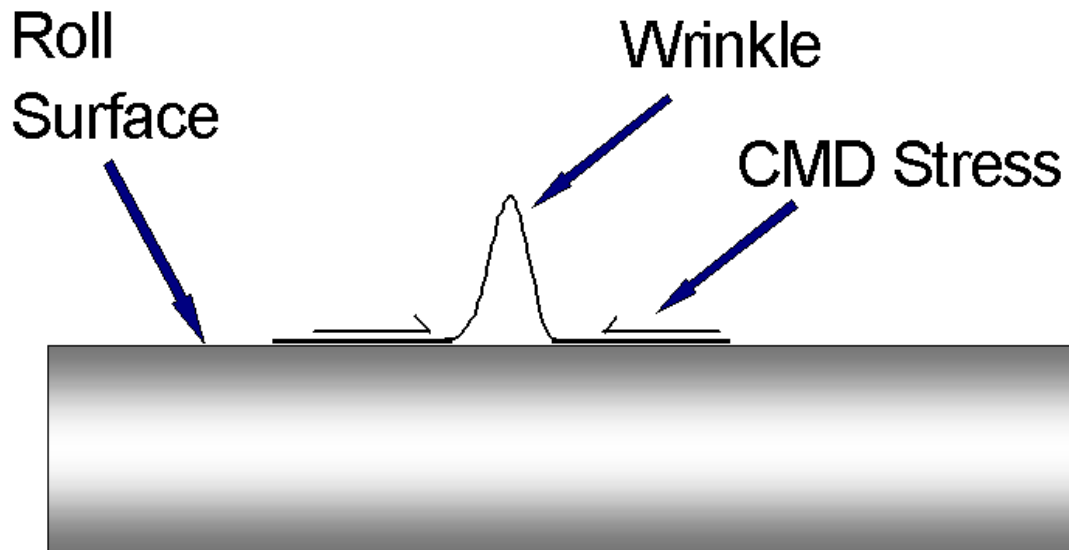


Figure 1 – A Wrinkle generated over the roller.

Webs with Discontinuities

Some webs may have holes of various shapes intentionally cut into them as a part of the manufacturing or converting processes, Example- A polymer film with holes used for packaging, to allow excess air to escape. These webs with holes might still have to undergo transportation through the web process machinery. Handling of such materials becomes difficult as the stress distribution varies across the web at the cross section of the hole. The goal of this research is to study how these holes affect the web's propensity to wrinkle.

CHAPTER II

Literature Review

Miller and Hedgepeth [4] developed an algorithm for plane stresses implementing the Stein-Hedgepeth wrinkle model numerically. They modified the stiffness of the elements based on their current strain. These elements, when used to handle a buckled condition, may take either elastic or wrinkles or slack state depending on their current state of strain.

The [D] matrix is given by

$$D = \frac{E}{1 - \lambda^2} \begin{bmatrix} 1 & \lambda & 0 \\ \lambda & 1 & 0 \\ 0 & 0 & \frac{(1-\lambda)}{2} \end{bmatrix} \quad \lambda = \frac{-\varepsilon_2}{\varepsilon_1}$$

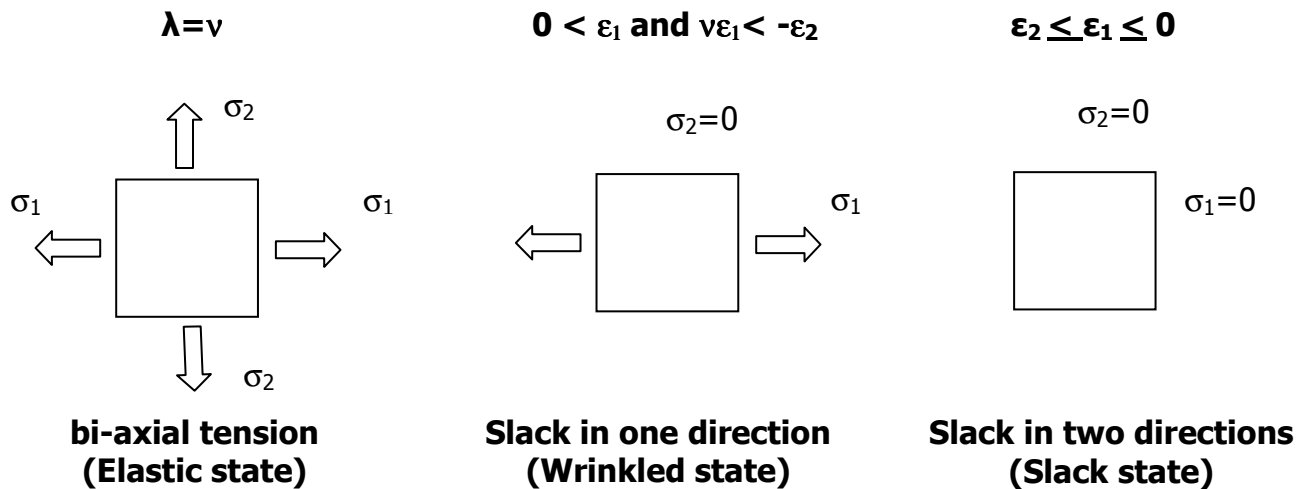


Figure 2 – States of wrinkling membrane elements

Figure 2 depicts various states of the wrinkling membrane elements. When the element is taut, the λ value is set equal to the Poisson's ratio ν , and this value of λ is used to determine the [D] matrix and the stiffness matrix. This is the elastic state of the element. When there is slack in any one direction, the bending stiffness along that direction is negligible. This corresponds to the wrinkled state of the element. In this state the λ value is greater than the Poisson's ratio, and this value of λ is used to calculate the [D] matrix and the stiffness matrix. In the slack state of the element, there is a slack along both the directions. In this case the [D] matrix and hence the stiffness matrix is set to zero. In essence, these elements cannot sustain any compressive load.

Their numerical algorithm retains the simplicity of the linear elastic case, but is consistent with the non-linear Stein-Hedgepeth wrinkle model.

Miller, Hedgepeth, Weingarten and Das [5] evaluated the accuracy and efficiency of a numerical algorithm for the stress strain behavior of partly wrinkled membranes. They compared the analytical and numerical results for stress displacement in a partly wrinkled flat membrane, under pure twist and pure bending and achieved the convergence of the required iterative procedure without excessive computation.

Webb [6] used wrinkling membrane elements to model the web with corrugations due to troughs. These elements have very low stiffness in the cross machine direction and cannot sustain any compressive stresses. Acceptable agreements were achieved but only after the rotations from the FE analysis were added to the rotations needed to form troughs as per Beisel [7].

Shelton [8] developed a theory for steering of webs. He focused on modeling the steering effects due to a misaligned roller. He presented a model for web deflection by treating the web as a beam. A significant development was the modeling of the developed slack edge in the web. He discussed the use of normal entry of a web to a roller that was previously used in the drive belt industry. The rule of normal entry is that, a web will always seek to align itself perpendicular to the axis of the roller it is approaching, assuming there is continuous traction between the web and the roller.

Beisel and Good [2] developed a model for predicting troughs and wrinkles due to shear. The models were verified by conducting experiments with tapered and misaligned rollers. They proposed a model to predict the onset of troughs and wrinkles due to crowned downstream rollers and achieved good agreement with experiments. Their models employed finite elements that were developed from the theories of Miller and Hedgepeth, referenced earlier. Beisel better implemented the boundary conditions of the membrane elements and achieved better agreement between the FE model and experimental results as compared to Webb [6]. Beisel set the stiffness matrix corresponding to the slack direction of the web to zero. Although his model had respectable agreement, it had limitations when applied to extremely short spans of 10" or less. A model for wrinkling, due to crowned roller and an enlarged sector of the web was also proposed and achieved acceptable agreement with the experiments.

Timoshenko [9] studied the buckling of a thin cylindrical shell under uniaxial compressive load and obtained an expression for the critical compressive force per unit length of the edge of the shell, as given below in equation (1)

$$\sigma_{y,cr} = - \frac{E * h}{r \sqrt{3(1 - \nu^2)}} \quad (1)$$

He also proved that the buckling stress for a sector of a cylinder is equivalent to the buckling stress for an entire cylinder. Since the web wrapped around a cylinder may be approximated to a sector of pressurized cylindrical shell, this expression can be applied to the web over a roller.

Shimizu, Yoshida and Enomoto [10], studied the stress distribution and buckling behavior of thin plates with a centrally located hole under tension. They did a FE analysis of plates under uniaxial tension and found that the tensile stress developed in a plate with a circular hole was 46% less and the compressive stresses were 12% less when compared to a plate with a rectangular hole under identical boundary conditions. The buckling load required for the plate with a circular hole was 41% more than that required for a plate with a rectangular hole. They concluded that in the case of a rectangular hole the curvature at the corners or the hole had a very small effect in improving the buckling strength. They assumed the plates to be simply supported at their four edges. No experimental data were provided.

Rice [11] studied the effect of stress concentration on the material properties of porous materials. He stated that the stress concentration is more in uniaxial tension than in

biaxial tension. The effect of pore shape on the material behavior is greater in tension than in compression. As the pore concentration increases and spacing between the pores reduces, its effect on the material properties also substantially reduces. In a pore-crack combination, stress concentrations are dominated by cracks and not pores.

Research Objective

Nothing in the literature could be found that relates to how holes or voids affect the instability of membranes traveling through web process machinery. Thus, the objective of this research is to explore how holes or voids affect the propensity of webs to wrinkle. This research is both unique and of economic importance, as described in the introduction.

CHAPTER III

Experimental procedure

Equipment Setup

In support of this research and future research efforts in wrinkling, a test bed was designed and constructed. When conducting research regarding web instability, it is preferable to establish controlled conditions. The literature references make it clear that issues such as roller misalignment and taper are variables that can impact web troughs and wrinkles. These references indicate that web span length is a factor in the instability.

This research is conducted at the Web Handling Research Center's High Speed Web Line (HSWL) at Oklahoma State University. Web wrinkling is often tension dependent and the high speed web line has the best tension control available.

A module already existed in the web line that was originally intended for instability studies. Precise roller alignment and change of web span length was not possible in the existing module, thus a modification was required. A roller with a precision surface was manufactured for this research. This is important as many instability

problems can be affected by irregularities in the boundary conditions, thus a roller with surface free of defects is important.

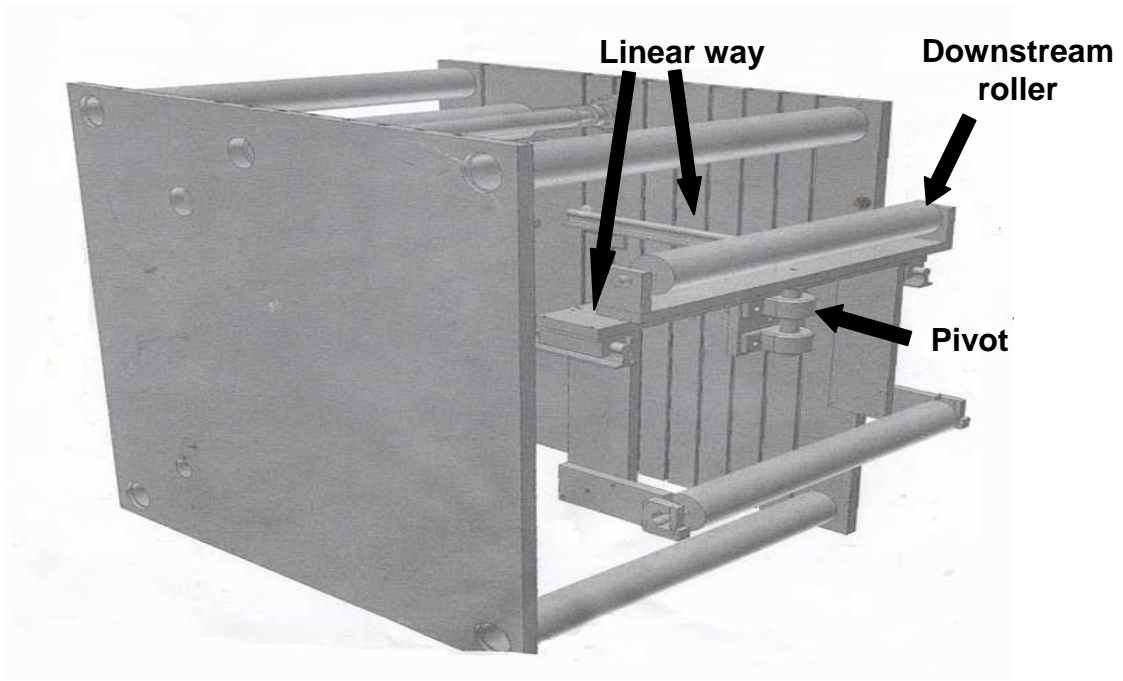


Figure 3 – 3D Model of the modified wrinkle Module in HSWL.

