PARAMETRIC STUDY OF NIP LOAD CONTROL ON A POPE REEL

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ABSTRACT

The secondary arms on a conventional pope reel control the nip load between the winding parent roll and the reel drum. As the parent roll grows, the secondary arms pivot away from the reel drum changing the angle of contact on the spool bearing housing. This changes the magnitude of the component of force that contributes to nip load. The moment caused by the secondary arm weight also changes as the roll grows. These two effects combine with actuator geometry to create a sinusoidal relationship between cylinder pressure and nip load.

Older reels typically relied on constant pressure control to maintain the nip load. Operators could manually adjust the pressure if they thought it was required. Once programable logic controllers (PLCs) became popular, the changing geometry of the secondary arms could be easily compensated for which made automatic nip load control practical. A look up table or polynomial in the PLC was used to create the pressure versus diameter function required for the desired nip load curve.

A comparison of the effects these two control methods have on radial and circumferential parent roll stresses has not been publicly documented to this authors knowledge. The purpose of this work was to perform this comparison and gain insight into the benefit of automatic nip load control. The question of whether the differences cause or solve any winding defects was beyond the limited scope of this study.

NOMENCLATURE

N	Nip load (kN/m)
T_w	Web tension (N/m)
K_1, K_2	Pfeiffer's constants
μ_k	Kinetic coefficient of friction
μ_s	Static coefficient of friction
WOT	Wound on tension (N/m)
h	Paper caliper (m)

F_f	Friction force between parent roll and reel drum
F_{roller}	Force exerted on the spool by the secondary arm roller
F_{cyl}	Net force of the secondary arm cylinder
W	Secondary arm weight
α,β,η,ψ	Angles of the force vectors
ω	Angular velocity of the reel drum

INTRODUCTION

A pope reel is a surface winder used on paper machines but also found on off machine coaters and supercalender windups. The purpose of the reel is to wind paper into large rolls called parent rolls. On a paper machine, it operates in a continuous process since the machine does not shut down to change parent rolls. The parent rolls are then transferred to a winder that operates in a batch process to create narrower and smaller shipping rolls.

Older reels typically relied on constant pressure control of the secondary arm cylinders to maintain an adequate nip load. Operators needed to manually adjust the loading pressure as they thought was required. Once programable logic controllers (PLCs) became popular, the changing geometry of the secondary arms could be easily compensated for which made automatic nip load control practical. A look up table or polynomial in the PLC was used to create the pressure versus diameter function required for the desired nip load.

The purpose of this study was to gain insight into the internal parent roll stresses created by these two control strategies while winding a parent roll in the secondary arms of a pope reel. The results of this study represent the situation in which the web is threaded to an empty spool in the secondary arms. Reeling in the primary arms and load transfer to the secondary arms are where roll defects are most likely to occur, but they are left for a future study.

THE POPE REEL

A typical pope reel is shown in Figure 1. It has a set of arms that pivot around the reel drum called primary arms. Another set of arms that have pivots slightly above floor level are called secondary arms. Both sets of arms control the nip load between the winding parent roll and the reel drum. An empty spool is loaded and waiting in the primary arms. When the parent roll in the secondary arms grows to a desired size, a spool starter accelerates the spool to a surface speed slightly faster than the reel drum. The primary arms rotate to a turn-up position where the spool is lowered onto the reel drum. At this time, a turn-up device such as a goose neck, water jet turn-up device or a tape turn-up break or cut the web and cause it to begin winding on the empty spool. The secondary arms pivot the full parent roll away from the reel drum and release it to a stopping station where brakes are used to stop its rotation. The primary arms simultaneously lower the new spool onto the rails. The secondary arms pivot back towards the drum and contact the spool of the new parent roll. The primary arm clamps then open which allows the primary arms to rotate back to the raised position in preparation to receive another empty spool and repeat this sequence.

To understand the potential problems on a reel, it is necessary to look at what is happening to the nip load during the reeling sequence. The weight of the spool causes a nip load when it is lowered onto the reel drum by the primary arms. This nip load is due to the clamping force of the primary hooks in addition to the weight of the spool. This causes a load several times larger than is typical for a given paper grade. As the primary arm rotates down to the rails, this excessive nip load decreases as a function of primary arm angle until the new spool is on the rails. Once on the rails, only the clamping force provides the nip load and the spool weight no longer contributes load. This is not the optimum way to control nip load at the beginning of a wound roll. It compacts the web and causes a substantial amount of lost production; essentially all the paper wound on the spool while in the primary arms [1]. Nip relief systems were developed to compensate for the weight of the spool and the clamping force to automatically maintain the desired nip load. Surprisingly, many reels in North America do not have nip relief systems even though they have been available since at least the late 1960's [2].

