

Crowns and cross-machine loading variations

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THE DESIRE FOR UNIFORM SHEET properties has generated a great amount of research and testing on cross-machine moisture and sheet profiles. The press section plays a great part in the sheet uniformity, since pressure is used to dewater the sheet. Variations in the cross-machine pressure may likely lead to variations in the sheet moisture content. In fact, nonuniform loading profiles are often used to correct moisture profiles. A better understanding of line load distributions will certainly aid papermakers in achieving more uniform sheet properties and moisture contents.

The papermakers are not the only ones who would benefit from a uniform or known loading profile. The roll cover suppliers are also interested in the line load distributions. Unlike the sheet, which enters each nip but once, each region of a roll cover enters each nip once per revolution over many revolutions. Highly loaded regions can result in accelerated aging, increased wear, and premature cover failure, which is not pleasant for the cover suppliers or for the papermakers.

There are several approaches to addressing the cross-machine pressure profiles. Theoretical approaches have been used to study the deflections of the rolls, which are used to establish the necessary crown amount and shape (1, 2). Crown specifications have been listed to help define the problem and to help standardize the terminology (3). Grinding tolerances are often set by the cover suppliers and by the mills. Measurement techniques have been developed to obtain the actual load-

ing distribution or consequences of the loading distribution (4-7). Other studies have shown loading variations caused by imperfect crowns, cover thickness variations, and other common factors (8-12). The present study falls in this last class, because it is concerned with loading variations that result from incorrectly specified crowns, cross-machine temperature variations, improper edge relief, and load biasing. This paper discusses the factors that must be considered for modeling cross-machine loading variations and presents examples of common factors that affect loading variations.

MODEL DESCRIPTION

In this section, our goal is to describe a model that is sufficiently broad to consider the major factors that cause loading variations. Since crowns are customarily ground into the rolls to counter the roll-bending displacements, we need a roll-bending model. Since the roll covers are compressed between the two mating rolls, we need a method of quantifying the load that results for a certain amount of cover compression. Finally, we need a versatile method to handle arbitrary crown distributions. One could assess the situation by modeling the rolls as beams separated by springs, as shown in Fig. 1. The main elements are described in more detail in the following sections.

Roll bending

In general, the roll bodies may be constructed using different materials for the journals and the core-shell region. Furthermore, these regions have different weights and different applied loads. Loading may be in the form of nip loading, vacuum loading,

ROLL CROWNS

ABSTRACT

Determining the correct crown for nipped rolls is a difficult task. Papermakers and suppliers have developed both theoretical techniques to predict what the crowns should be and experimental methods that measure what the resulting nip widths and pressure profiles actually are. This paper provides quantitative estimates of the effect of several variables on loading nonuniformities. Specifically, the paper shows the loading variations that occur because of incorrectly specified crowns, cross-machine temperature variations, improper edge relief, and load biasing. These load variations are dependent on felts, cover hardness, and cover thickness. These effects are demonstrated through examples of straight-through presses, Tri-Nip presses, gate roll size presses, and calendars.

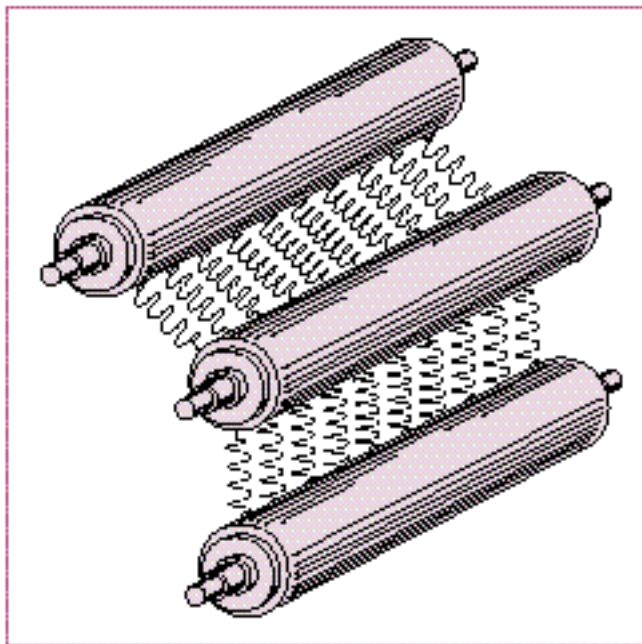
Application:

This information's key application is assisting papermakers to better understand and predict the causes of load variations in the press section to meet the goals of improved sheet quality, increased cover life, and reduced operating costs.

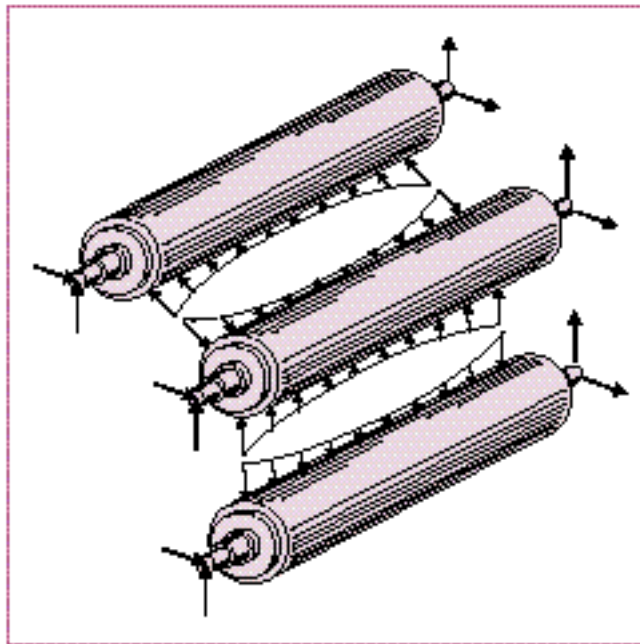
self weight, felt tensions, and others. None of these loads are assuredly uniform across the machine width, as is illustrated by the nonuniform nip loading in Fig. 2 for the idealized model. However, at a particular axial location, one may construct a free body diagram similar to the one shown in Fig. 3 for each roll.

The variations in roll construction as well as loading make analytical solutions cumbersome. Therefore, we use the finite element method to calculate the displacements across the machine width. Now we must choose an element type for our analysis.

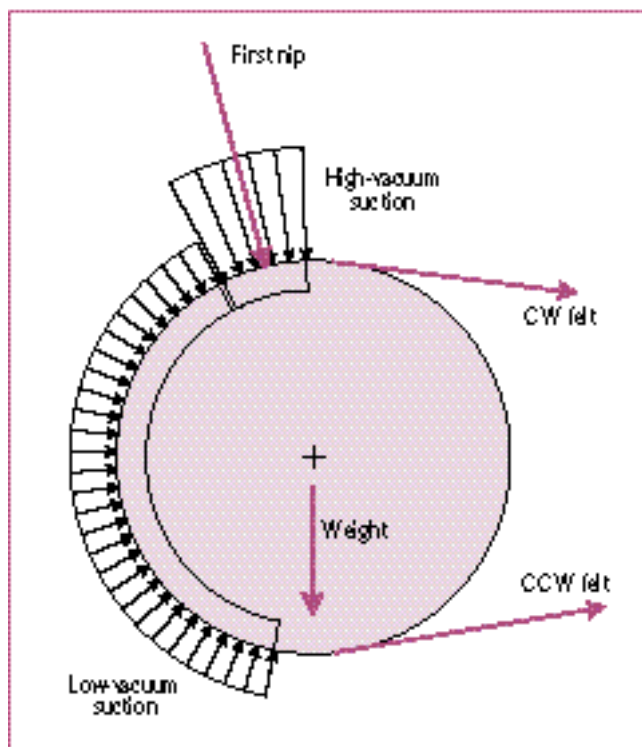
Simple beam theory is commonly used to model roll bodies, although



