The mechanics of web spreading: Part 1

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ABSTRACT: Web spreading systems are governed by a universal set of web-handling principles such as bending, minimal energy path, normal entry, and traction. These laws, which apply for all web materials and spreading systems, can be used to understand the influences which affect spreader operation. This report covers the mechanics of spreaders such as: bowed rollers, dual bowed rollers, concave rollers, expander rollers, D-bars, and Pos-Z™ bars. Also covered are spreader design considerations, applications, and troubleshooting techniques.

KEYWORDS: Mechanics, rolls, spreading, web spreaders.

Spreaders are required on most web processes to prevent or remove wrinkles, to widen a web, or to separate slits during winding. They are used in the converting of a variety of materials including film, foil, nonwovens, paper, and textiles. However, they are also found in manufacturing as well. Forming wires and drying felts are just a few examples where spreaders are required on "endless belts" to keep them flat.

There are many types of spreading systems in use, including the bowed roller, dual bowed rollers, concave rollers, expander rollers, D-bars, and Pos-Z™ bars. Some have a single element, while others have two or more elements. Some spreaders can be adjusted for local effects, while others can be adjusted only for overall spreading or may be completely fixed in shape.

Despite their various appearance and their many diverse applications, all spreaders follow a universal set of web-handling principles that govern their operation. Understanding these principles allows us to make the most appropriate choice of spreader for a particular application, and then to operate that spreader most effectively. In doing so, we will see improved manufacturing and converting efficiency, while at the same time reducing waste due to causes such as wrinkles, foldovers, and stuck rolls.

Indeed, immediate gains can be made by removing so-called "spreaders" such as wormed rollers and cigar shaped rollers, which actually contract the web as we shall see. Other common pitfalls include undersized spreading systems that may not remove wrinkles or separate slits, and oversized spreaders that cause instabilities in the web's edge position. Finally, even well designed systems may not do the job, for example, if the bow is pointed in the wrong direction.

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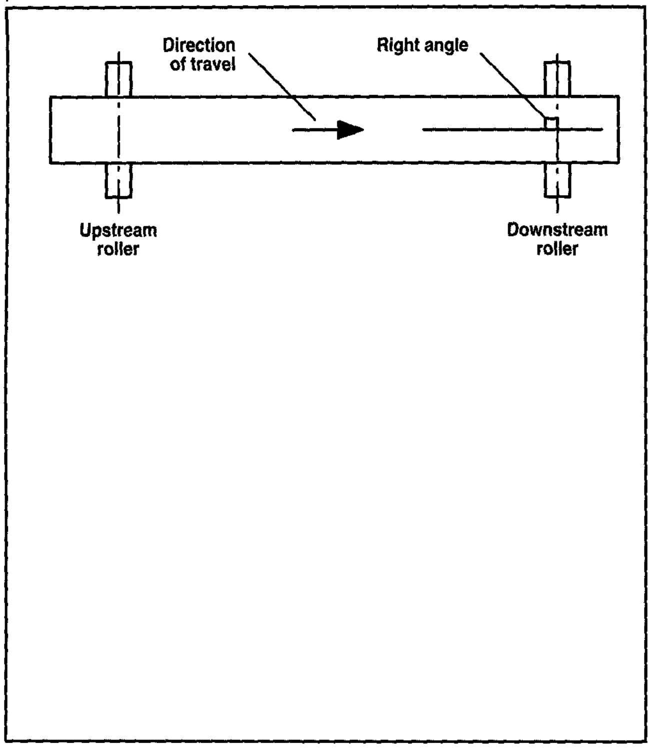
Web-handling principles

Perhaps the single most important web-handling principle which governs spreading systems is the Normal Entry Law *(1, 2)*. As seen in **Fig. 1**, a web will seek to enter a downstream roller at a right angle to the roller's axis at the point of first contact. If for a variety of reasons the web is not currently entering at right angles, it will move sideways at an ever decreasing rate, as seen in **Fig. 2**. This universal principle not only governs spreading, but also describes web behavior at misaligned rollers, guides, and winders. Similarly, the web will also tend to exit a roller in a normal direction. This normal entry/exit principle will be used later to help determine the path of a web through a machine.