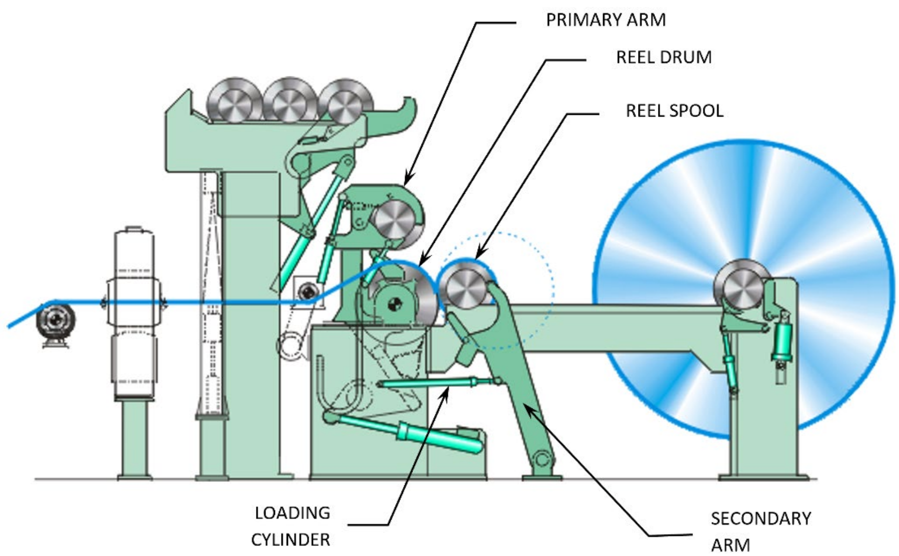


Figure 1 – A Typical Pope Reel

The next problematic event is the transfer of nip load from the primary arms to the secondary arms. Double loading can occur without a control system strategy designed to minimize this disturbance. This was initially recognized on tissue machine reels in the mid 1950's but a controlled or 'bumpless' transfer of load didn't become more widespread until the 1980's [1]. Reels without nip relief inherently lack this bumpless transfer because nip load is not controlled in the primary arms.

The final event in the sequence is secondary arm loading. The secondary arms on a conventional pope reel control the nip load between the winding parent roll and the reel drum. The parent roll spends most of it's time winding in these arms. As the parent roll grows, the secondary arms pivot away from the reel drum changing the angle of contact on the spool bearing housing. This changes the magnitude of the component of force that contributes to nip load. The moment caused by the secondary arm weight also changes as the roll grows. These two effects combine with actuator geometry to create a sinusoidal relationship between cylinder pressure and nip load.

POPE REEL GEOMETRY AND EQUILIBRIUM

A conventional pope reel uses pneumatic or hydraulic cylinders to load the parent roll against the drum with the secondary arms. The pressure in the cylinders can be controlled simply with a manual pressure regulator or it can be controlled to follow a pre-programmed curve in a PLC. The curve typically tapers the nip load as the parent roll grows in diameter. This creates a hard roll near the spool to prevent defects such as crepe wrinkles. Then the loading is smoothly reduced as the radius increases to prevent excessively high internal stresses [3], [4]. To calculate the values in the nip load curve, the forces of the arm, parent roll and drum must be calculated as a function of either diameter or arm angle.

Secondary Arm Equilibrium

The secondary arm mechanism is treated as a planar force system to calculate nip load as shown in Figure 2. While it doesn't require a very sophisticated analysis, it's not trivial either due to the dependency of the angles on parent roll diameter (and time). A quasi-static analysis can be performed because the relatively slow growth of the parent roll results in inertial forces that are negligible compared to the nip load and other forces. The friction forces required to rotate the parent roll are ignored in the analysis because they are orthogonal to the nip load.