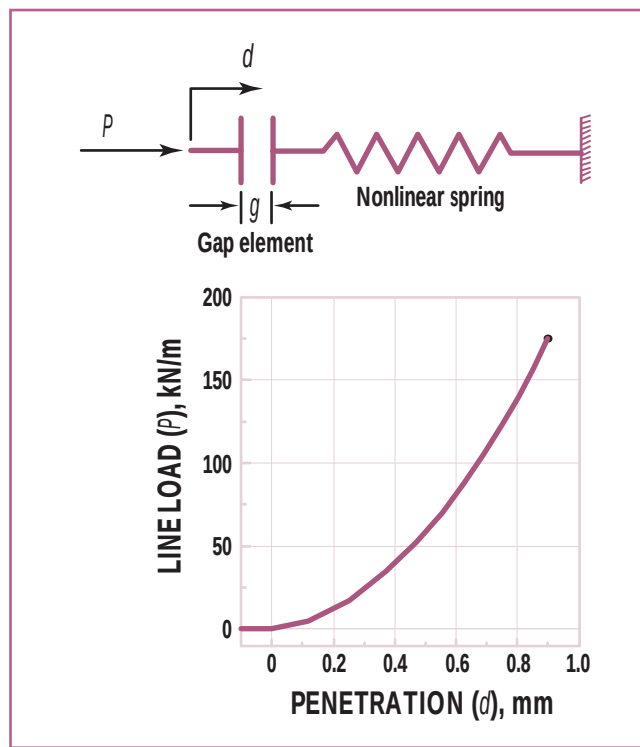
1. Idealized model



2. Idealized model free body diagram



3. Free body diagram at one axial position



4. Spring performance

beam theory is not adequate for the complex deflection modes seen in Yankee dryers. The beam theory should include the effect of shear deformation (1), account for nonuniform loading, allow for trussed wall

cores, and permit general boundary conditions. The present analysis is based on the Timoshenko beam theory (13) and uses a generalization of the element presented by Bathe (14). For the purposes of code

development, comparison, and verification, we also included simpler elements that do not account for shear deformation (15) and a two-node beam element that does not suffer shear locking (16). The computer

program was organized to permit the rapid integration of other models, such as Yankee shells, when necessary.

Cover deformation

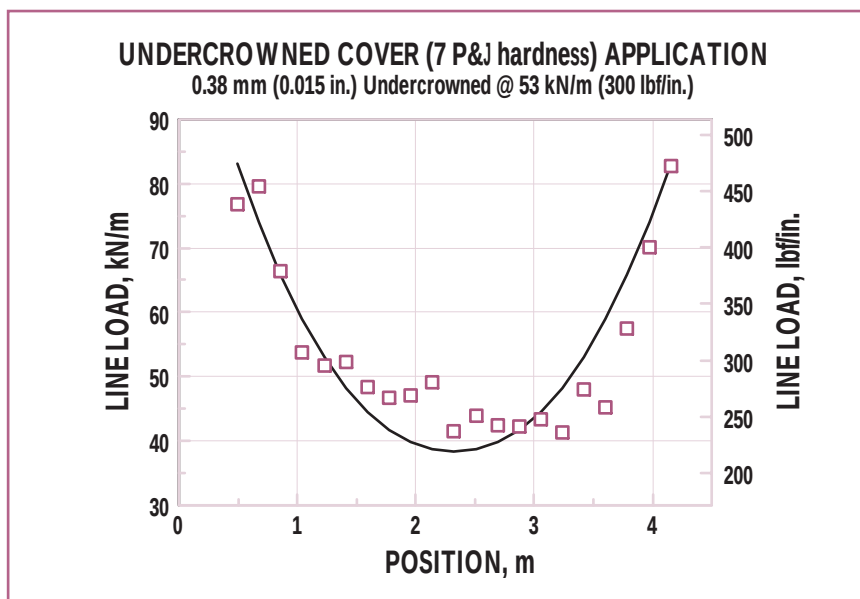
The cover response is modeled by a gap element in series with a nonlinear spring, as illustrated in Fig. 4. The gap element accounts for the fact that the crown, sag, and bending may result in regions that are not loaded and that the contact zone cannot support tension. The nonlinearity in the spring accounts for the facts that the contact zone grows as the load increases and that nonlinear material behavior may be present. The load vs. penetration curve shown in Fig. 4 may be generated through analytical models, such as those found in the literature (17-21), but the finite element models account for more complex factors, such as felts and thermoviscoelastic materials (22). The cover response will also be different for dynamic service conditions and static nip impressions.

The springs may have varying stiffness depending on the position across the roll face. This feature helps account for the following situations:

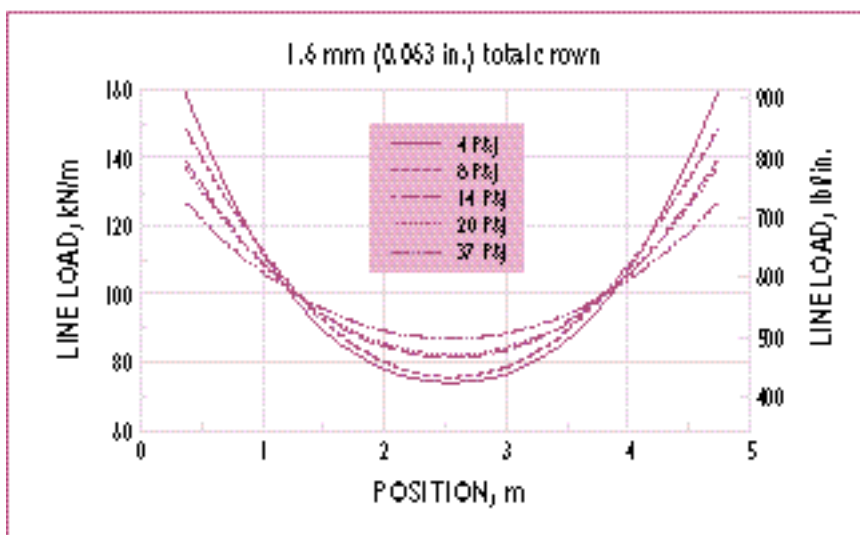
- Where the variation in cover thickness is significant, since thinner covers may act stiffer than thicker covers
- Where the felt compaction or thickness may vary, and hence, the felt stiffness may vary
- Where there is a temperature variation across the face of the roll, since the cover will not act as stiff in high-temperature regions as in cooler regions.

Crown specification

Crown specifications come in many forms, including station-by-station, simple specifications, and compound specifications. The program accepts the crown distribution in many forms, but the station-to-station approach is most useful for irregular and/or worn configurations. Such an



5. Undercrowned loading distribution



6. Cover hardness effects

approach also helps account for diameter distributions that are caused by temperature and swelling variations. The crown distribution is used in the initial gap distribution calculations.