The modified Wrinkle module is shown in Figure 3. The pivoting roller and the linear way that allows the span length to be modified are shown at the right end of the module. A Schematic of the web path through the High Speed Web Line is shown in Figure 4.

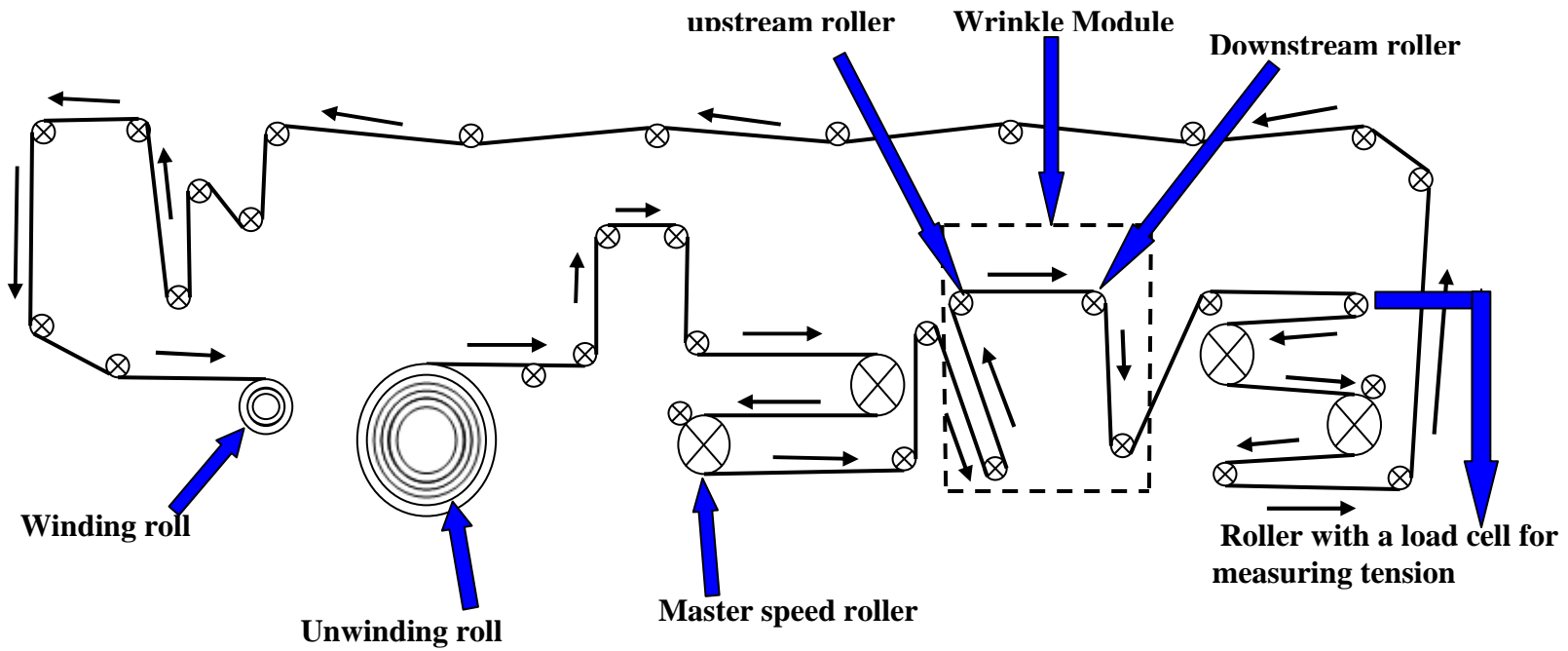


Figure 4- Schematic of the web path through the high speed web line.

Test Procedure

In a typical test, the web line would be started in motion and allowed to achieve a steady state velocity and tension. Care has to be exercised to ensure that the wrinkling did not occur until the voids reached the test span. This was accomplished by setting the unwind tension zone at as low a web tension as possible. If wrinkling persisted at the rollers prior to the test span, the rollers were taped locally at the web edges to provide a spreading effect. Wrinkling always results in inelastic deformation of the web and thus, web wrinkles occurring on the rollers upstream of the test span could cause an increased variability of the test results.

Typically, the data collection consisted of recording the distance between the downstream edge of the hole and the web entry point to the downstream roller (L) in the test span when the wrinkle would appear and the corresponding web tension. In most cases two wrinkles form, one on either side of the hole and in that case the dimension W would also be recorded. Repeat tests would be performed at the same web tension. Tension would then be altered and testing would commence again. The dimensions recorded are shown in Figure 5.

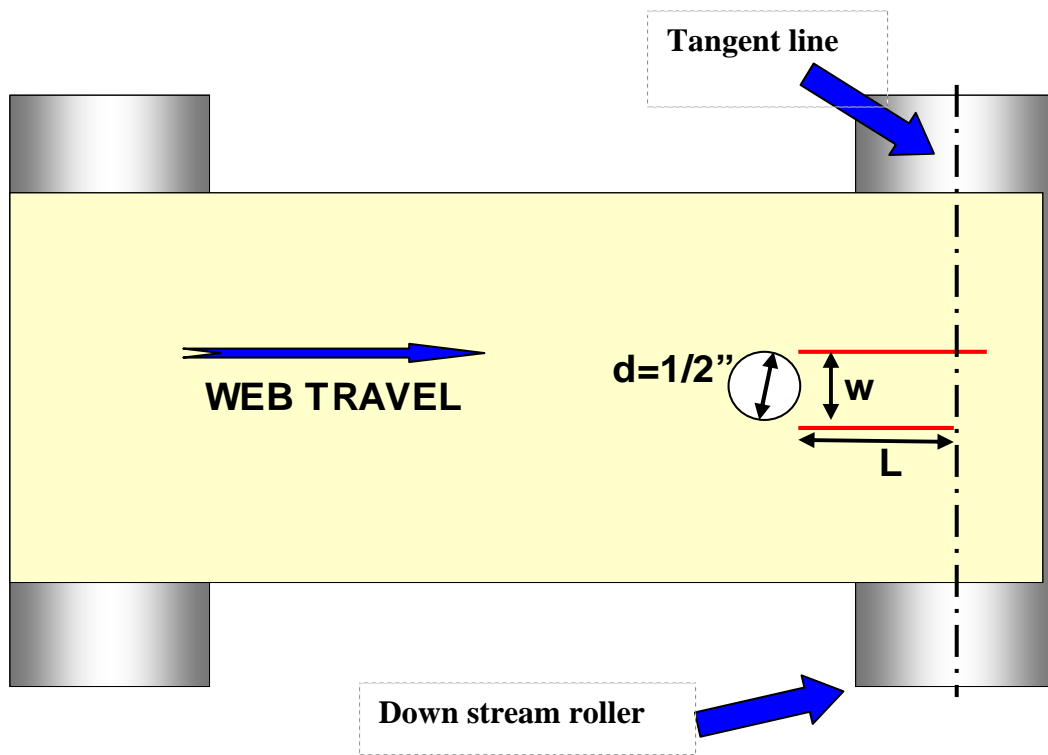


Figure 5 – Data recorded during tests.

CHAPTER IV

Prediction of Wrinkles in a web due to a Circular hole/discontinuity.

To effectively reach the goal of predicting instabilities in webs due to discontinuities, the effect of different shapes of voids may be studied and ultimately combined. The first step is to study the instability due to the simplest shape, which is a circular hole in the web span on a nearly isotropic web. First the behavior of the web with a hole in a web span is studied, followed by analysis to see if the behavior can be predicted.

Experiment:

A 12” wide 79 gauge polyester web was used in this study. A half inch bore was drilled exactly at the center of the roll with the help of a brad bit drill, as shown in Figure 6. An axial stretch test was conducted and the modulus was found to be 712000 psi . The stretch test consisted of a web length 50 feet, subjected to various levels of tension along its length while simultaneously recording the resulting deformation. The data from this test were used to construct charts of stress vs strain where the slope determines the machine direction Young’s modulus. This test was developed at the WHRC to minimize grip effects that have been observed in modulus tests in films conforming to ASTM specification D882 [12]. The results of the stretch test for the 92 gauge polyester are shown in Figure 7.



Figure 6- Hole being drilled in the web roll.

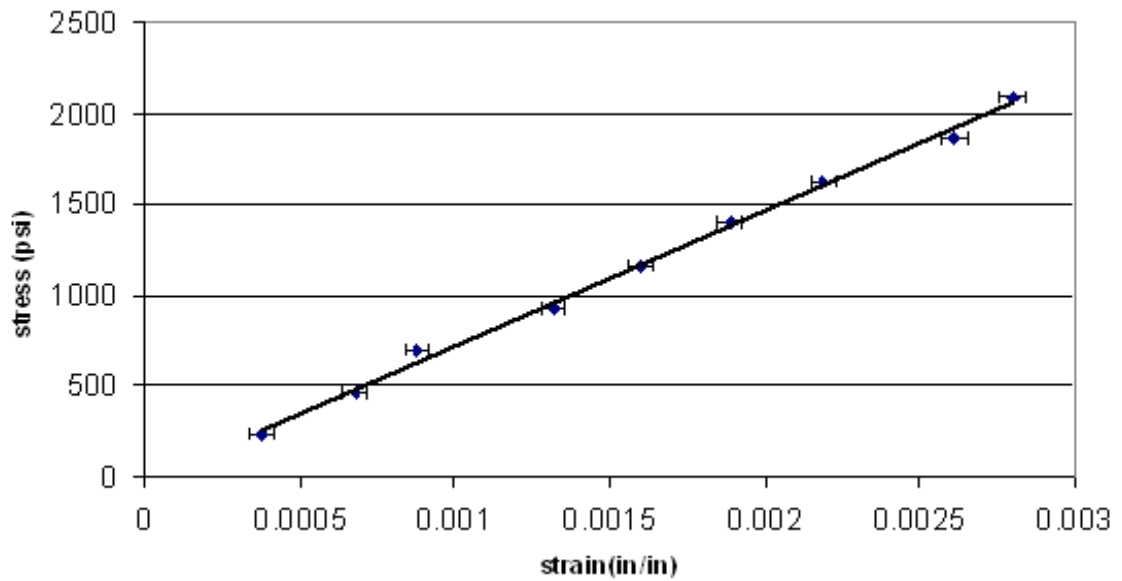


Figure 7- Data from the stretch test 79 gauge Polyester, $E=712000$ psi

The Polyester web was unwound on the unwinder of the High Speed web Line at a speed of 10 feet per minute. Wrinkling of the web on any other roller prior to the downstream roller in the test span is undesirable. Once wrinkles occur in a web they result in permanent inelastic deformation and will cause a permanent web defect. A web with such defects will wrinkle prematurely in the test span and produce wide variability in the test results. The rolls of web used in these tests were discarded after one set of experiments.

To reduce the potential for wrinkling on rollers upstream of the test span, the tension in the unwind tension zone was maintained low. Lateral friction forces are necessary to sustain wrinkles on the rollers. By decreasing web tension, the contact or normal forces between the web and the rollers are also decreased to the point that wrinkles may not be sustainable on the roller surface. In some cases where decreasing the web tension was not sufficient to eliminate wrinkles upstream of the test section, some of the upstream rollers were taped to ensure adequate spreading of the web over the rollers. Taping the edges of the rollers causes the web edges to be steered away from the web center and results in web spreading. The wrinkles module is located in a tension zone just downstream of the unwind section of the High Speed Web Line and its tension could be set higher or lower than the tension set in the unwind zone. Since, web tension was a test variable in the experiments that were conducted, taping the roller edges was the only resource to prevent wrinkles in this section of the machine.