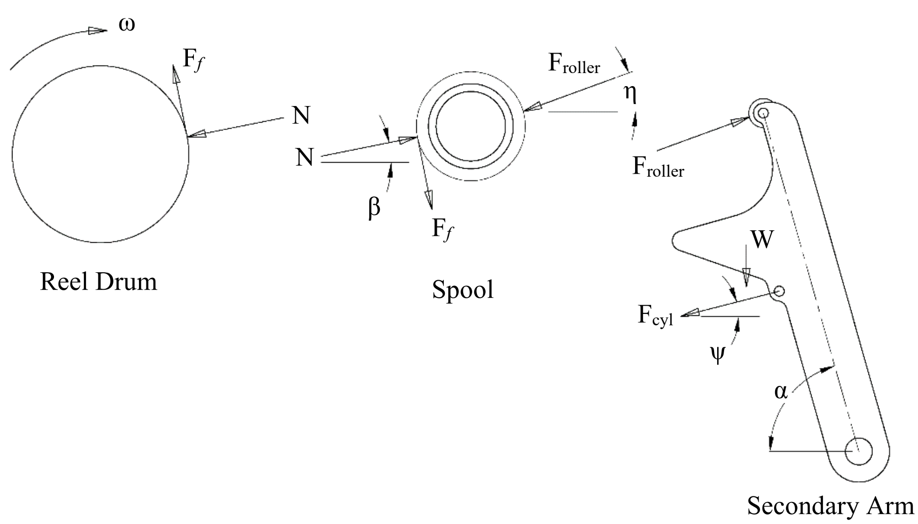


Figure 2 – Nip Load Free Body Diagram[1]

The procedure is to find the angles for a given roll diameter, then resolve the loading forces acting on the spool at the desired nip load. This gives the force acting on the secondary arm roller that contacts the spool bearing housing. Moments can then be summed about the arm's pivot to solve for the required cylinder rod force. From this force, the required cylinder pressures are calculated. This is repeated for several roll

[1] Several forces are omitted for clarity. For example, the reaction forces at the secondary arm pivot, the spool weight, the normal force of the rail acting on the spool, etc.

diameters from empty spool to maximum parent roll diameter. The result is a curve of pressures versus diameters or the loading curve.

The loading curve can be approximated by a least squares fit to an n^{th} order polynomial which requires only a handful of coefficients to be programmed in the PLC. A more recent approach is to use a graphical operator interface that allows the curve to be directly modified to any desired shape within pre-defined limits.

Non-ideal Effects

There are several non-ideal phenomena that occur in an actual reel. Friction exists in multiple locations in the nip loading mechanism. The cylinders used to provide loading have friction between the piston seals and cylinder walls. Pneumatic cylinders have significantly higher friction that hydraulic cylinders. This can make the actual nip load obtained vary significantly from what is calculated by the control system. There is also friction in the mechanics such as the secondary arm pivot and primary arm clamps. These effects have been minimized on modern reels by using hydraulic based control systems, load cells to measure nip load, and using linear bearings in place of rectangular ways.

Winding a parent roll, like any winding process, is a 3-dimensional phenomenon. The model used for this study does not take into account the cross machine deflection of the reel spool which is critical in avoiding winding defects [3], [4], [5]. To avoid defects, spool diameter is often increased beyond what mechanical criteria would otherwise dictate.

PARAMETRIC STUDY

Newsprint was chosen as the web material for this study because it has been widely used in winding research and the necessary material properties were readily available. The simulations were performed using the software WINDER 6.2 developed at Oklahoma State University [6]. The surface winder type was used with Hakiel's model. Air entrainment was not used in the simulations. The main dimensions of the pope reel used in the study are shown in Table 1.

Drum diameter	1.219 m (48 in)
Spool diameter	0.864 m (34.02 in)
Max. parent roll diameter	2.875 m (113.2 in)
Web width	8.077 m (318 in)

Table 1 – Main Reel Dimensions

Model Verification

When doing a numerical study, the question arises of how to ensure the results are meaningful. Fortunately, there is a large body of work related to surface winders that can be used to check that results are reasonable. Two papers by Good et al. [7], [8] experimentally determined that WOT had a slope of zero to slightly positive with respect to roll radius. He also noted that WOT is independent of tension at low nip load but becomes dependent on tension at higher nip loads. This work was performed on relatively small lab sized wound rolls. Garg's thesis [9] more closely resembled the winding process on a reel. The experimental configuration that he used resembled a pope reel and the drum diameters used were in the size range used in paper mills. The parent roll diameters were larger than Good's but were still extremely small in diameter and width compared to a production reel in a paper mill. Also, the wound roll was loaded in a linear fashion by hanging weights to generate a nip load versus a pivoted secondary arm on a reel.