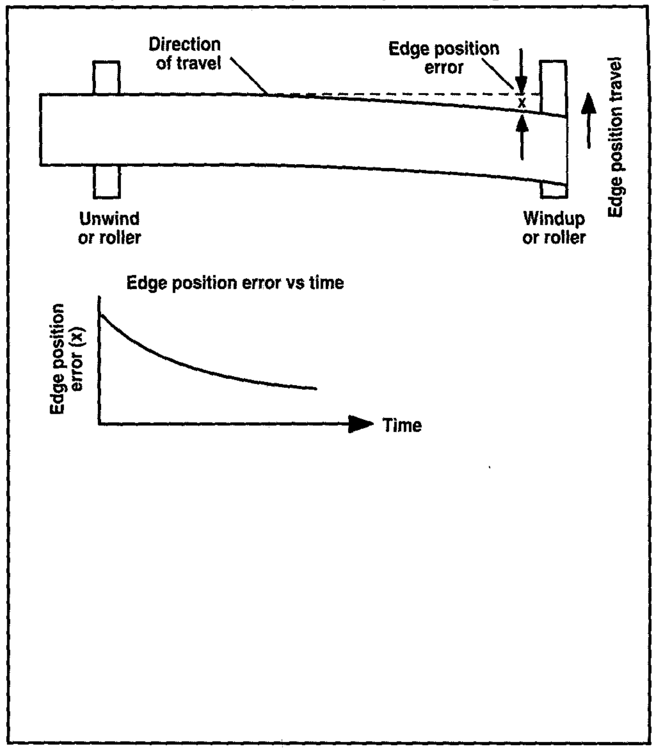
An important exception to the Normal Entry Law, is that it applies only when there is no slippage between a web and its roller. Thus, while it would not describe behavior at a sliding spreader such as the D-Bar or Pos-Z, the web will enter and exit at right angles to the nonslipping upstream and downstream rollers. In any case, traction is such an important parameter that anything that improves traction should also improve spreading. Traction is increased by the variables shown in **Table I** *(3, 4)*.

To understand spreaders it is important to know about the forces that can move a web sideways. There are three distinct spreading mechanisms, but they are often seen in combination on any spreader type. As seen in **Fig. 3**, the lateral force is the most straightforward, where an outward CD tension at a spreader will consequently move the web outward. However, in-

1. Normal Entry Law. The web will seek entry at 90° to roller axis at the point of contact.



2. Getting normal: if the web is not entering normal (90°) to the roller, it will attempt to do so at an exponentially decreasing rate.



plane bending (ZD moment) applied at a spreader will also move a web sideways in a similar fashion. Finally, there is the folding mechanism which displaces the web sideways through simultaneous folding (CD moment) and twisting (MD moment). Folding is the basis for most dual element spreaders. Folding/twisting is also the most powerful because the web is not as stiff with this mechanism as it is with lateral forces and in-plane bending.

Another constraint with in-plane bending is that it must always be accompanied by sufficient line tension to keep the web taut everywhere. As seen in **Fig. 4**, if pure bending is applied to a web, the slack side will simply sag or flop out of control. As the line tension is increased, however, more of the web's width is under tension and the amount of slack web is reduced. Finally, there is a critical minimum line tension that ensures that the entire web is under tension, which can be calculated from simple beam formulas for long span/width ratios.

While it might be surprising to some, the web really does behave much like a beam, albeit a very tall and skinny one *(5,6)*. Thus beam, or better yet, membrane theory is used to analytically model many web-handling situations such as spreading. Rather than focusing on math, however, this paper is intended to help the reader visualize spreading based on simple principles. One of these principles, borrowed from beam theory, is that the path of a web through a machine will be a smooth and gentle curve. With this background, we can now explain the operation of several spreading devices.