The distance between the upstream and the down stream rollers in the test section (called the span length), in this experiment was set at 28 inches. The idler or smooth test roller at

the downstream end of the test span was 4 inches in diameter. The alignment of the smooth roller was adjusted such that there were no shear wrinkles in the span due to misalignment. The only variable in the experiment was web tension in the machine direction. The effect of web tension on wrinkle formation is studied.

As the hole in the web approaches the downstream roller, the first observation was out-of-plane web deformation occurring in the vicinity of the hole. This is referred as troughing [2, 6, 13]. As the hole in the web got closer to the down stream roller, at some point a critical distance was reached and two wrinkles of different lengths were formed in the region between the hole and the downstream roller. These wrinkles traveled over the roller and formed a crease in the material. The point at which the tip of the wrinkle is formed on the roller was marked (Figure 5 and 8). At the down stream location, the web was stopped and the distance of the tip of the wrinkle from the hole was measured and recorded. Also, the separation between the wrinkles were measured and recorded. The tension was increased at a rate of 0.5 pli, the tests were repeated, and the length of the wrinkles formed were measured and recorded. The length of the wrinkles and separation between the wrinkles are defined in Figure 5 and seen in Figure 8. For each tension value, ten values were taken. The averages of these values with error bars are plotted in Figure 9 and 10.



Figure 8 – Two wrinkles traveling on the roller

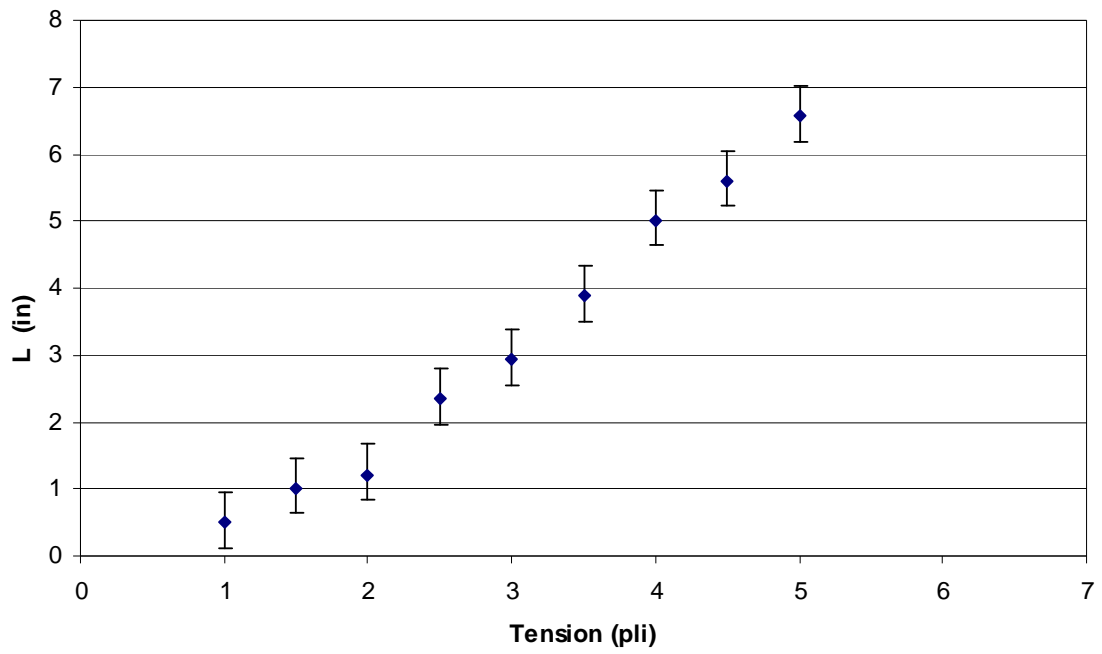


Figure 9- Length of wrinkles vs tension for the web with hole.

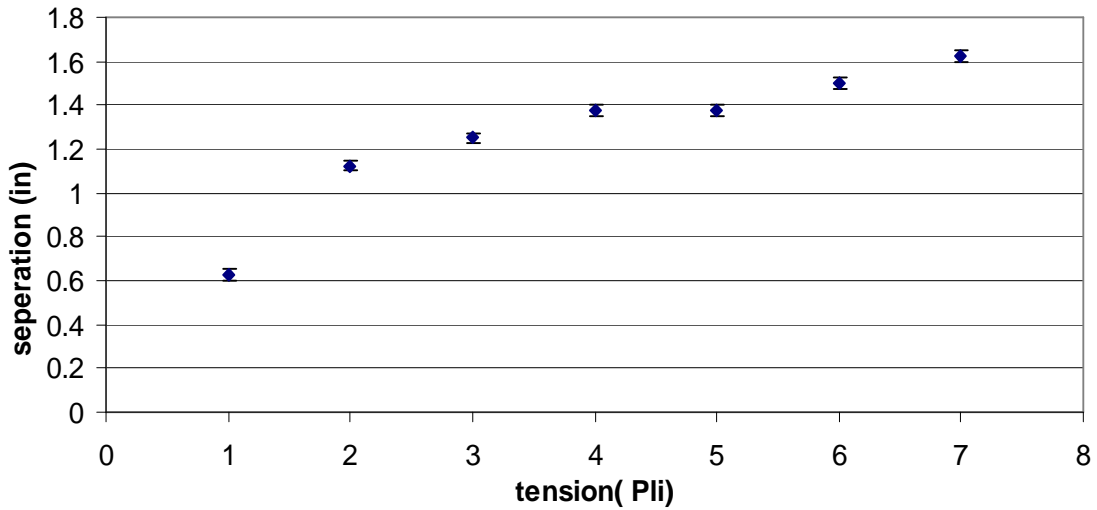


Figure 10– CMD separation between the wrinkles.

The separations between the wrinkles were measured. The data are presented in Figure 10.

Observations regarding test data

With an increase in the web tension, the wrinkles formed on the downstream roller earlier, with the hole further upstream from the entry point of the web on to the downstream roller. At higher web tensions, the presence of the hole further upstream from the roller, was able to produce CMD compressive stress in excess of the critical value as compared to lower tension cases. Thus the wrinkles formed earlier as compared to the lower tension case. As the tension is reduced, the distance between the wrinkle tip and the hole reduces, and at a particular low tension value, the wrinkle might disappear.

Theoretically there is a minimum tension required [14] to sustain a wrinkle over the surface of a roller. Assuming the web tension to be uniform across the web width, from Figure 11:

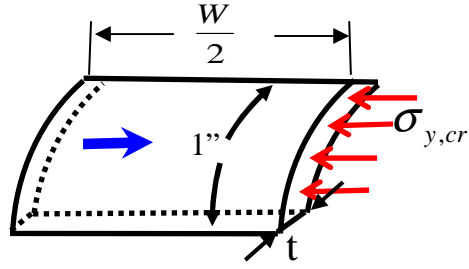


Figure 11 - section of web over the roller.

$$F_{\text{friction}} = \frac{T_w}{r} * \frac{w}{2} * 1 * \mu \quad (2); \quad F_{\text{wrinkle}} = \sigma_{y,cr} * t * 1 = \frac{t^2}{r} \frac{E}{\sqrt{3(1-\nu^2)}} \quad (3)$$

$$F_{\text{CMD}} = 0;$$

Coefficient of friction (μ), between PET and the Aluminum roller was determined to be 0.3, by performing the ASTM standard test, D1894 [15].

$$\frac{T_w}{r} * \frac{w}{2} * \mu = \frac{t^2}{r} \frac{E}{\sqrt{3(1-\nu^2)}}$$

$$T_w = \frac{2t^2}{\mu w} \frac{E}{\sqrt{3(1-\nu^2)}} = \frac{2(0.00079)^2 * 712000}{0.3 * 12 * \sqrt{3(1-0.3^2)}} = 0.15 \text{ pli}$$

In reality the web tension downstream of the void is non uniform, thus the value of minimum tension required to sustain a wrinkle is an approximation.

Although at a machine direction tension as low as 1 pli the web did not wrinkle as early as in the case of high web tension, it did wrinkle before the hole crossed the down stream roller. Thus taping the upstream roller would be necessary, to transport the web over a roller without wrinkling.

Modeling

Finite Element Modeling was used to model the wrinkling behavior witnessed in the laboratory. The FEA package COSMOS was used to model the web. The web upstream and downstream of the test roller was modeled in five sections as shown in Figure 12. Three of these sections represent the web on rollers and the other two sections represent the web in free span. The web on the upstream and down stream rollers has the shape of a cylindrical shell and is capable of sustaining a considerable cross machine direction compressive stress prior to wrinkling. Linear elastic quadrilateral eight node elements were used to model these webs sections. In the free span, wrinkling-membrane quadrilateral 8-node elements were used to model the web. The wrinkling membrane elements have characteristics defined by Miller and Hedgepeth [4]. The stiffness matrices of these elements change depending on the relative strains within the elements. This process, therefore, requires a non linear iterative process to handle the state dependent properties associated with the wrinkling membrane elements.

One of the nodes in the web span was constrained in the X-direction so that the web is constrained against rigid body movement in the X-direction. The row of nodes on the web centerline was constrained in the Y-direction to enforce symmetric behavior about the web centerline. This was appropriate since a symmetric void was located on the centerline of a symmetric web. All nodes were constrained in the Z-direction so that the web remains planar. The cross machine direction deformations of rows of nodes on the rollers are coupled to lock them together near the rollers so as to enforce normal entry of the web to the rollers. This coupling is enforced separately on each row of web nodes

crossing a roller and will not restrain Poisson's contraction of the web due to tension but will enforce normal entry of the web to the regions of the web on the rollers. Several aspects of this modeling have already been proved by Beisel [2] to be appropriate. In Beisel's research symmetric web deformations could not be assumed as is possible in this research.

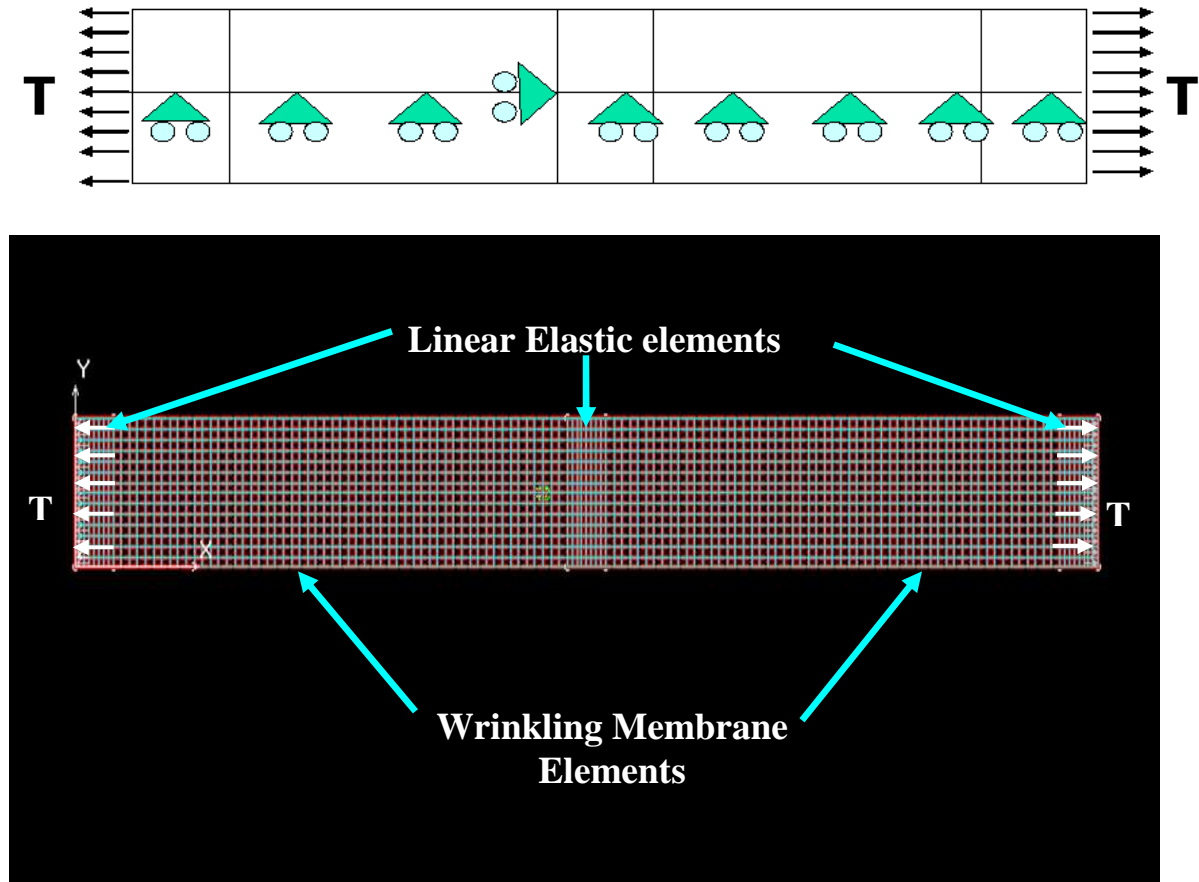


Figure 12 – FE model of the web span with a hole

When the finite element mesh was created, a uniform mesh was established for the three sections of element used to represent the web on the rollers and two uniform meshes were created for the free spans between the rollers. The hole in the web was made by deleting a few elements in the region where the hole was to be located, and modifying the position of the neighboring nodes to create a circular hole of 0.5 inch diameter. Tension was

applied by using a pressure curve on the edges of the webs along the X-direction as shown in Figure 12.