The first step for verification was to take Good's newsprint properties from [8] and Garg's newsprint properties from [9] and use them to calculate WOT for three drum diameters on a production size reel. Figure 3 shows that WOT decreased as the drum diameter is increased. This was an encouraging result because Garg recognized this relationship in his experimental results. This allows one to conclude that the model used in this study qualitatively shows the same phenomenon.

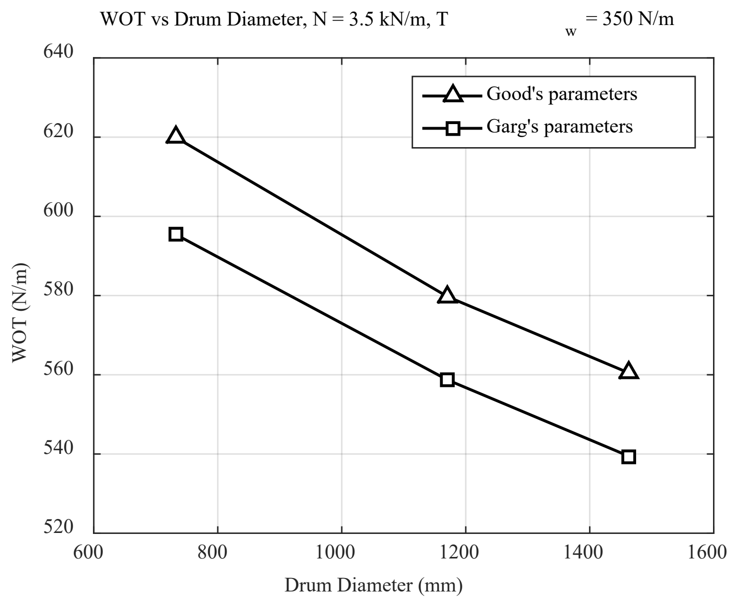


Figure 3 – WOT at Various Drum Diameters

The difference[2] between the two sets of results ranges from 3.8% to 4.0% at each diameter. This was less than the 4.06% to 16% difference that Garg found between successive trials when he checked the repeatability of experimental results. Based on this, it was inferred that either set of parameters can be used. Good's were arbitrarily chosen to be used for the remaining simulations performed and are shown in Table 2 along with some parameters estimated from the literature.

[2] Since neither set of results can be considered an accepted value, percent difference was used instead of percent error. The equation to find the difference for a pair of results X_1 and X_2 is $|X_1 - X_2| / \left[\frac{1}{2}(X_1 + X_2)\right] \cdot 100\%$.

K_1	24.25 kPa
K_2	24.49
E_{md}	5.14 MPa (745,494 psi)
μ_k web to web	0.19
μ_s web to web	0.35 (estimate by author)
μ_k web to drum	0.4 (estimate by author)
h	70.5×10^{-6} m (0.00278 in)
v	0.016

Table 2 – Winding Parameters for Newsprint [8]

The next step in verification was to try a wide range of layers in the simulation to see how the results change as suggested by Roisum [10]. It should be pointed out that Hakiel's model uses finite differences to approximate the derivatives in the winding differential equations. The layers in the model are discrete fixed increments in diameter chosen by the user. Therefore, a layer as used here does not represent an increment by caliper.

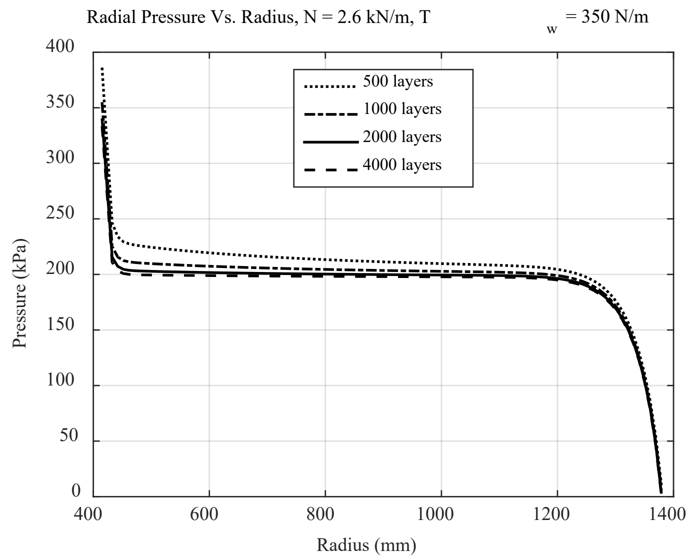
Good's parameters for newsprint were used and the number of layers were varied from 500 to 4000 in Figure 4. The nip load was held at a constant value of 2.6 kN/m (15 pli). The results show a dependency on the number of layers, but the sensitivity appears to reduce as the layer number increases. This suggests that the simulation was converging on a solution around 4000 layers. One simulation was performed with 10,000 layers but it became numerically unstable which further confirmed the likelihood of convergence. Two thousand layers was chosen as a compromise between computational speed and accuracy. Even on a modern computer, 4000 layers took excessively long to calculate the results and the assumed additional accuracy did not justify the extra time.