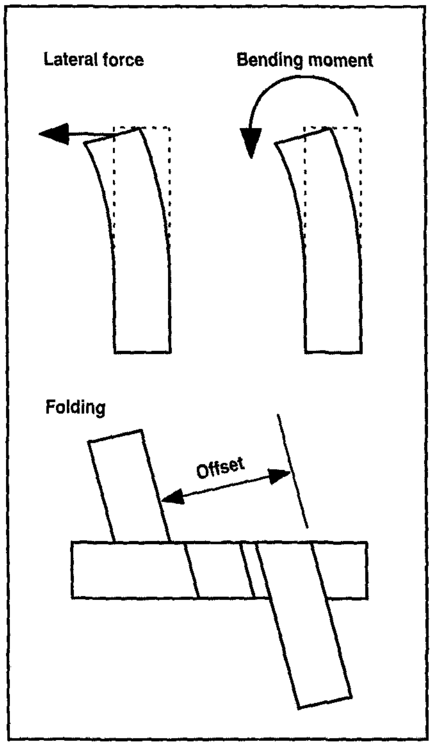
The concave spreader roller

The simplest and least expensive spreader is the concave roller. As seen in **Fig. 5**, this spreader is a conventional roller whose diameter at the ends is slightly greater than at the center. In its ideal configuration, the diameter profile of the roller is cut as an arc of a circle. However, a simpler version can be made for unslit webs by cutting a roller with conical ends and a cylindrical center. Finally, the simplest of all arrangements is to add a couple of wraps of tape to the ends of a straight roller. Taping straight rollers is successful on only narrow unslit webs, but it can be highly effective in that limited application however.

Sizing the diameter ratio is application-dependent. However, a rough starting point would be a reduction of diameter at the center of about 10% of the MD strain induced by web-line tension or draw control. For example, this would be a 0.020-in. diameter reduction on a narrow 2-in. diameter roller running a very stretchy film, nonwoven, or tissue grade at a 10% strain. Clearly a spreader roller for this example would be quite easy to manufacture. However, a 10-in. diameter roller running a flat paper grade at 0.2% strain would require only a 0.002-in. diameter difference to cause moderate amounts of spreading. Manufacturing a spreader roller for this flat-paper example to a controlled profile would be extremely difficult at best.

From these two examples, we can immediately see that the concave roller is limited to stretchy materials because of diametrical tolerances of roller

3. Spreading forces: there are three forces that can move a web outward from its centerline.



1: Increase of traction and spreading with variables

Direction	*Variable*
Increasing	Friction coefficient
Increasing	Porosity
Decreasing	Roller diameter
Decreasing	Speed
Increasing	Tension
Increasing	Wrap angle

manufacturing. However, the flat-paper example also illustrates that we can inadvertently induce spreading effects on any roller by unintentional and tiny diameter variations. Unfortunately, those "spreading" effects will be unpredictable and nonuniform and will span both spreading and contraction across the same roller.

Understanding how a concave spreader roller operates begins with surface speed variations across the roller. Any solid roller will have a *constant rotational speed (rpm)* across its width. However, it will have a *varying surface speed (ft/min)* that is proportional to the local diameter at every position. Thus, as seen in **Fig. 6**, the surface speed of the concave roller is higher at the ends than at the center. This surface speed difference causes an ingoing web tension distribution that is shaped similarly to the speed profile. More precisely, the ingoing tension distribution is a superposition of the nonuniform surface speed induced tension profile onto the constant webline tension.

The last two schematics in Fig. 6 describe the mechanism for concave roller spreading. For illustration purposes, we will look only at the left half of a center slit web, where the unshown right half mirrors the left. The same principles also apply to arbitrarily slit or unslit webs. The top edge of the schematic web is the contact line with the spreader, and the bottom edge is the upstream roller.