Solution approach

The first step in solving a given problem is to read in the problem inputs, including the shell dimensions, the cover properties, the crown distributions, the press geometry, and the spring parameters. The program initially assumes that the loading is uni-

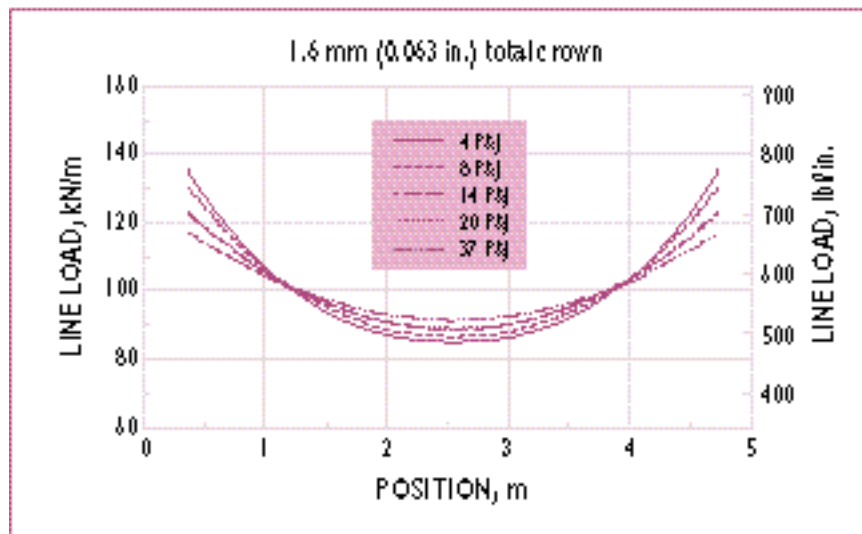
form across the machine in each nip and then solves for the resulting deflections for each roll. These deflections are then used to estimate how much the cover is deformed in each nip, and a new set of line load distributions is generated. These new line load distributions result in a new set of roll deflection curves. This process repeats until all line load distributions have converged. The results are then stored in a file for subsequent viewing and plotting.

The computer predictions have

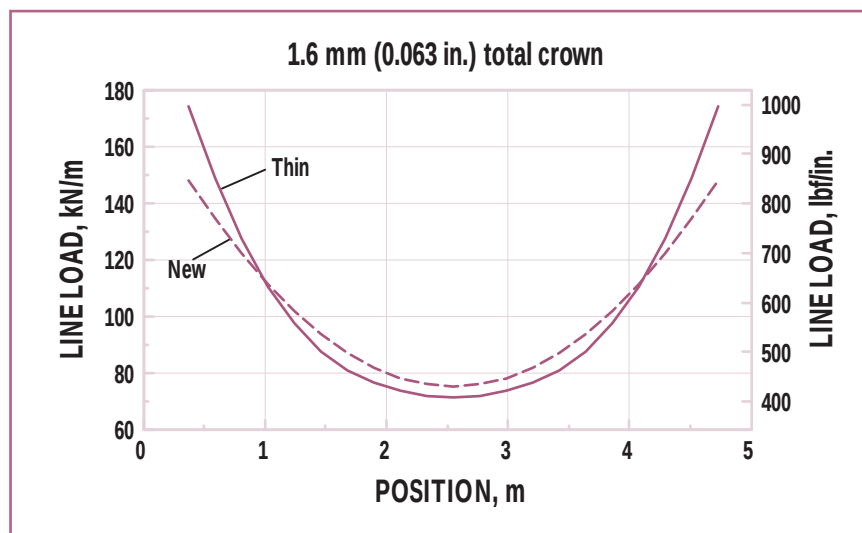
Parameter	Top roll	Bottom roll
Core OD, mm (in.)	850 (33.5)	800 (31.5)
Core ID, mm (in.)	0	625 (24.6)
Bearing mounting center distance, mm (in.)	5,100 (200)	5,100 (200)
Shell face length, mm (in.)	4,600 (180)	4,600 (180)
Loaded face length, mm (in.)	4,360 (172)	4,360 (172)
Shell modulus, GPa (psi)*	43.1 (6.25×10^6)	137.9 (20×10^6)
Cover hardness	Granite	4-37 P&J
		Polyurethane
Cover thickness, mm (in.)	N/A	19 (0.75)
Weight, kN (lb)	60.7 (13,600)	70.1 (15,800)
Correct crown, mm (in.)	1.04 (0.041)	0.951 (0.037)
Speed, m/min (ft/min)	700 (2,300)	700 (2,300)
Line load, kN/m (pli)	100 (571)	100 (571)

*Effective modulus for the specified OD and ID to account for both the granite and the steel center shaft

1. The model parameters



7. Cover hardness effects with felts



8. Cover thickness effect

matched the experimental nip impressions and prescale film studies fairly well. An example of the computer results is shown in **Fig. 5** for the case of an undercrowned nip. The solid line is the theory, and the symbols represent the prescale film pressures that were converted to load. [Prescale film contains ink-filled microcapsules that rupture at varying pressure levels. The resulting film color is related to the maximum applied pressure. Therefore, pressure profiles may be obtained by feeding prescale film through the nip. Sprague and Woo (6) provide more information.]

The use of line load rather than peak pressure in **Fig. 5** allows us to emphasize a few points. First, the line load at a certain x -axis position represents the load applied at that point. Even though the machine builders' curves indicate a certain average line loading for a given set of bag pressures, there is no guarantee that that line load is distributed uniformly across the length of the roll. Second, the line load distribution may be more familiar to mill personnel than peak pressures and nip widths. We have seen several cases where severe loading distributions have been ignored because the nip width variations were within 5 mm (0.2 in.). A more desirable response is usually obtained by estimating the line load variation that caused the 5-mm (0.2-in.) nip width variation.

RESULTS AND EXAMPLES

The computer solution approach described previously is sufficiently powerful to model most of the critical factors that affect the cross-machine loading distribution. We will discuss many of these factors in the following examples. The first six examples use the properties delineated in **Table I**.

Cover hardness effect

Although common experience and theory show that the cover hardness does not affect the crown specification, both theory and experience show that the cover hardness plays

an important role in cross-machine pressure variations. Softer covers tend to be more forgiving than harder covers, as shown in Fig. 6. Note that the pressure distributions flatten out for softer covers.

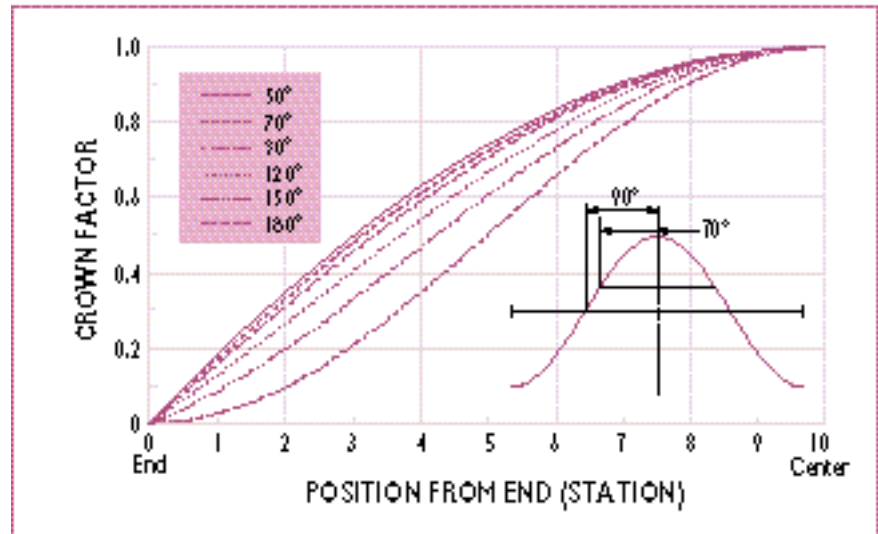
Such variations, from 4 to 37 Pusey & Jones (P&J) hardness, are rarely seen in a single press. Furthermore, we must account for the effects of felts. Felts tend to soften the nip pressure distribution, as shown in Fig. 7. Note that felts are often omitted during static nip impressions and slow dynamic tests, such as with prescale films. Of course, applications such as size presses do not benefit from the softening effect of felts. These feltless applications require more care in selecting the crown parameters. Another softening effect is seen when two soft covers mate. Not only do the peak pressures decrease, but the cross-machine loading variations also decrease.