The final step in the verification process was to examine what Good and Roisum suggested in [11]. They stated that there are four common characteristics of wound rolls:

- Radial pressure will be highest at the core (spool)
- Radial pressure is zero at the outside of the roll
- Circumferential stresses are compressive through the middle of the roll
- Circumferential stresses are similar to wound on stress at the outside of the roll

Figure 4a shows that the radial pressure is highest near the spool and zero near the outside of the parent roll. Figure 4b shows that circumferential stresses are compressive through the middle of the roll although this only occurs when using larger numbers of layers. The raw data confirmed that circumferential stresses were similar to the WOT at the top of the parent roll. For example, in one set of data, the circumferential stress was 1458 psi at the top of the parent roll and the WOT was 1458 psi at the same diameter.

It should be kept in mind that this verification process does not imply that the results of this study are quantitatively correct. It merely means that the results are expected to qualitatively portray trends in the internal stresses and the WOT of a production sized parent roll.



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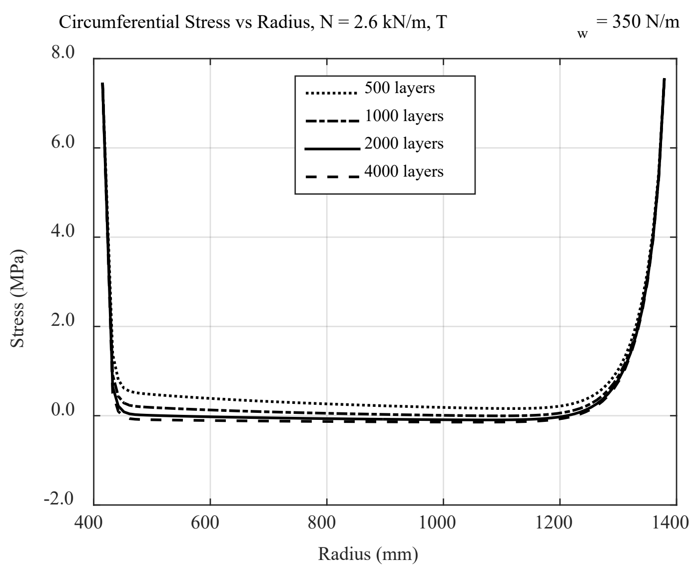


b)

Figure 4 – Internal Stress for Different Quantities of Layers

Tapered Nip Load

A series of simulations was conducted by varying the secondary arm cylinder pressure as necessary to obtain a desired tapered nip load. Three starting nip loads of 2.63 kN/m (15 pli), 3.50 kN/m (20 pli), and 5.25 kN/m (30 pli) were used. These were decreased in a straight line as a function of increasing parent roll radius. The total reduction was 0.88 kN/m (5 pli) at the maximum parent roll radius. The nip load curves are shown in Figure 5a. Web tension was held constant at 350 N/m (2 pli) for all three simulations. The WOT and radial pressure decrease as a function of radius similarly to the nip load. The circumferential stress did not have a tapered effect like the other variables but does appear well behaved.

These results show that the nip load control system of a pope reel is capable of controlling the parent roll structure. This is the reason why machine manufacturers include this type of control system on reels. The main limitation on this capability with a pope reel is that sufficient nip load must be maintained in order to drive the parent roll with the drum. This limitation can be overcome by adding a center drive to the secondary windup. Ability to use lower nip loads and wind larger parent rolls are also benefits of the center drive.

Machine manufacturers typically use density to describe parent roll structure because it is relatively easy to measure on a production machine. Figure 6 shows an example of a typical density curve measured on a newsprint reel by a field service engineer using portable density analysis equipment [12]. The radial pressure and WOT in Figures 5b and 5c qualitatively resemble this density graph even though these are different reels. It should be noted that there is cross sensitivity between density and caliper that can conflate density measurements [10]. Caliper was measured for Figure 6 at the winder unwind. It increased in a straight line from 0.00225 in. near the spool to approximately 0.00275 in. at the top of the parent roll.