The critical value of the buckling stress for a cylinder under axial compression is given by the Timoshenko buckling equation [9]. Beisel [2] has proven that when the cross machine direction stress value exceeds the critical value, wrinkling will occur. For the web used in the experiments the critical stress is:

$$\sigma_{y,cr} = -\frac{E * h}{r\sqrt{3(1 - \nu^2)}} = -\frac{0.00079 * 712000}{2\sqrt{3\{1 - (0.3)^2\}}} = -170.2 \text{ psi} \quad (4)$$

The hole was modeled in the web with its center on the axis of symmetry and the tension was increased until the cross machine direction stresses in the web on the roller reached the critical value (-170.2psi). When the hole was 1” away from the roller, it was observed that a MD stress of 2050psi or 1.62pli was required to develop the critical buckling stress (Figure 13).

Figure 14 depicts the Critical stresses developed in the web when the hole was at a distance of 5 inches from the roller. Here a machine direction stress of 5443psi, or a machine direction tension of 4.3pli, was required to develop the critical stress.

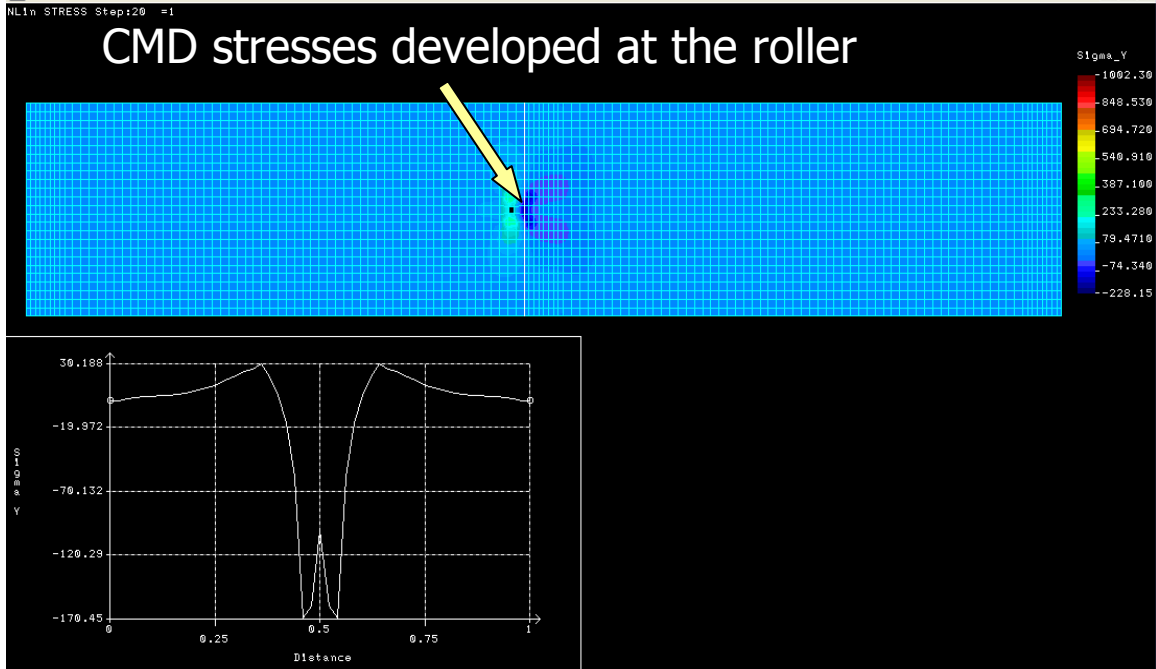


Figure 13- Critical σ_y stresses developed in FEA with hole at 1" from the roll.

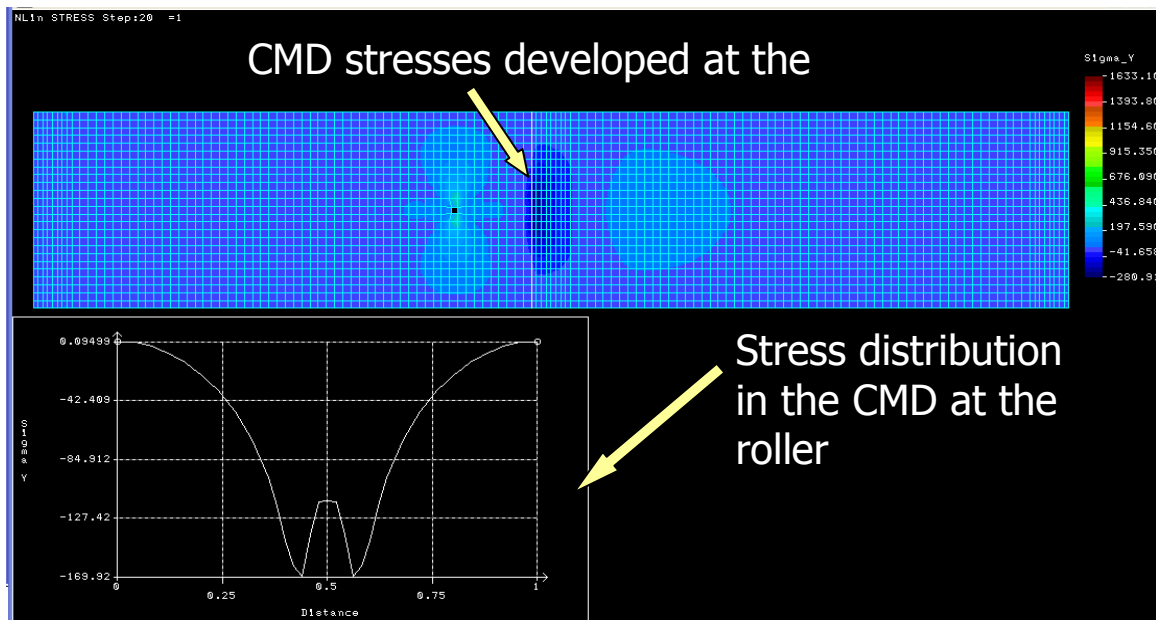


Figure 14 – Critical σ_y stresses developed with hole 5" away from the roll.

The FE analysis was conducted, with the hole at different distances from the roller. The tension levels which produced the critical Cross machine direction stress of -170.2psi are recorded in the Figure 15 and 16.

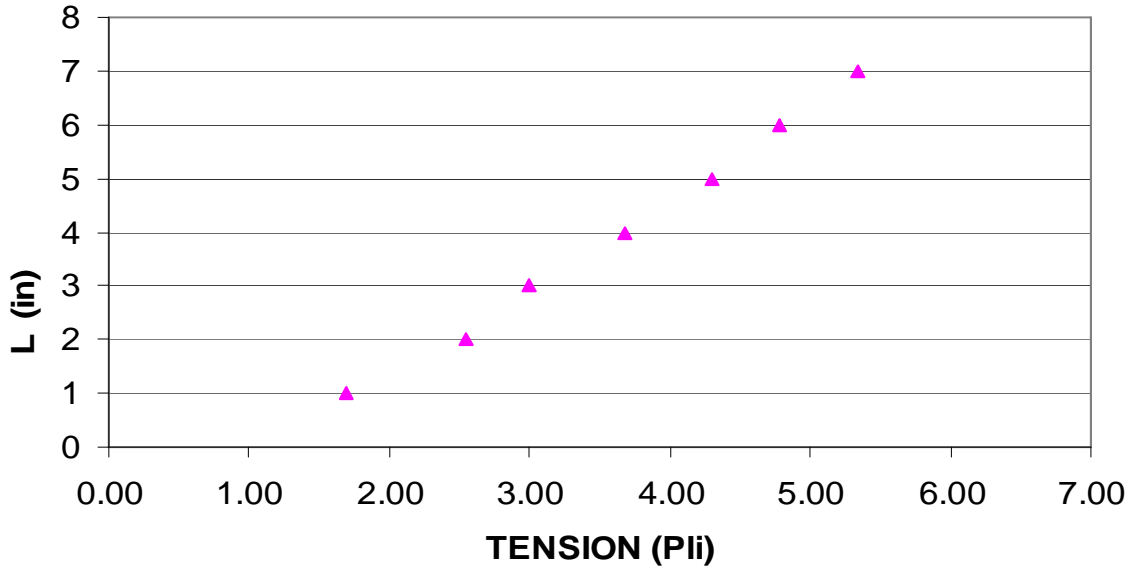


Figure15- FE data for wrinkle formation.

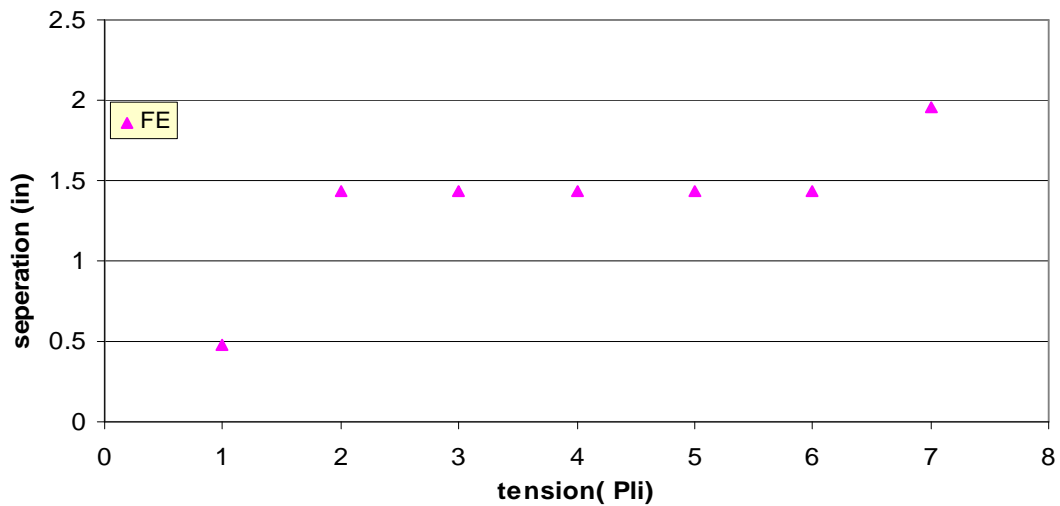


Figure 16- FE data of CMD separation between the wrinkles.

These recorded values are overlaid on the test results in Figure 17. The correlation between the experimental values and the FE results are respectable.