Cover thickness effect

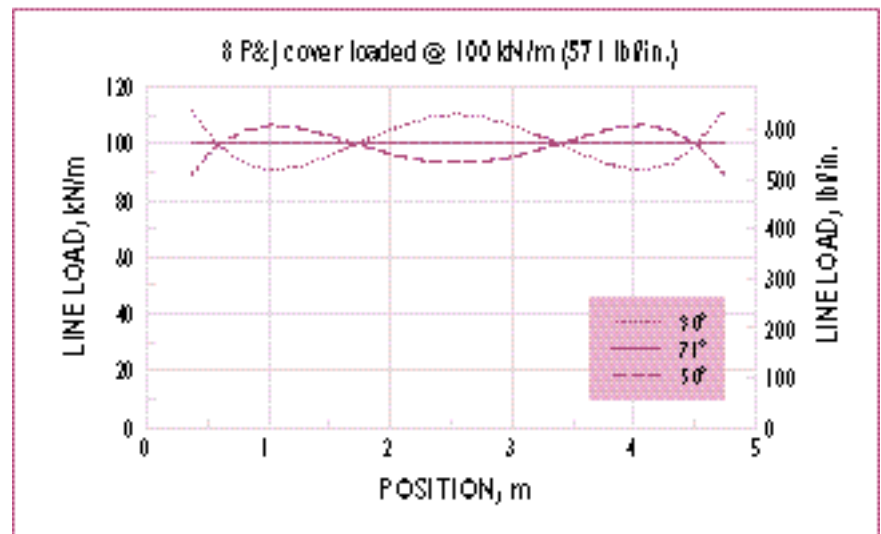
Covers having the hardness range shown in Figs. 6 and 7 are rarely substituted in practice. A more likely scenario is that a single cover at one hardness becomes thinner with grinds. Thinner covers act as stiffer covers, as shown in Fig. 8. We have seen consistent systematic cover failures after the third grind in one paper mill. Presumably, the cover is operating near its threshold when it is new and fails at a certain thickness. Failures of this type call for a re-examination of the cross-machine loading variations as well as the stresses within the cover.

Grinder cosine cam angle

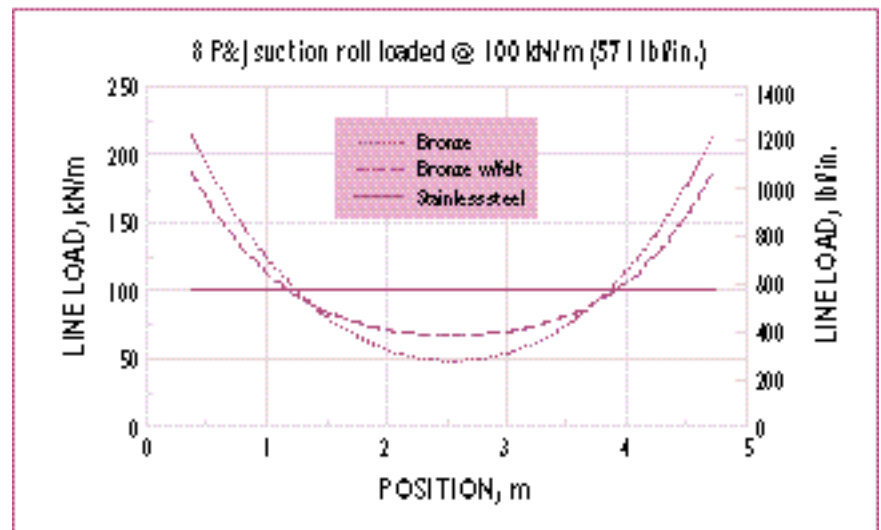
Crowns are often determined by matching the centerline deflection of a loaded roll and by matching the shape of the deflection profile from centerline to end. Thus, simple crowns are specified by the difference in diameters from center to ends and by the shape of the diameter distribution from the center to the ends. A good shape match is often produced using a section of a cosine curve, as shown in Fig. 9. The