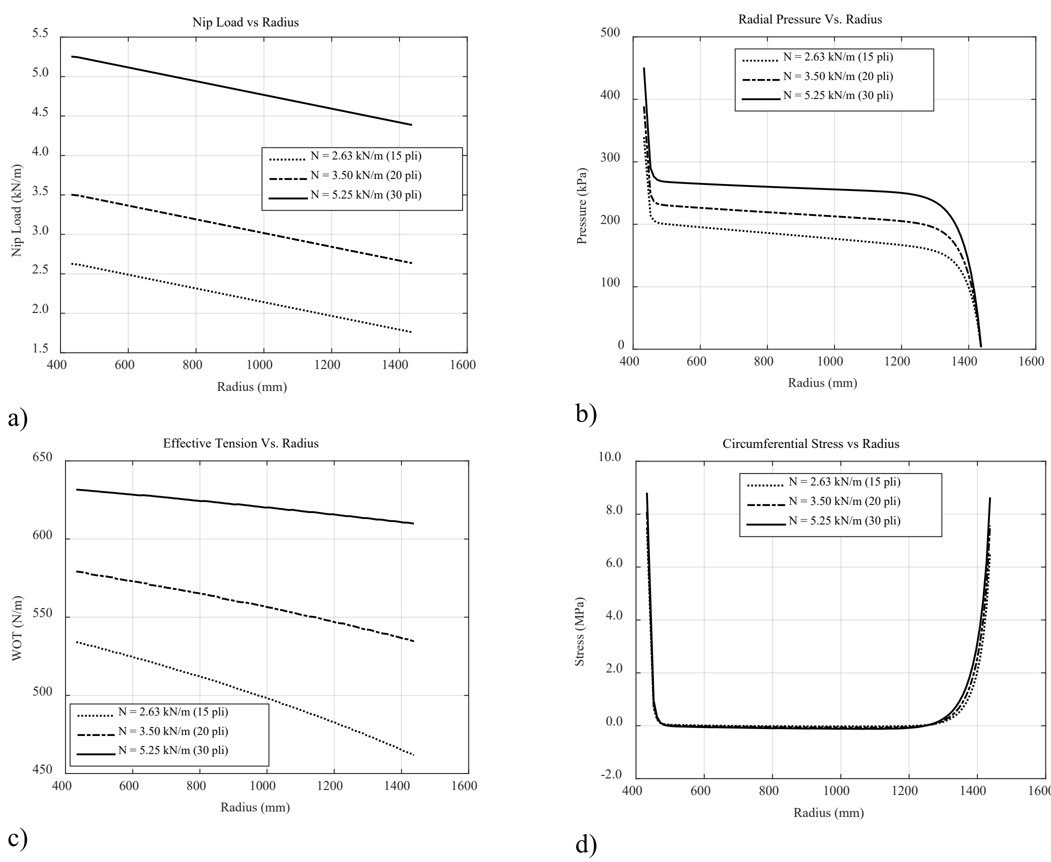


Figure 5 – Results with Various Tapered Nip Loads, T_w = 350 N/m (2 pli)

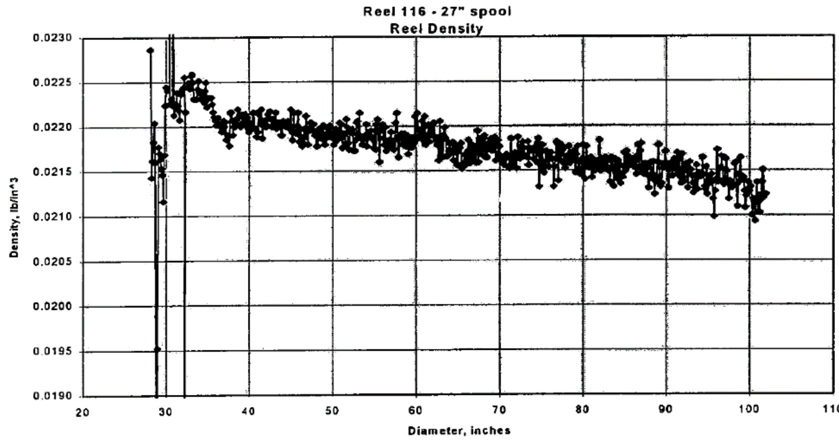
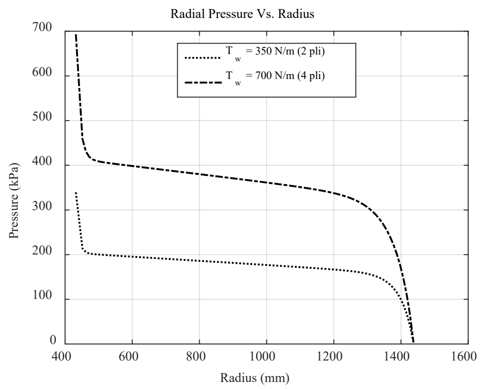