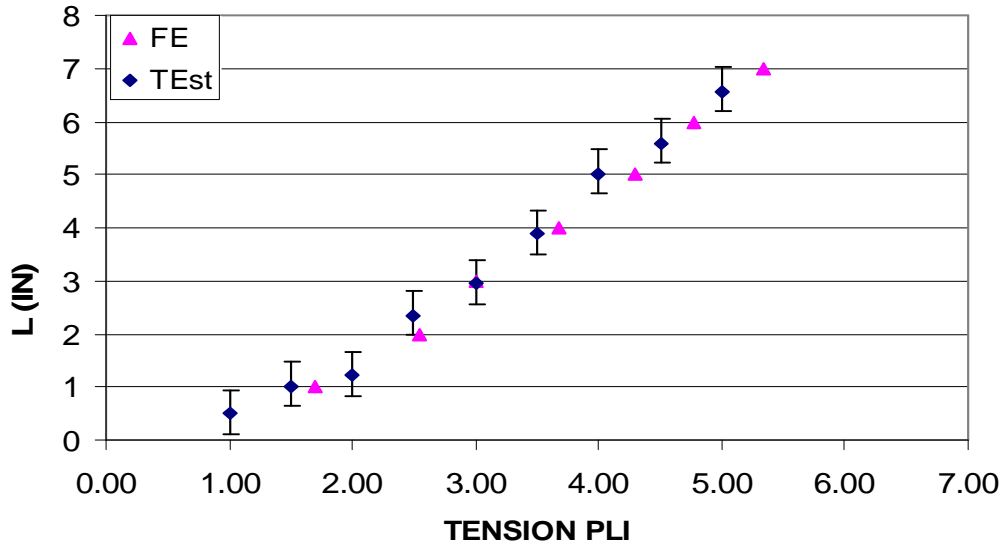


Figure 17 – FE data overlaid on the experimental data.

The separation between the wrinkles is also compared in Figure 18. The agreement is again respectable.

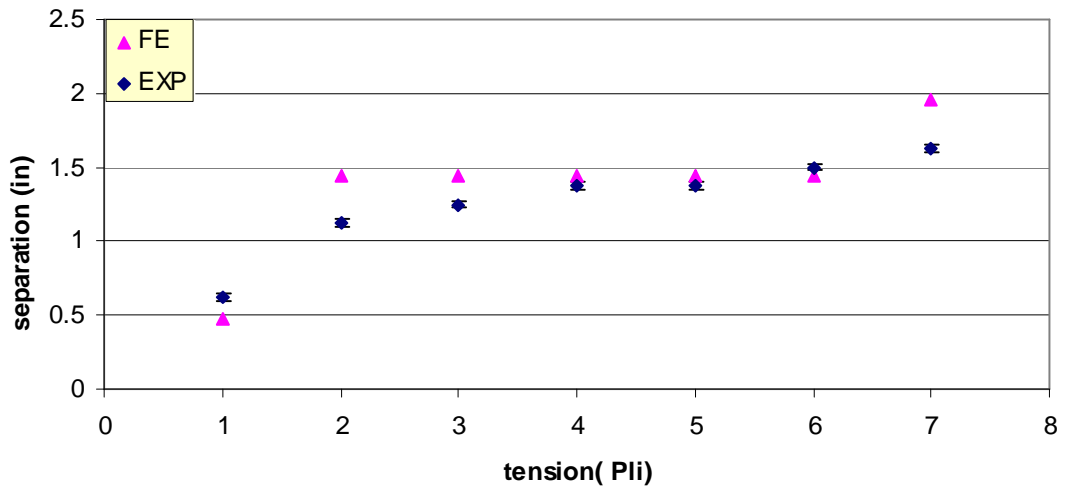


Figure 18 –Experimental and FE data of Separation between the wrinkles.

Observation regarding Analysis

From the FE analysis, it is observed that the cross machine direction stress reached the critical value at 2 points on the web near the tangent line. The distance from the hole at which these critical stresses developed nearly match to the point the web buckled on the roller, as shown in Figure 17. The distance between the two points where critical stresses were developed also match with the separation between the wrinkles. This demonstrates the role of cross machine direction stresses in the buckling of the web over the roller.

Chapter V

Prediction of Wrinkles in a web due to an elliptical Void/discontinuity.

To determine whether the modeling method was applicable to voids of various shapes, testing and analysis of the type defined in chapter 4 were conducted for an elliptically shaped void with the major axis aligned with the machine direction. This effort is an introductory exploration of the significance of void shape and answers the question of the type: If voids must exist in the converted web product? is there a preferred void shape from the web stability perspective?

Experiment

A 6" wide 92 gauge polyester web roll was used for the experiment. An elliptical punch was developed by Mr. Ron Markham with minor axis of 0.5 inches and a major axis 0.75. The punch was driven into the surface at the cross machine direction center of the roll as shown in Figure 19.



Figure 19 – Elliptical hole being punched in the roll.

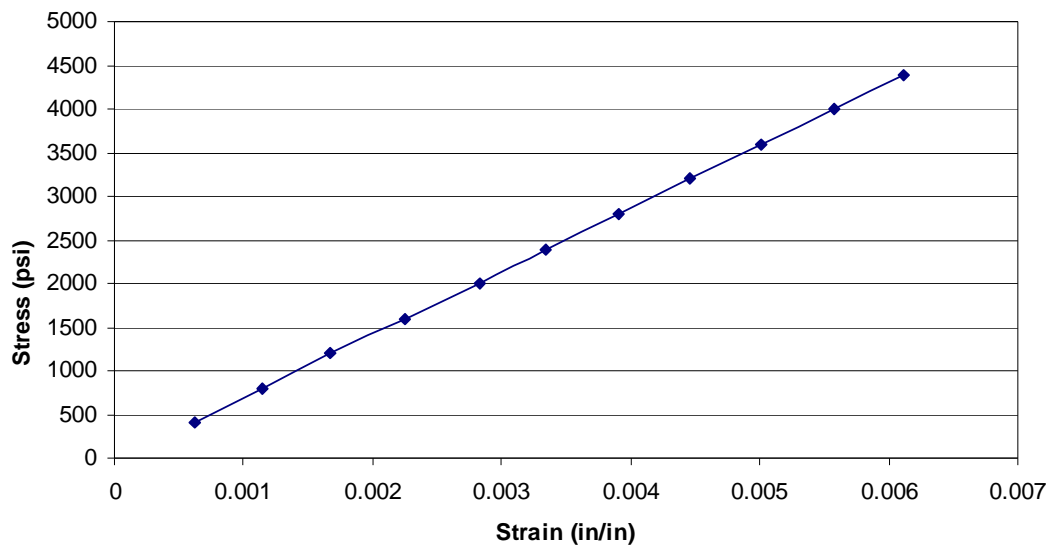


Figure 20 – Data from the stretch test 92 gauge Polyester, E=718000 psi

A MD stretch test was conducted and the modulus of the web was found to be 718000 psi. Figure 20 shows a plot of the data of the stretch test. The polyester web was unwound on the unwinder of the High Speed web Line again at a speed of 10 feet per

minute. In spite of the tension being maintained low in the entry span, the web wrinkled on each and every roller upstream of the wrinkle module. Hence, the ends of upstream rollers were taped until adequate spreading of the web over the rollers, upstream of the test roller was achieved.

The same test setup used for the previous experiments with the circular hole was used. The entry span was again maintained at 28 inches and down stream roller of the wrinkling module was 4 inches in diameter. The alignment of the down stream roller was adjusted so that there are no shear wrinkles in the span due to misalignment. A diagram showing the test span with the onset of wrinkles is shown in Figure 21.

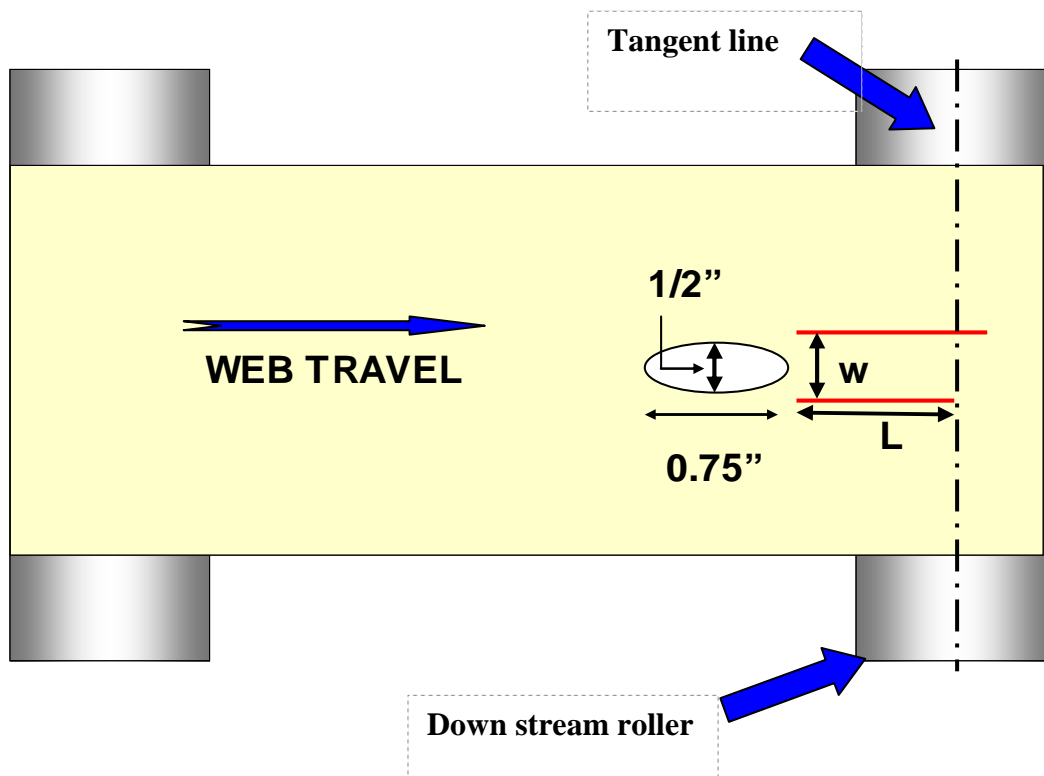


Figure 21 – Test span with the onset of wrinkles

The proximity of the ellipse from the tangent line on the downstream roller with the onset of wrinkling and the separation between the wrinkles formed were recorded for every 0.5pli increase in web tension. For each web tension, ten values were recorded and the averages of these values with error bars indicating the maximum and minimum of the measured values are plotted in the chart in Figure 22. The cross machine direction separations between the wrinkles are plotted in the chart in Figure 23.

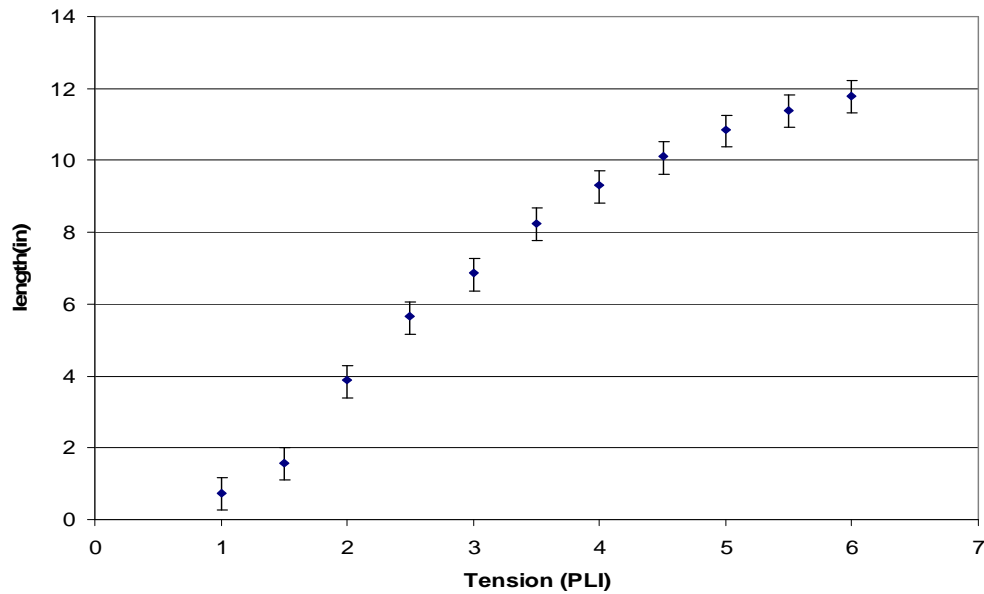


Figure 22– Proximity of an elliptical void to a down stream roller at the onset of wrinkling.