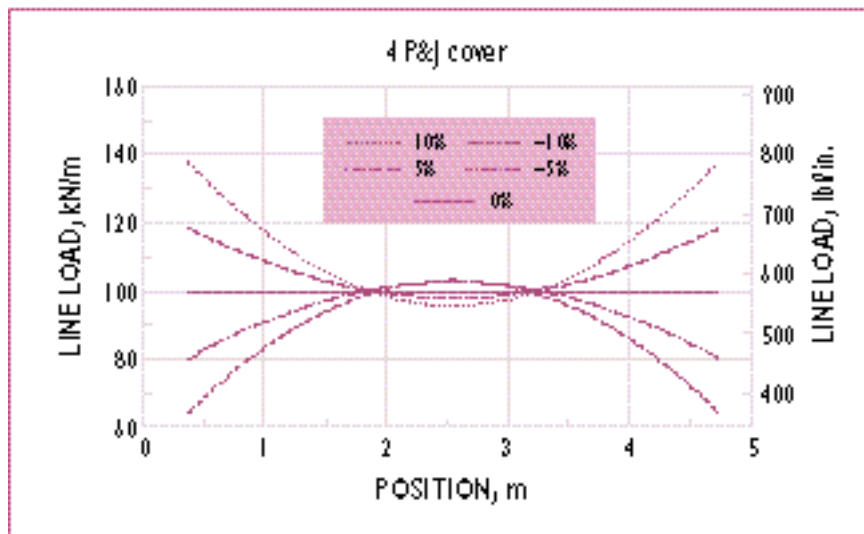
9. Cosine crown distribution shapes



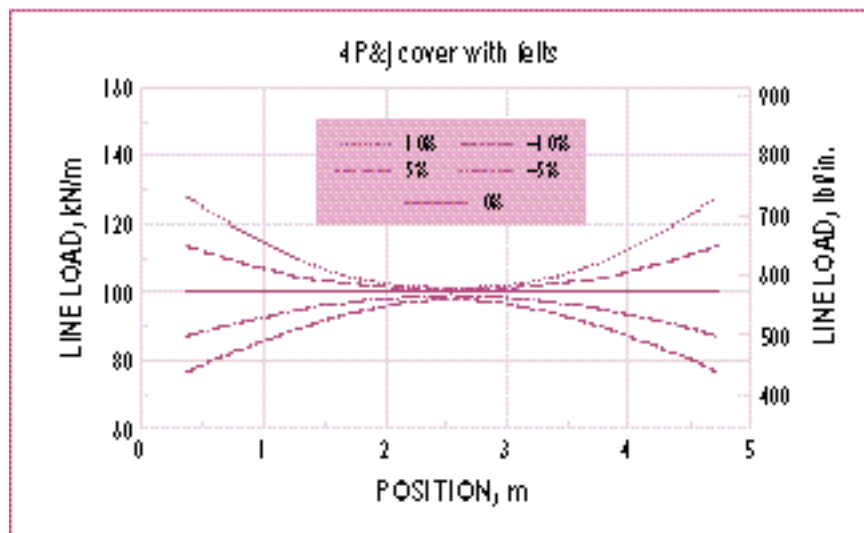
10. Cam angle effects



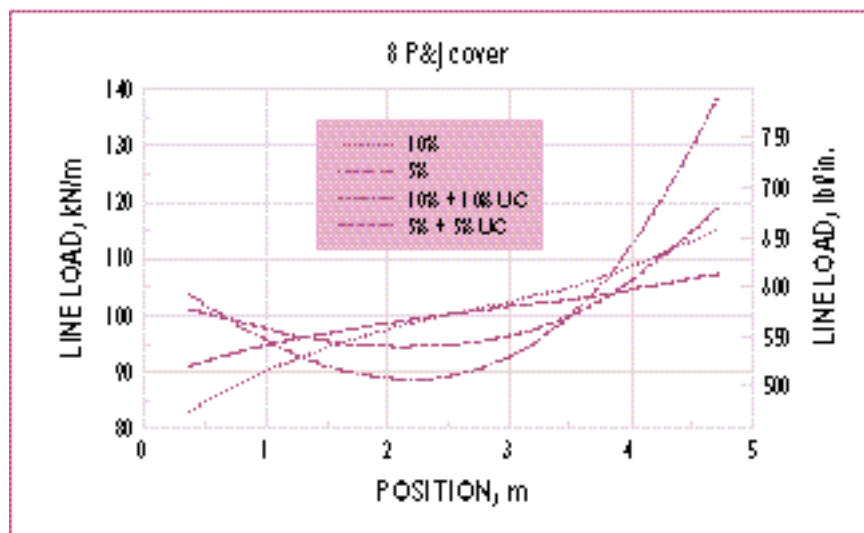
11. Shell material effects



12. Effect of overloading



13. Effect of overloading with felts



14. Front/back journal misloading

cam angle or degrees of cosine crown specify the size of the section of the cosine curve. Note that the shape differences are most significant near the third station, and greater cosine angles result in smaller diameters near this station. Physically, the cam angle is the number of degrees that the grinder cam rotates from the roll centerline to the end. The 70° cosine curve is the most common choice. See TAPPI TIS 0420-06 (3) for more details concerning crown specifications.

For an 8 P&J cover, the effect of a cam angle choice on the nip pressure profile is not great, as shown in Fig. 10. Therefore, many crown specifications do not mention the cam angle requirements. One word of warning is that for Yankee pressure rolls and other situations where one or more rolls have significant hoop bending, the cam angle is much more important. Furthermore, the use of compound crowns may be necessary. Kennedy *et al.* (23) discuss the need for compound crowns in Yankee dryers. Proper cam angles are also more important for very hard covers, such as those found in calender stacks.

Shell material variations

The roll deflection depends on the modulus of the shell material and the cross-sectional properties as well as the weights and loadings. It is common for spare rolls to be constructed of different materials and have different cross-sectional properties. For example, a suction roll position may have both a bronze shell [modulus of 62 GPa (9.4×10^6 psi)] and a newer stainless steel shell [modulus of 200 GPa (29×10^6 psi)]. If the crown were specified and maintained on the stainless steel shell and inadvertently applied to the bronze shell, then one would expect a cross-machine loading distribution as shown in Fig. 11. The conclusion is then that each roll body should have its own crown specification.

Line load changes

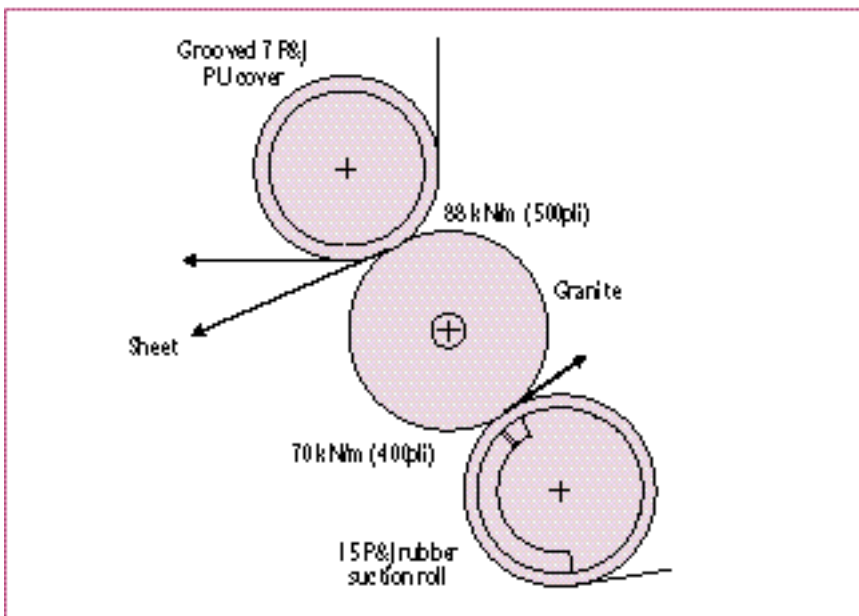
Perhaps the most common occurrences are changes in line load with-

out corresponding changes in crowns. For the model problem, increases in the line load will affect the cross-machine loading variation. The effects are shown in Fig. 12 when the journal forces are increased by 5 and 10%. Notice that a 10% increase in the journal forces results in an edge overload of 38% and a 2% decrease in center load. Similarly, for the case with felts shown in Fig. 13, the ends are again overloaded more than the center. This example shows that increases in the journal loads do not always result in benefits to the roll center; the center may be relatively unaffected. Second, the ends see a disproportionately high load for small increases in the journal loads. Such an edge overloading may correct for wet edges, but it may result in overly dry and/or crushed edges and could result in premature cover failures. Graphs, such as those shown in Figs. 12 and 13, may be used to establish safe operational limits for journal loading.

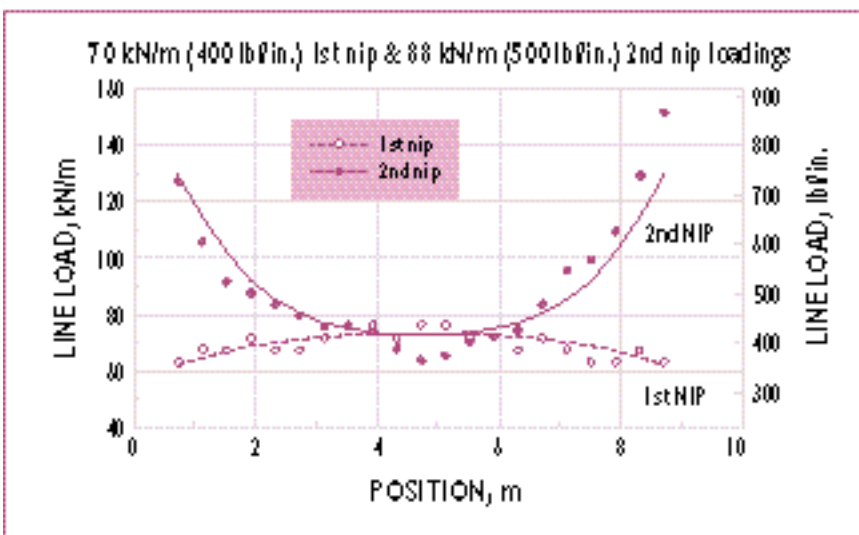
Not all of the loading variations of the type shown in this example are caused by operators changing the journal forces. Quite often, the target specification is incorrect. Changes in the shell weights, the use of auxiliary equipment that adds to the journal weights, and the amount of cooling water in the roll bodies can add or subtract from the nip loading. These factors can change over time and emphasize the need for a regular nip impression program to keep the loading under control.