Figure 6 – Typical Example of Measured Density on a Newsprint Reel [12]

The two sets of results shown in Figure 7 were both performed with the same tapered nip load starting at 2.63 kN/m (15 pli). For one simulation, the web tension was set to 350 N/m (2 pli) and for the other it was 700 N/m (4 pli). The radial pressure and WOT increase significantly for the higher tension. Good's empirical algorithms in [7] state that for a nip load between 1.75 kN/m and 5.83 kN/m the WOT is dependent on web tension as well as nip load. So, an increase would be expected with a nip load that starts at 2.63 kN/m and tapers to 1.75 kN/m.

Figures 5c and 7c show that doubling the web tension has a greater effect on WOT than doubling the nip load does. Tension can be used to affect the internal parent roll structure but it seems to be rather large in this case. Regardless, the tension must not be too high or web breaks will become more likely. It must also not be too low or the web will not be properly transported to the reel. These two constraints are some of the reasons why web tension is held constant in practice instead of varying it to control parent roll structure.

The circumferential stress in Figure 7b became compressive during most of the winding with the higher tension. This effect was sufficiently small that no firm conclusion can be made other than it could cause crepe wrinkles. The higher tension did cause the circumferential stress to increase more rapidly at the top of the parent roll.



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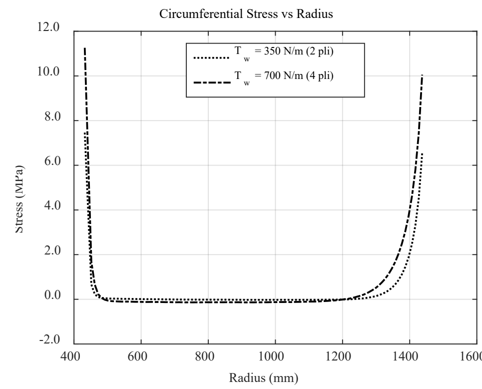

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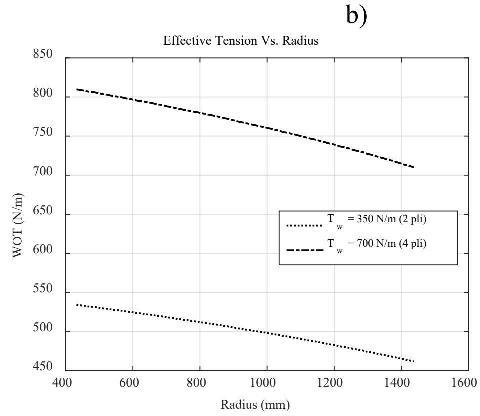
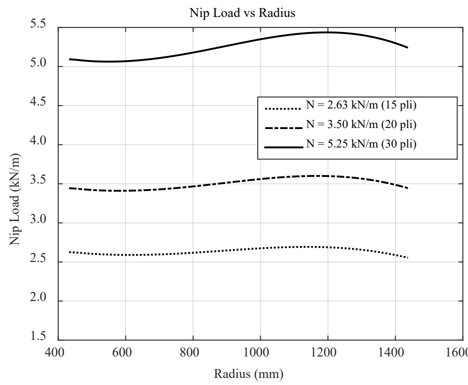


c)

Figure 7 – Results with Tapered Nip Load at Two Different Tension Levels, N = 2.63 kN/m (15 pli) at start