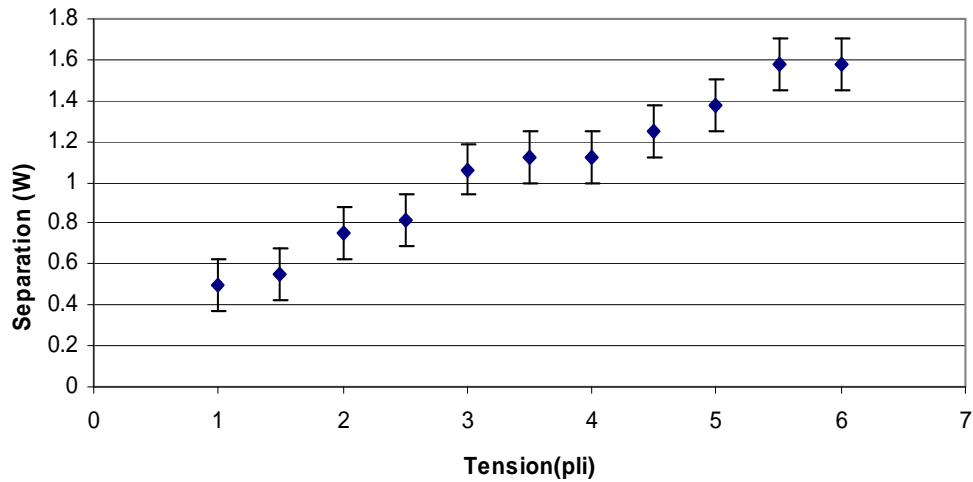


Figure 23 – CMD separation between the wrinkles.

Observation regarding Test data

The observations during the experiments were similar to those made earlier for the circular void. Where earlier the distance between the circular hole and the down stream roller appeared almost linear (Figure 9) it appears that the relation is now non-linear in Figure 22

With the increase in web tension, the wrinkle formed with the hole further upstream from the entry point of the web on to the downstream roller. It was observed that at a low machine direction stress, the ellipse gets very close to the downstream roller before the web buckles. The separation between the two wrinkles formed depends on the tension in the machine direction. It increased with the increase in tension.

Modeling

The modeling technique which was previously used (chapter IV) for modeling the wrinkling of the web due to a hole was used in this case as well. Now instead of the circular hole, the elliptical void was modeled in the web span.

The critical value of the buckling stress for the web used in this experiment as given by Timoshenko buckling equation[9] is:

$$\sigma_{y,cr} = -\frac{E * h}{r\sqrt{3(1-\nu^2)}} = -\frac{0.00092 * 718000}{2\sqrt{3\{1-(0.3)^2\}}} = -200 \text{ psi} \quad (5)$$

The void was modeled at a certain location and the tension was increased the tension until the cross machine direction stresses reached the critical value of -200psi. It was observed that when the hole was 1.4” away from the roller 1720psi of MD stress or 1.58pli of web tension was required to develop the critical stress level. Figure 24 shows the FE analysis of the web with ellipse at a distance of 1.4 inch from the tangent point on the downstream roller.

When the hole was 7.3” away from the roller, a MD stress of 3400psi or a web tension of 3.128pli was required to develop critical stresses. FE analysis of this case is shown in Figure 25.

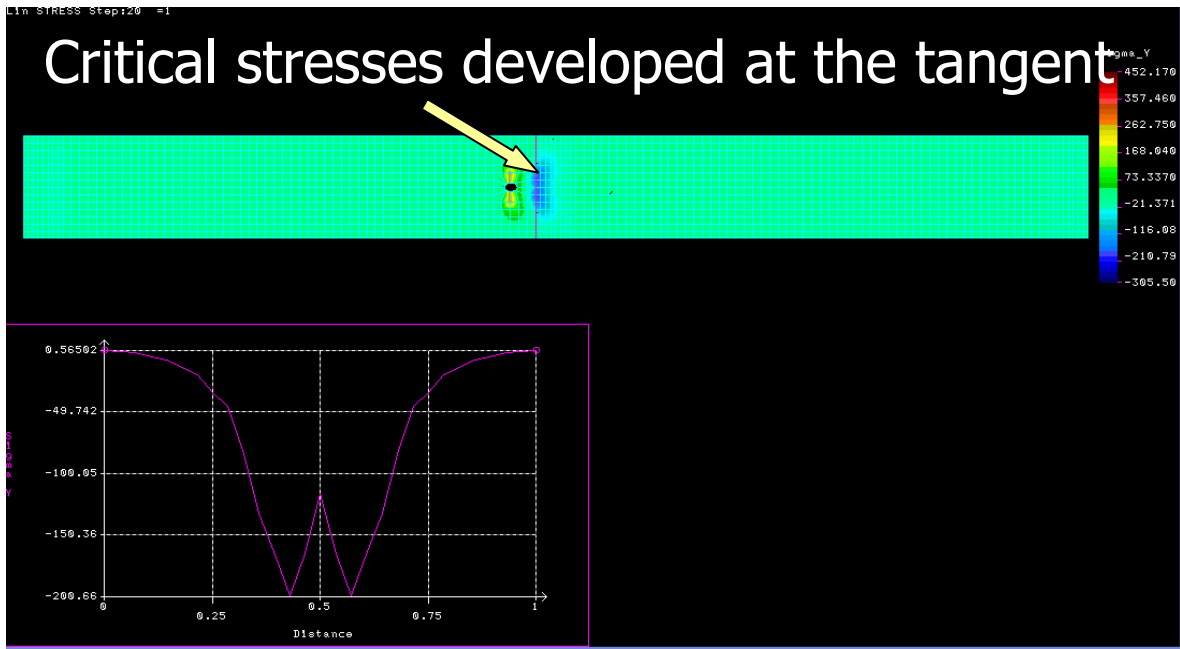


Figure 24 – Critical stresses formed with ellipse at 1.4” from the roller

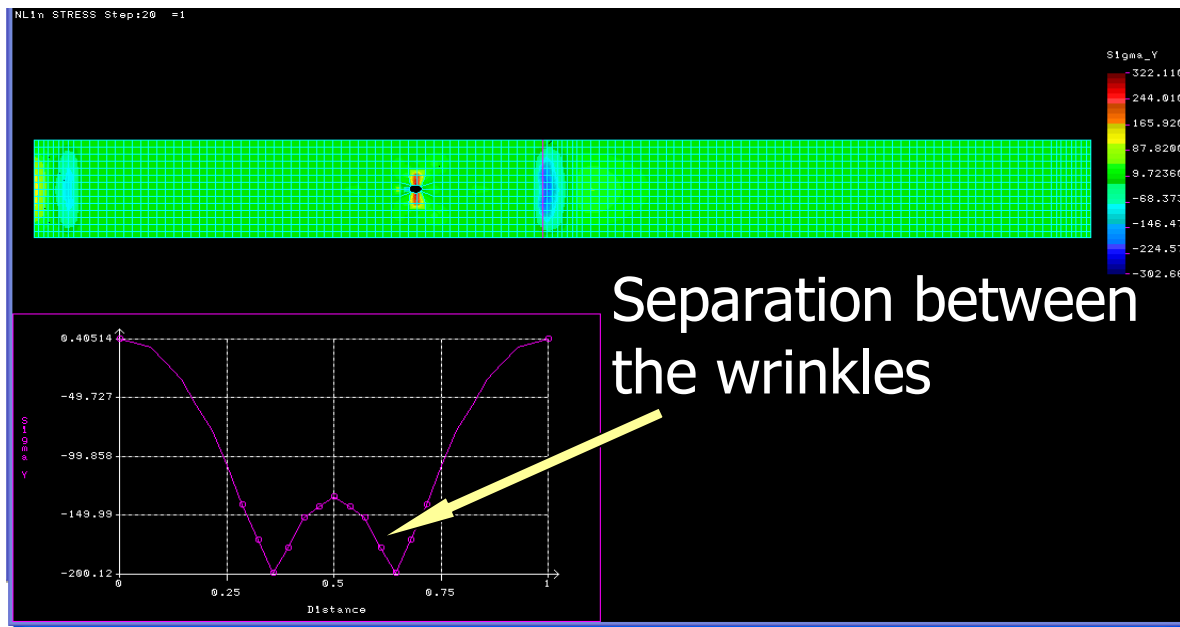


Figure 25 – CMD stresses developed with ellipse at 7.3” from the tangent.

The hole was modeled at different distances from the roller, and FE analysis was conducted. The stress in the machine direction was increased until the cross machine direction stress at the tangent to the roller reached the critical stress value of -200psi. The results are plotted in the chart in Figure 26. The separation (W) between the wrinkles is plotted in a chart in Figure 27.

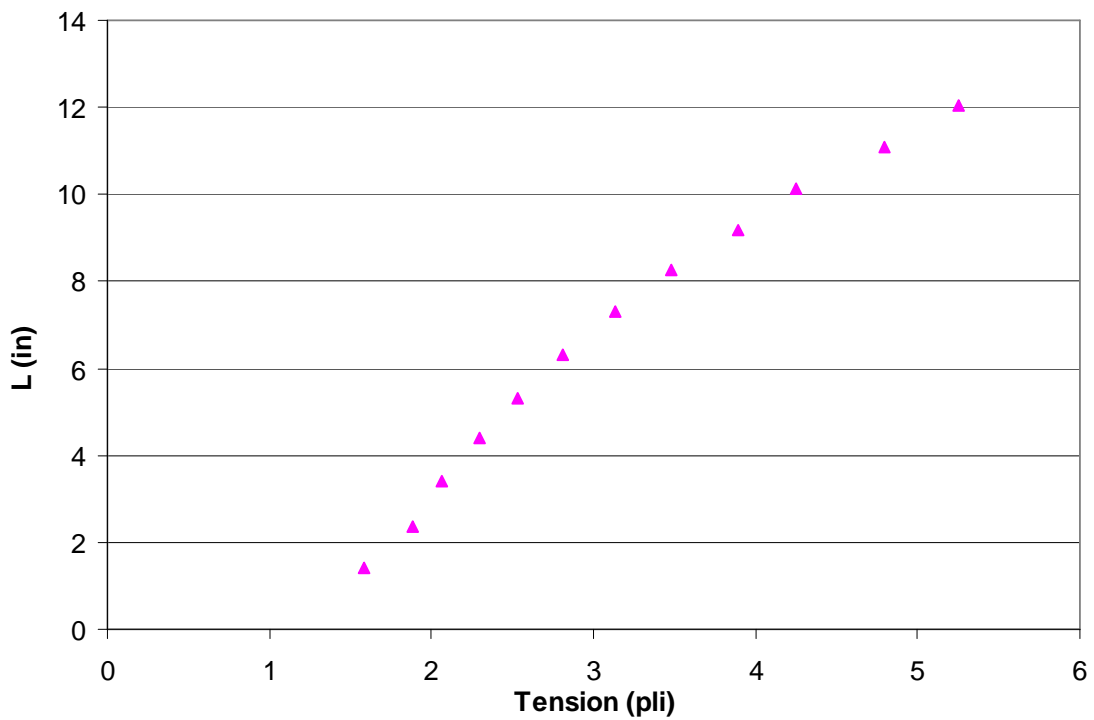


Figure 26 – Data obtained from FE analysis of web with the ellipse.

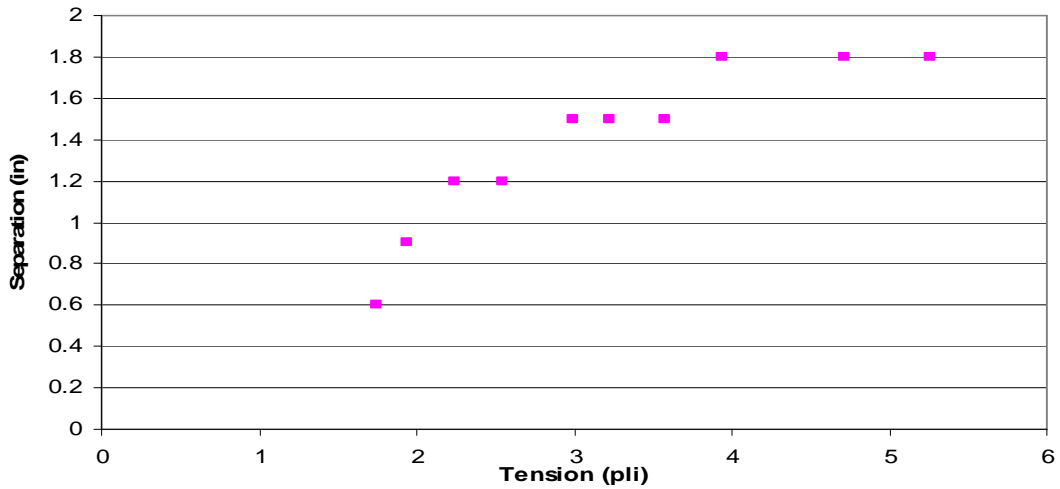


Figure 27-FE data of CMD separation between the wrinkles.