Front/back journal load variations

Many of our experimental studies using prescale film and static nip impressions have shown end-to-end loading variations. The air bag pressures should be checked regularly, and the pressure gauges should receive frequent calibration. When the back-end journal is loaded 5% and 10% higher than the front journal, we could expect loading variations as shown in Fig. 14. Also shown are 5% and 10% under-crowned conditions that are super-



15. Inclined press geometry



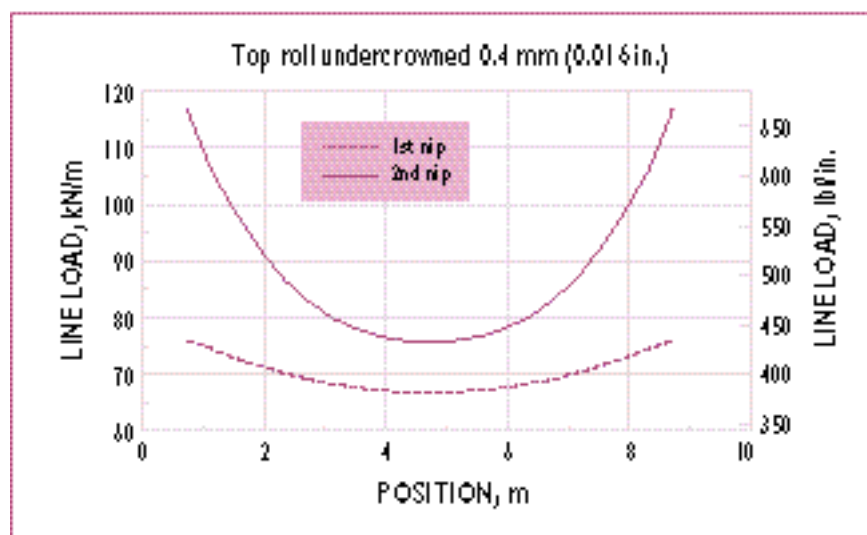
16. Inclined press loading variations

imposed on the front/back misloads. Note that the undercrowned condition results in greater end loading than the uneven journal loads for this 8 P&J application. The crowning error influence will decrease for softer covers, as shown in the first example. However, the softer covers will not substantially reduce the consequences of the journal load imbalance.

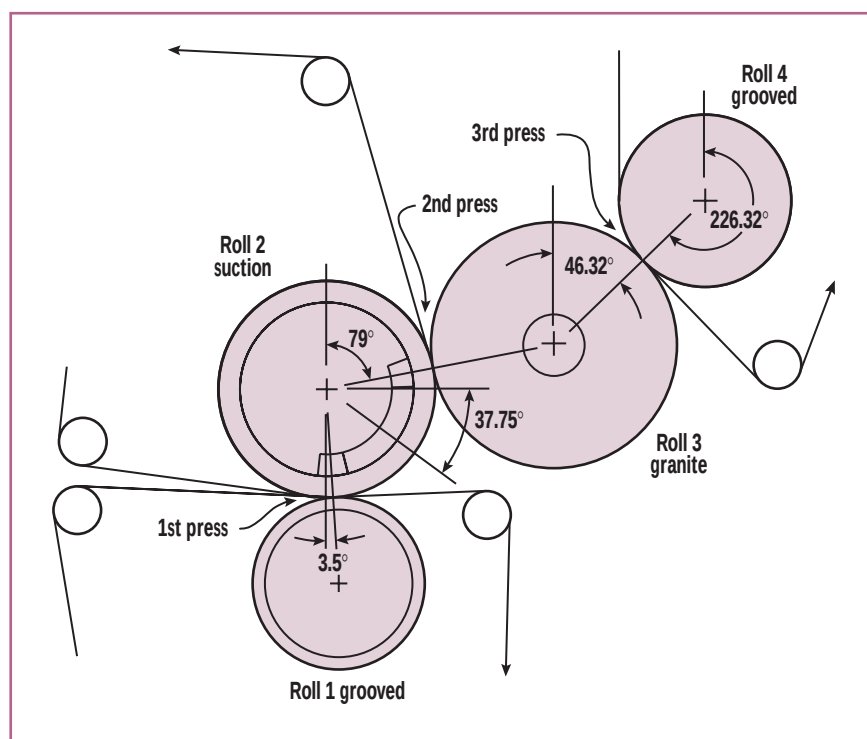
Inclined press

The inclined press introduces a new level of complexity to these exam-

ples, since there are three rolls and two nips that have offset angles. The press shown in Fig. 15 had nip loading variations as shown in Fig. 16. The symbols represent prescale film pressure results that were converted to line load, and the solid lines represent the program predictions. As with Fig. 5, we want to demonstrate the loading variations rather than the peak pressure variations that are typically shown with prescale film. Note that the second nip was badly under-crowned, and the right side (back



17. Loading variations that result from the undercrowned top roll



18. Tri-Nip configuration

end) had higher loading than the left side. We did not attempt to model the front/back load bias for this case. For this case, both nips required crown adjustments to achieve uniform loading.

We would like to illustrate another point using this press example. If we start with the crown parameters that result in uniform loading and then reduce the top roll

crown by 0.4 mm (0.016 in.), we would expect the loading shown in Fig. 17. Notice that both nips appear undercrowned, instead of just the second nip. The addition of 0.4 mm (0.016 in.) of crown to the top roll will result in uniform loading for both nips. Again, one would not need to increase the total crown in the first nip, because the first nip loading variation was caused by problems in

the second nip. If that same 0.4 mm (0.016 in.) of crown were added to the center roll, then the second nip would have the correct crown total, but the first nip would have too much crown. Both nips would appear overcrowned.

In short, improper crown parameters for one nip may affect other nips. This transfer of misloading is caused by the roll bending to a different shape than for the uniformly loaded case. This is the reason that the computer program updates the whole set of roll deflection profiles for each set of nip loading profiles. This example also illustrates why crown corrections based on nip impressions often require more than one attempt.

Tri-Nips

Tri-Nips present a greater crowning challenge in that there are four rolls involved, and there are felt and vacuum loads to consider. Furthermore, the bottom and top roll may be interchanged. Static nip impressions are difficult, since it is difficult to load the rolls evenly. See Kennedy (4) for special directions for taking nip impressions. Other techniques, such as prescale films that are fed into the nips at low speed, allow the press to be loaded before the measurements are taken. For the Tri-Nip configuration shown in Fig. 18, the cross-machine loading variation shown in Fig. 19 would result when the suction roll is undercrowned. The dashed lines in Fig. 19 are the target line loads.

Note that the undercrowned suction roll results in significant end overloading in the first two nips. The third nip is not affected much, since this is a narrow-width machine. The machine width in this example is half that of the previous example, but the granite roll diameters are nearly the same. The granite roll deflection profile did not change enough to affect the third nip significantly. One concern in this example is that the covered suction roll experiences two harsh end loads.