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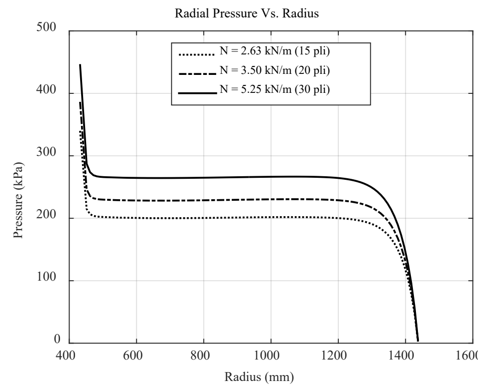

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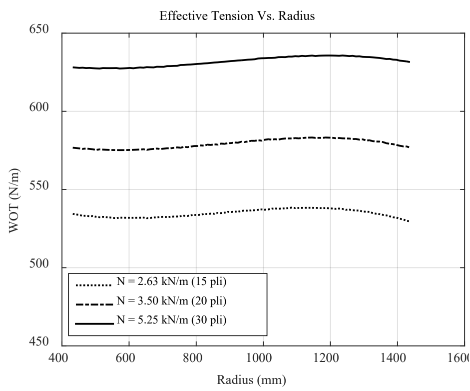

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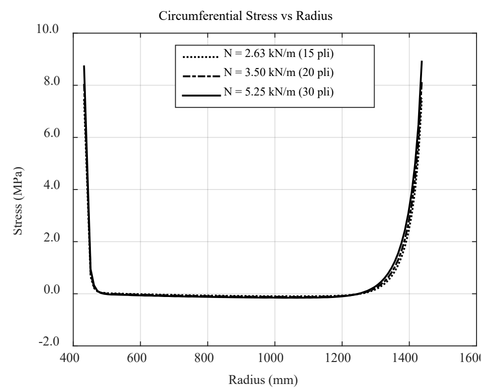

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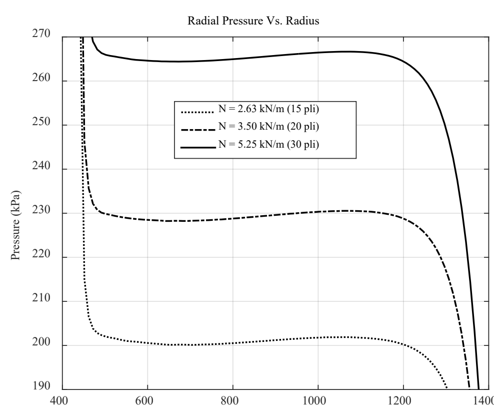

e)

Figure 8 – Results with Constant Cylinder Pressure, T_w = 350 N/m (2 pli)

Constant Cylinder Pressure

The final series of simulations was performed by holding secondary arm cylinder pressure constant. The pressures were chosen to give an average nip load of 2.63 kN/m (15 pli), 3.50 kN/m (20 pli), and 5.25 kN/m (30 pli). Figure 8 shows the nip load varies in a sinusoidal manner with respect to parent roll radius. This is due to the geometry of the secondary arms and the constant cylinder force. The varying nip load had a small effect on the WOT which varied in a manner similar to the nip load. The radial pressure did show a sinusoidal variation, but one must look closely to see it in Figure 8e.

The nip load did not decrease near the outer diameter of the parent roll wound with constant cylinder pressure. Comparing Figure 8b with Figure 5b shows that the radial pressure is slightly higher near the top of the parent roll when using constant cylinder pressure instead of tapered nip load.

The circumferential stress did not show a sinusoidal variation like the other quantities. It does become compressive under this nip load condition. Like the results with tapered nip load, this effect was very small.

CONCLUSION

It was shown that for newsprint, the radial pressure and WOT have a tendency to follow the secondary arm nip load created by the control system. Tapered nip load control does indeed appear to taper the WOT and radial pressure of a parent roll. It was also seen that constant cylinder pressure control caused a sinusoidal nip load. This in turn generated a WOT with a small sinusoidal variation and to a lesser degree, a sinusoidal radial pressure. These effects were very small and could explain why constant cylinder pressure served as an adequate although not ideal secondary arm control strategy until PLCs became more widely used.

The only parameters available to affect the parent roll structure on the pope reel are web tension and nip load. The results indicate that web tension has an effect at higher nip loads. However, in practice on pope reels, web tension is held constant to avoid other process upsets like increased frequency of web breaks. On the other hand, nip load is very easy to manipulate with a PLC and is the main tool used for roll structure control.

Unfortunately, this was a limited study that ignored many interesting areas of the reel. A future effort including primary arm nip relief and the effects of load transfer would be extremely helpful in understanding how the entire reeling process affects the parent roll structure.

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