The experimental results are overlaid over the FE data in Figure 28. The experimental results are in good agreement with the FE data until machine the direction stress in the web reached 4228.26psi (3.89pli). The experimental data curve experiences a downward bend after this point.

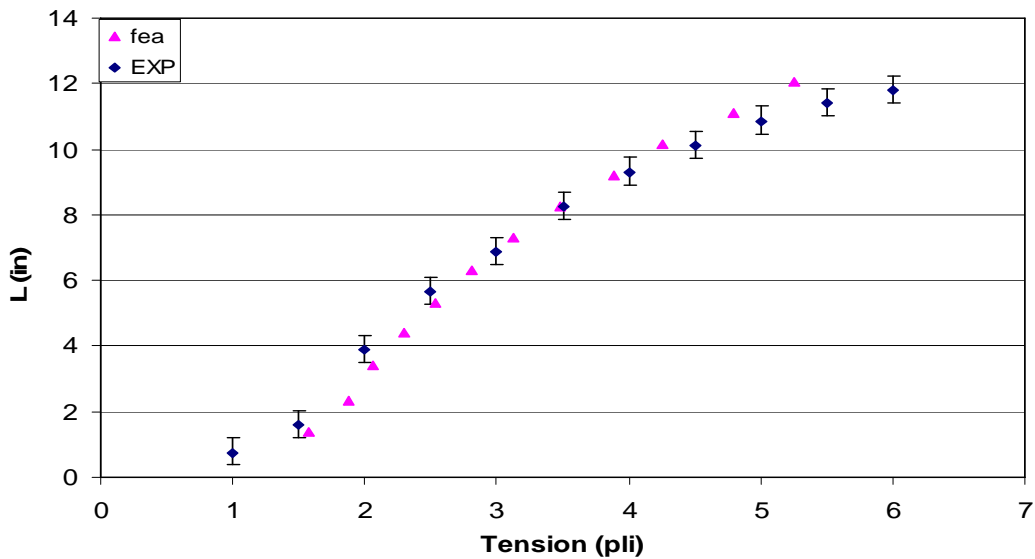


Figure 28 – FE data overlaid on the experimental data.

Even in this case it was observed that the distance between the wrinkle tip and the void decreased as the web tension decreased. The theoretical minimum tension to sustain a wrinkle over the roller in this case would be:

$$T_w = \frac{2t^2}{\mu_w} \frac{E}{\sqrt{3(1-\nu^2)}} = \frac{2(0.00092)^2 * 718000}{0.3 * 6 * \sqrt{3(1-0.3^2)}} = 0.41 \text{ pli}$$

There will be no wrinkle generated over the roller, when the web tension is below 0.41pli. Again the web tension downstream of the void is non-uniform and the minimum tension to sustain a wrinkle is an approximation.

To study this nonlinear behavior of the web, a second stretch test was conducted on the web with the elliptical void. A stress-strain plot of the data obtained is shown in the Figure 29.

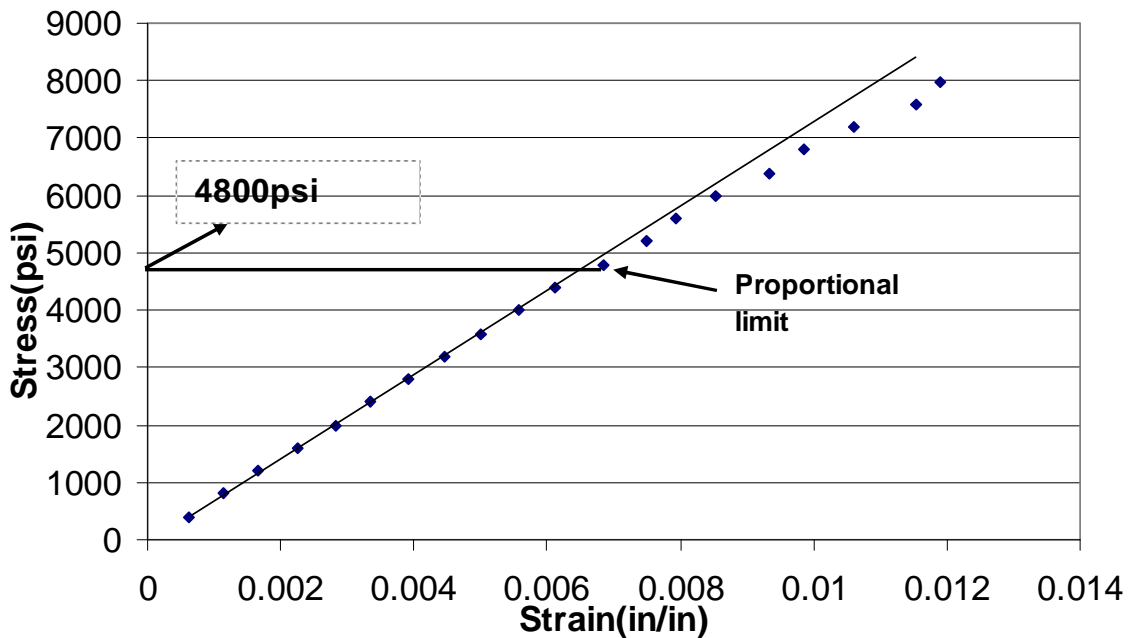


Figure 29 –Stretch test conducted for the web with elliptical discontinuity.

It was observed that the web exhibited slight non-linear behavior at a stress of 4800 psi which is shown in Figure 29. The deviation of the experimental data from the linear path might be due to this.

The cross machine direction separation between the wrinkles obtained through experiments and FE analysis are compared in Figure 30.

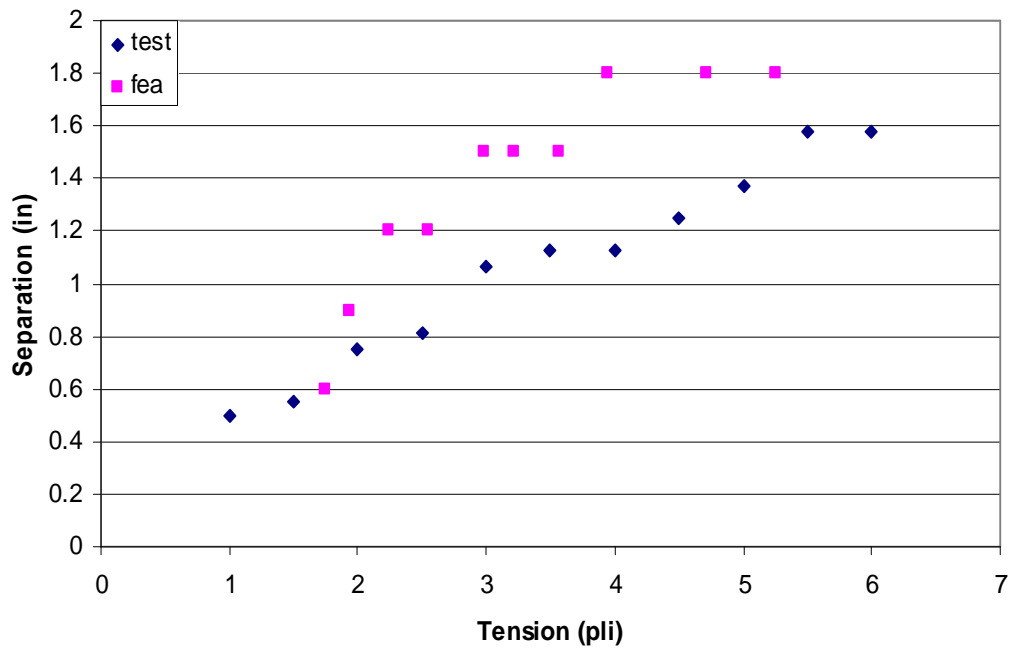


Figure 30 -CMD separation between the wrinkles.

The FE data shows some deviation from the experimental data, but the trend of increasing separation with the web tension is seen in both the cases.

Comparison between the effect of an elliptical void and a hole.

To better understand the effect of the shape of the void, the test results obtained from both the hole and the elliptical void are compared in a chart in Figure 31. The CMD separations between the wrinkles formed in the case of a hole and elliptical void are compared in Figure 32.

When the web tension was 1pli, at the onset of wrinkling in the web, the distance between the elliptical void and the downstream roller was 0.75inch and the distance between the hole and the downstream roller was 0.5inch. At 2pli web tension the elliptical void was at a distance of 3.87inch from the downstream roller where as the hole was at a distance of 1.2inch from the downstream roller at the onset of wrinkling in the web. The elliptical void is able to induce the critical CMD buckling stress when it is further upstream from the roller, than the circular void. At a given distance from the downstream roller the elliptical void wrinkles at a lower tension when compared to the hole and hence it is a worse shape to have in a web as compared to the hole. The behavior of CMD separations between the wrinkles is similar in both the cases. The separation between the wrinkles is assumed to be a function of the CMD dimension of the void which is 0.5” in both the cases. The comparison is shown in Figure 32. It is should be noted that this is only a quantitative comparison, since the two webs have different thickness and widths.

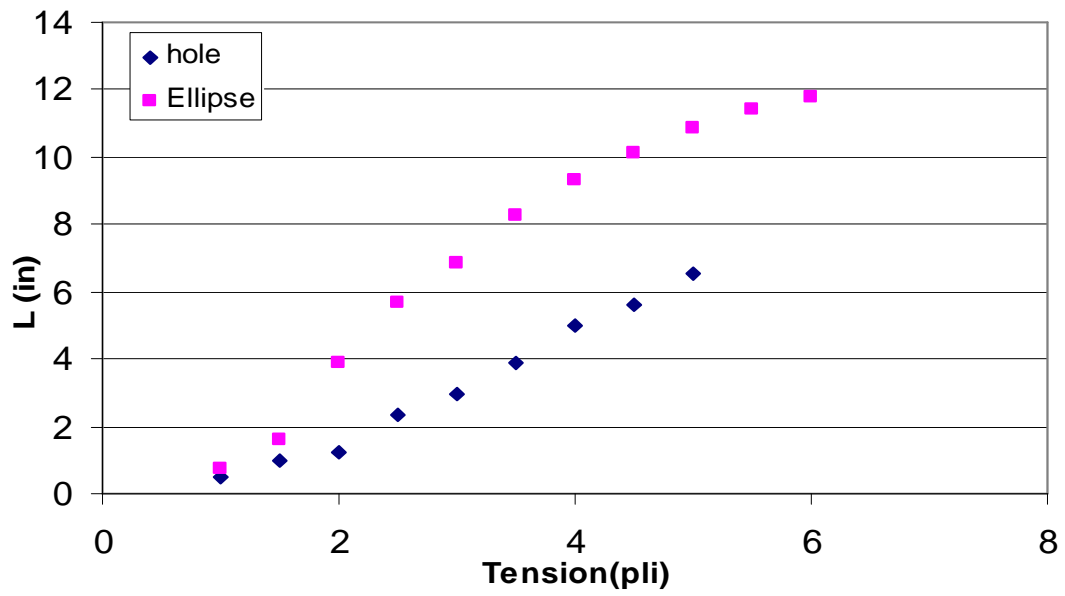


Figure 31- Proximity of the hole and ellipse from the downstream roller at the onset of wrinkles.