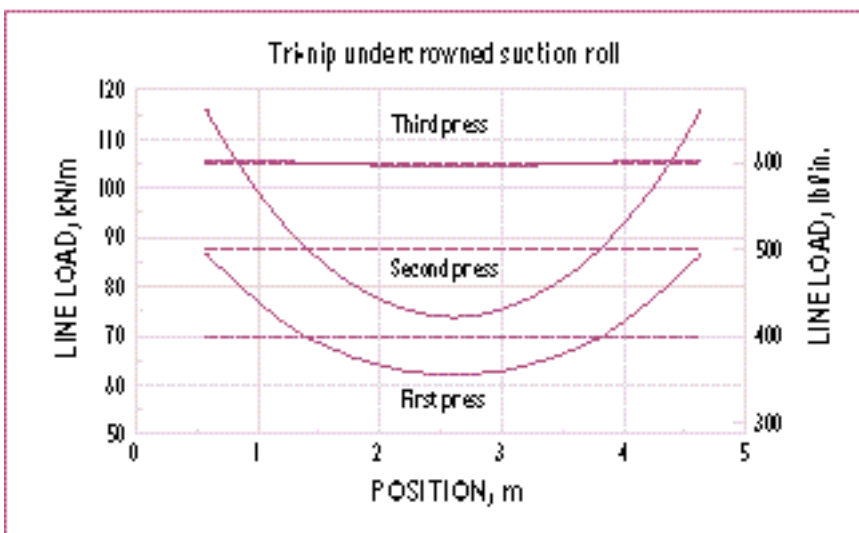
Gate roll size presses

The gate roll size press (GRSP) is perhaps the greatest challenge in crown studies because there are six rolls and five nips involved. Furthermore, in most applications, one may interchange the upper and lower gate rolls, so the crown specifications for each should be the same. The same holds for the applicator and metering rolls. As usual, there is only one set of loadings that apply to the one set of crowns that are ground in the rolls. Many mills use uncrowned metering rolls; this adds further constraints to the system. The cross-machine loading profile for undercrowned applicator and gate rolls is shown in **Fig. 20**. Notice that the ends of the applicator rolls experience high loading from both nips. One must take care in loading these applicator rolls correctly, as the lack of felt coupled with two nips could result in reduced cover life.

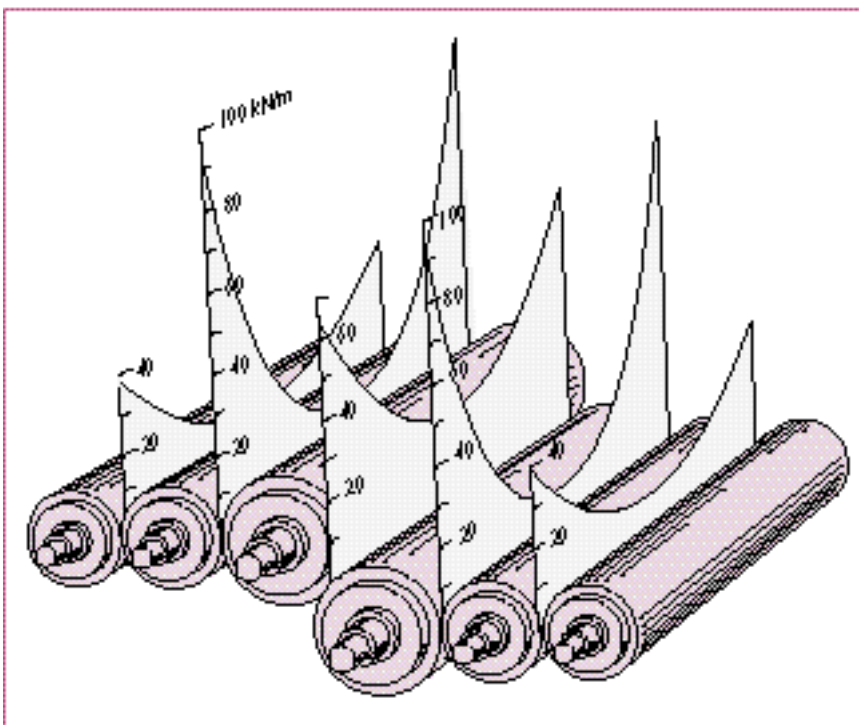
For the loads chosen in this application, the metering roll would need to be crowned to achieve uniform loading, but crowning these rolls was not an option. For this example, if the nip between the two applicator rolls were to have uniform loading, then the nips between the applicator rolls and the metering rolls would be undercrowned. Similarly, if the applicator/metering roll nips were uniformly loaded, then the applicator/applicator nip would be overcrowned. A compromise must be made.

Thermal crowns and calender stacks

Line load variations in calender stacks have received attention in the literature. Stotz and Schuwerk (24) and Mueller and Hadlock (25) used the finite element technique to show that simple crowns alone would not alleviate the cross-machine loading profiles that are caused by overhung loads. The more modern calender stacks provide overhung load relief that result in more uniform nip profiles. Since these references provide an excellent overview of the problem and a solution to overhung



19. Tri-Nip loading profile



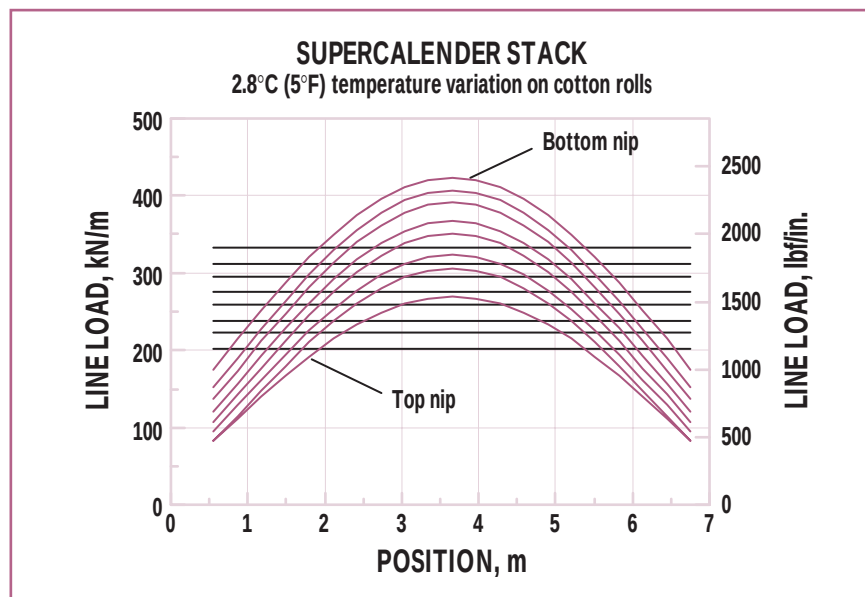
20. Undercrowned GRSP application

loads, we will pick up with a different, but common, problem.

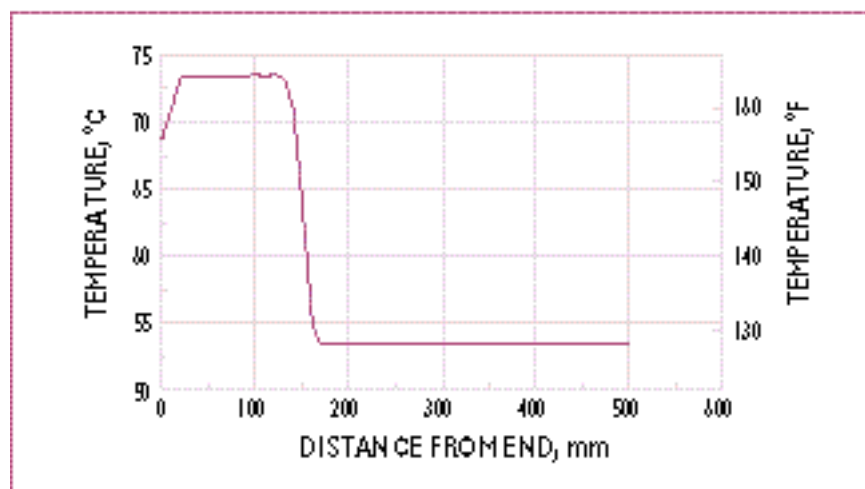
We have seen temperature variations across the face of the rolls in calender stacks. In some cases, the center of the rolls featured a higher temperature than the ends. Hall and McLemore (26) reported a composite temperature graph showing the center temperatures 22°C (40°F) higher than the ends. Further work

by Hall and McLemore showed an inverse relationship between temperature and sheet caliper.

We can show that higher temperatures result in greater loads for a different case. If we assumed that each of the four cotton-filled rolls on a nine-roll stack was 2.8°C (5°F) hotter in the center than on the ends, then the thermal crown associated with this variation is sufficient to result in



21. Overcrowded calender roll



22. Temperature distribution at ends

the line load distribution shown in Fig. 21. The net result is about a 90-kN/m (500-pli) overload in the center of the bottom nip. Presumably, the small temperature distributions in each roll add up to produce sig-

nificant loading variations. The conclusion is that detailed temperature records should be kept on stacks, and that composite temperature studies are very beneficial.

Temperature and dubs/hot ends

In the previous example, we considered temperature variations that were distributed over broad regions. Now we are concerned with the common problem of localized hot spots just outside the sheet edge. We have seen several cases where a covered roll mates with a heated roll, and the ends outside the sheet region are not relieved sufficiently.

When the roll indentation is greater than the minimum sheet thickness, these ends are in direct contact with the hot mating roll and suffer elevated temperatures, as illustrated in Fig. 22. The hotter end cover regions expand more than the cooler regions, as shown in Fig. 23. These local high regions suffer much higher loading, as shown in Fig. 24. The combination of high temperatures and high loads can result in premature cover failure. The problem is easily alleviated through the use of a more aggressive taper. More information on edge relief may be found in the literature (27).

The previous two examples illustrate that thermal variations can cause loading variations. Since the thermal variations require time to develop, one should recognize that nip impressions and prescale tests at startup may miss these loading variations. One should perform additional testing after the stack or rolls reach steady-state operating temperatures. A second concern is that the highly localized nature of the second example may be missed if only 21 stations are marked off. One should perform extra measurements near the edge of the sheets.

SUMMARY AND CONCLUSIONS

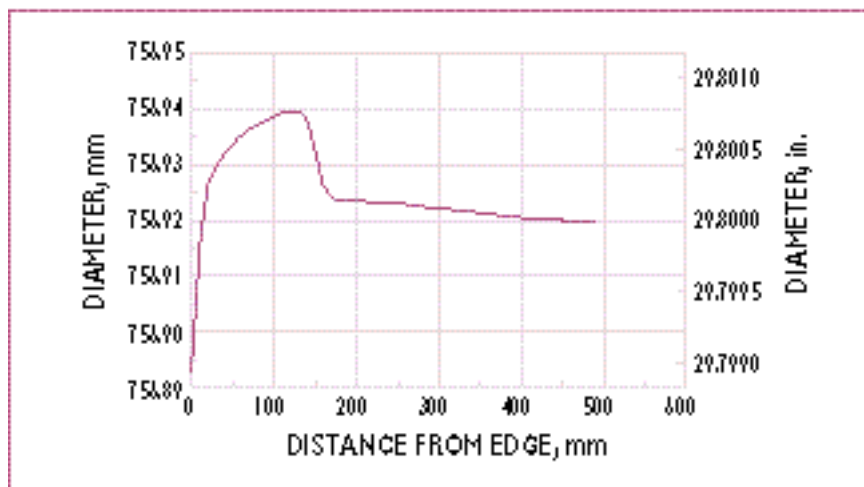
We have discussed many common events that lead to variations in the nip pressure. We also discussed a quantitative modeling approach to estimate the severity of these variations. The following conclusions were reached:

- Softer covers reduce the loading variations for crown errors.
- Felted nips result in softer nips and reduced loading variations.
- Thinner covers act stiffer in the nip and result in greater loading variations than thicker covers.
- The grinder cosine cam angle is important and can result in variations, but these variations are often much smaller than variations caused by other effects, such as crown amount errors.

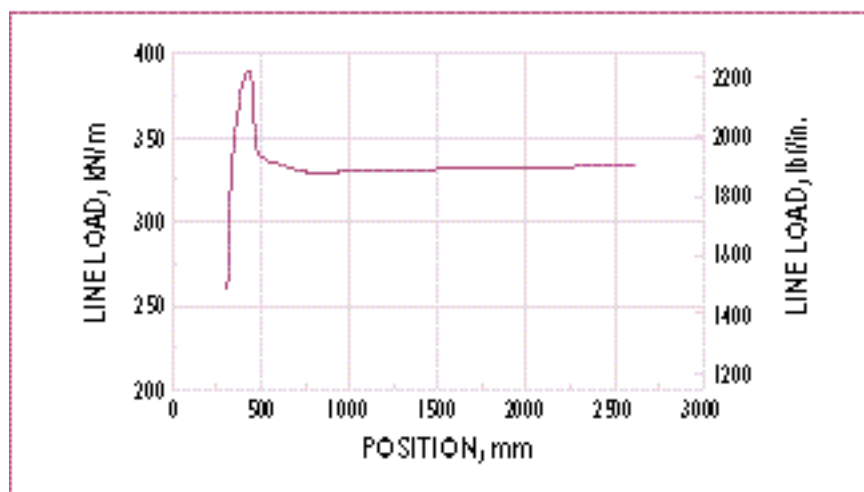
KEYWORDS

Bibliographies, coverings, cross direction, felts, force, loads, machine clothing, machine components, models, nip, press felts, press sections, process variables, profiles, roll crown, rolls, temperature, variability, variables.

- Each roll body will have its own crown. Different shell materials and thickness and weights require different crowns. Consult the machine builder and/or cover suppliers for assistance in determining acceptable crowns.
- Line load changes without corresponding changes in crown affect the ends more than the roll center. One should be aware that increasing the line load may not produce the desired effect.
- Mismatches in journal forces produce end-to-end line load variations. These variations are not diminished much through the use of softer covers. This observation is in contrast with the fact that cover hardness strongly influences the loading variations for broad crown errors.
- Crown errors in one nip may influence the loading variations in other nips. One should be aware of highly loaded regions that have more than one nip.
- Thermal variations may cause loading variations, since the shell and cover expansions are functions of temperature. Therefore, the loading uniformity tests, such as nip impressions and prescale film tests, should be performed after the rolls have reached operational temperatures.
- When taking nip impressions, extra measurements should be taken near the ends to check for localized highly loaded regions.
- Many loading variations are caused by a combination of effects, such as an undercrowned roll with a heavy back-end load.



23. Roll expansion caused by hot ends in calender stack



24. Loading variation caused by hot ends

The author hopes that this discussion will benefit the papermakers and suppliers by explaining many of the factors that influence the loading profiles and by sparking ideas for future adjustments of the loading profile. The goal, of course, is more uniform sheet quality, longer-lasting covers, and reduced operating cost.

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