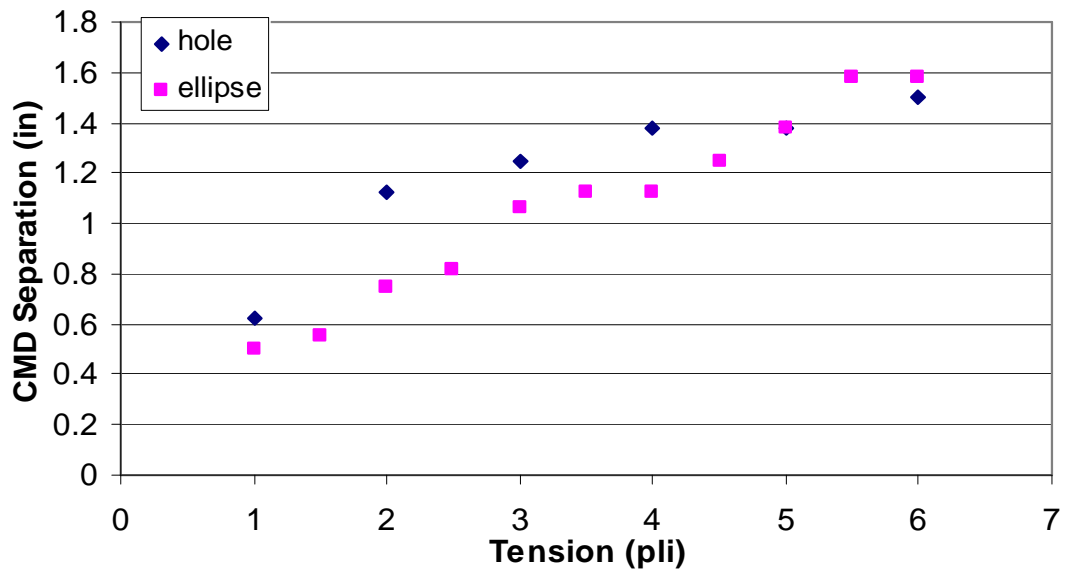


Figure32 – Comparison of CMD Separation between the wrinkles in the case of a hole and an elliptical void

The FE data obtained in the case of wrinkles due to circular hole and elliptical void are compared in Figure 33 and 34.

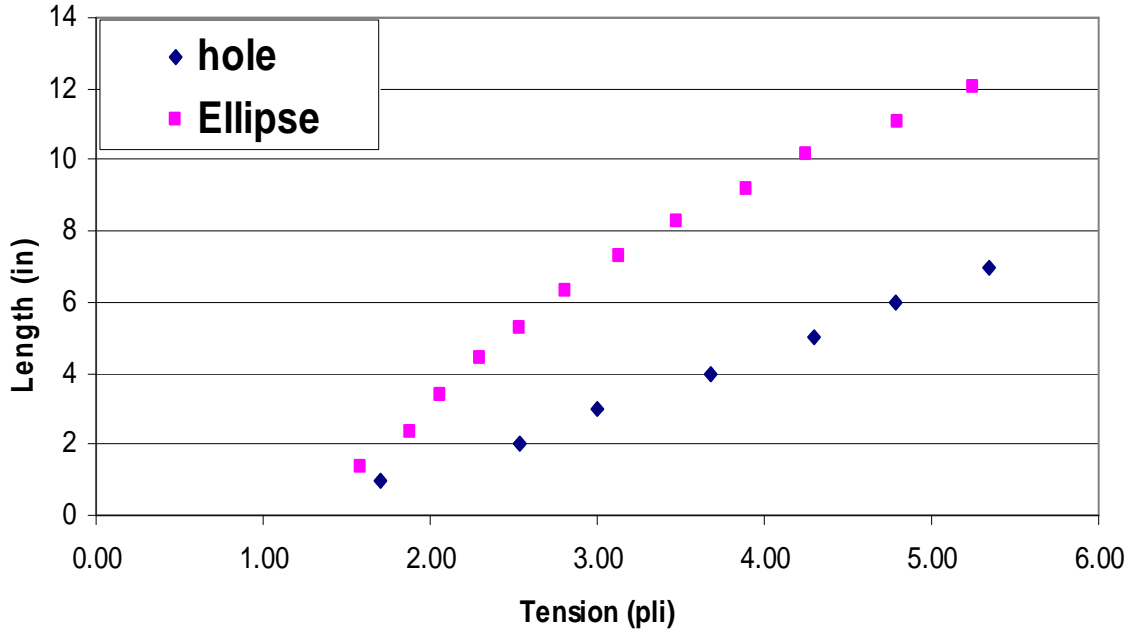


Figure 33- FE data of the MD distance of the hole and the elliptical void from the wrinkle tip.

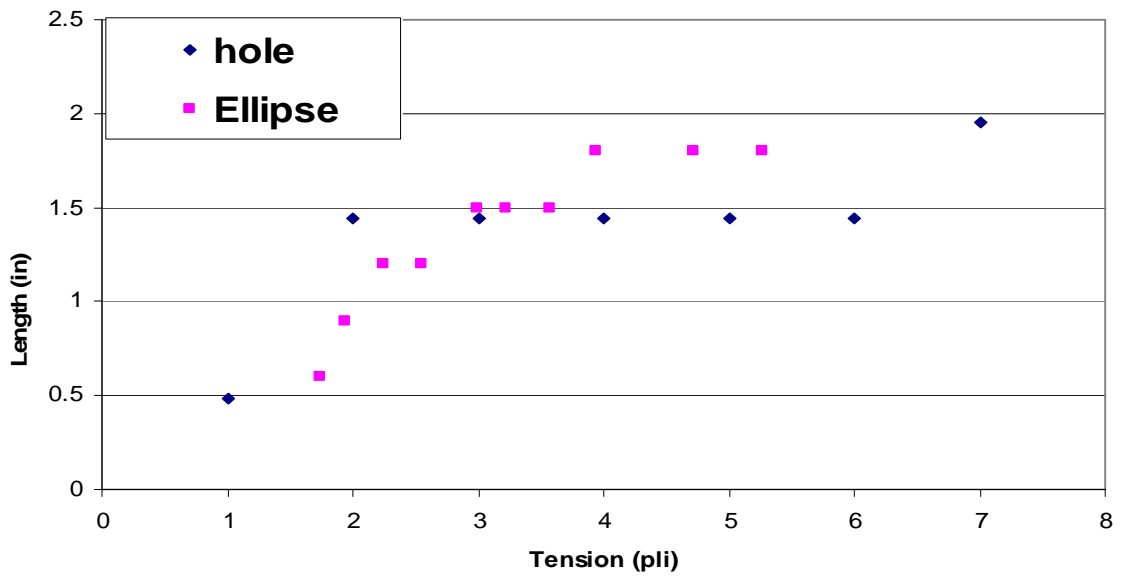


Figure 34- MD Comparison of CMD Separation between the wrinkles.

From Figure 33 and 34 it is observed that as the tension is reduced that distance between the hole and the wrinkle tip decreases. If the tension is decreased below 1pli, a value of tension may be reached, corresponding to the minimum tension to sustain a wrinkle over the roller, below which the web does not wrinkle. If precise tension control is possible, the web can be transported in a web line at this low tension without being wrinkled.

Chapter VI

Conclusion

Experiments were developed to study the behavior of webs with voids traveling over a roller. The conclusion drawn from this research includes:

1. The presence of voids in webs greatly affects the web instability as shown in Figure 9 and 22. Had these webs been free of voids, no web instability would be expected until the machine direction tension in the web exerts stresses beyond the proportionality limit of the web.
2. The finite element modeling outlines by Beisel [2] which employs the Miller Hedgepeth element, can successfully model web wrinkles due to voids. The results shown in Figure 17, 18, 28 and 30 support this conclusion.
3. For the two cases studied, it appears that a web with an elliptical void is worse than a circular hole in terms of generating wrinkles. The web with the elliptical void was able to produce the critical buckling stress in the web at the downstream roller with the void further from the downstream roller than the circular hole.

4. The void may also create machine direction stress concentrations that cause the applied stresses to be in excess of the proportional limit.
5. The Miller-Hedgepeth finite element accounts for geometric nonlinearity due to the web troughing in the free span. Since this is a nonlinear analysis, conducted in piecewise fashion, the effects of material nonlinearity could also be incorporated.

Future Work

It has been shown in this research that elliptical voids are worse than circular voids in producing web instability. There may be optimal void shaped that can be found with the modeling technique described that provide greater web stability that others. Thus if the void shape is not important in the final product that is being produced, there may be void shapes which make it easier to transport the webs with voids to through web process machinery.

The effect of span length on the wrinkling phenomenon has not been studied in this research. Also behavior of webs with voids with straight edges like square and rectangle has not been studied in this research. It is possible that there are shapes which are more critical than a circular hole or an elliptical void.

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Appendix A

We used the FE package COSMOS 2.8 for modeling purpose. Modeling was started by creating the geometry of various sections of the web. Then the element group for the section of web on rollers was selected and we utilized the PLANE 2D element. The element is a 8 node quadrilateral with one node each at the corners and centers of sides. Linear elastic elements were used. The material properties of E and ν were entered. Thickness of the material was then entered. The surface was meshed. Next the element group for the free web span was chosen as PLANE 2D. this time we used WRINKLING MEMBRANE elements. These elements have very low stiffness in the transverse direction, i.e. they cannot withstand compression. The material properties of E and ν were entered and the surfaces were meshed. The adjacent nodes were merged.

Next the void was modeled in the web span. Few elements were deleted at the location where we needed the elliptical void and the adjacent nodes were pushed to the circumferential location of the void. Since it is a symmetric problem, all the nodes along the middle row were constrained in the Y direction. One of the nodes in the span was constrained in the X direction. The Z degree of freedom and rotations of all the nodes were constrained. Rows of nodes were locked together by coupling them in X direction. This was done to ensure normal entry.

Tension was applied using pressure curve on either side of the web and the web was slowly loaded using a time cure. Since the analysis is non linear, an important issue relating to convergence of the model is time step. The total time was set to be 1 with a time step of 0.05. Which means the load was applied progressively in 20 steps. The convergence and constraint tolerance was set to 0.01. Newton Raphson method was used with the wrinkling elements instead of the default Modified Newton Raphson. Also the nodes were not allowed to update after each run.

A sample session file of analysis of a web with hole is given below. The web parameters are

Web material= Polyester

Width = 6”

Thickness = 0.00092”

Major axis of the void = 0.75”

Minor axis of the void = 0.5”

Modulus, E = 718000psi

$\nu = 0.3$

Tension, T= 2440psi or 2.24pli

```
VIEW,0,0,1,0
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PT,3,29.278,0,0
PT,4,31.556,0,0
PT,5,58.556,0,0
PT,6,60.834,0,0
PT,7,0,6,0
PT,8,2.278,6,0
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 PT,11,58.556,6,0
 PT,12,60.834,6,0

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 SF4PT,2,2,8,9,3,0
 SF4PT,3,3,9,10,4,0
 SF4PT,4,4,10,11,5,0
 SF4PT,5,5,11,12,6,0

PT,13,26.153,3,0
 PT,14,25.903,3,0
 CRSCIRCLE,20,26.153,3,0,26.153,3.25,0,4
 CRSCIRCLE,24,25.903,3,0,25.903,3.25,0,4
 CRLINE,28,18,15
 CRLINE,29,20,16

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 MPROP,1,NUXY,0.3
 RCONST,1,1,1,2,0.00092,0
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 MSFDEL,2,2,1
 MSFDEL,3,3,1

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 ACTSET,EG,1
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 EGROUP,2,PLANE2D,0,1,0,0,10,0,0,0
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 ACTSET,EG,1
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NDUPDATE,0

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Pages in study: 57

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Scope and Method of study: Webs such as paper or plastic films may have holes of various shapes cut into them as a part of the manufacturing or converting processes. These webs might still have to be transported through the web process machinery for further processing. Handling of such materials becomes difficult as the stress distribution varies across the web at the cross section of the hole. When this variation of stress travels down the web with a hole, it can cause troughs and wrinkles in the web as the web crosses the roller. The goal of this research is to study how these holes affect the web's propensity to wrinkle.

Findings and conclusions: It was observed that the void in the web generates a compressive cross machine direction stress in webs passing over rollers. When this cross machine direction stress exceeds the critical value of the compressive stress for a particular material, the web buckles over the roller and generates a wrinkle. It appears that among an elliptical void and a circular hole of comparable dimensions, the elliptical void is worse than a circular hole in terms of generating wrinkles. The effect of voids on instability behavior of webs has been successfully predicted. If the shape of void present in the web is insignificant, the void shape generating least cross machine direction stresses can be used.

ADVISOR'S APPROVAL _____