The first step is to replace the nonuniform tension distribution with an equivalent force acting at the centroid of the web half (quarter point of the machine) and a bending moment using the parallel axis theorem. The central force merely makes the web longer, and does not enter into the spreading picture until we discuss Poisson contraction in a later section. The bending moment definitely has an effect on the shape of the web, however. As seen in the figure, the clockwise moment causes the web to rotate clockwise toward the machine centerline. Something else must be going on here, because the inward movement is obviously in the wrong direction for spreading! More importantly, the web edge does not enter at right angles to the roller axis as required by the normal entry law.

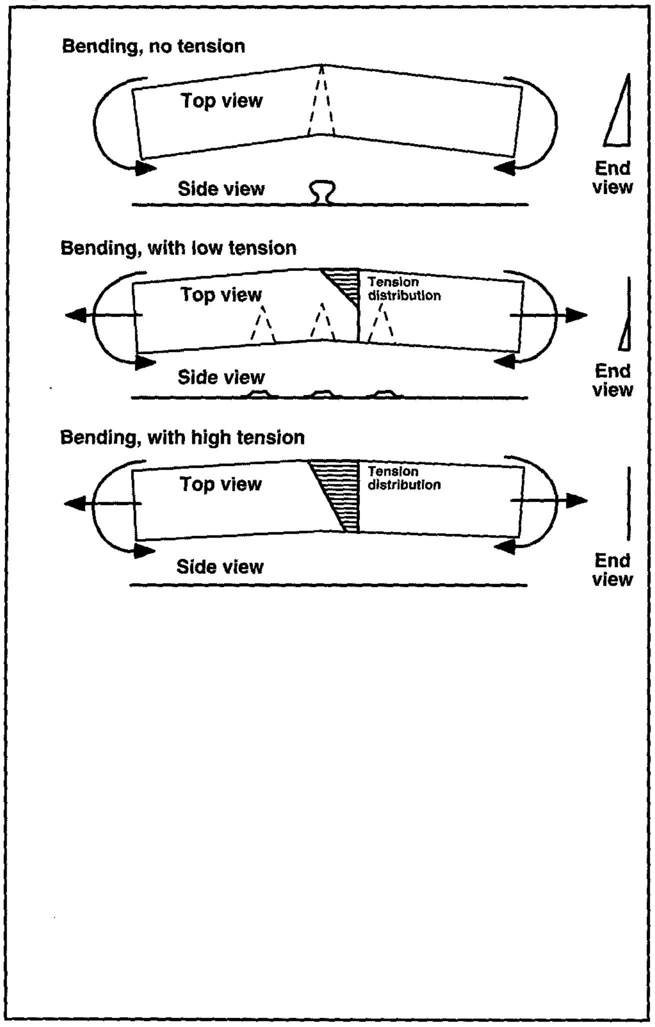
This something else is the outward lateral force that is missing. We know that this must exist for two reasons. First, it is the only remaining load type from our Fig. 3 discussion that can move a web sideways (remember the bending moment is already accounted for). Secondly, and more intuitively, it is quite reasonable to expect that an outward force must be present in order to move the web outward. Now when we superpose the outward lateral force onto the central MD force and clockwise moment, we end up with a shape which meets the normal entry and exit laws and does indeed cause spreading. While it might be tempting to conclude that only a lateral force is present, the absence of the bending moment and lateral force combination will not conform to the normal entry law, as the reader will again verify from Fig. 3.

This subjective description of the behavior of concave spreaders is simplified as much as possible while retaining the essence of its mechanics. Now we can understand why a cigar-shaped roller would actually contract the web because its effects are opposite to those of a concave spreader. As the reader may suspect, however, many subtleties have been left out. An analytical description which quantifies friction forces, stresses, and displacements requires complex models. Research centers *(7)* have developed custom computer programs for spreading which yield design information such as spread magnitudes and web stresses, as shown in **Fig. 7**.

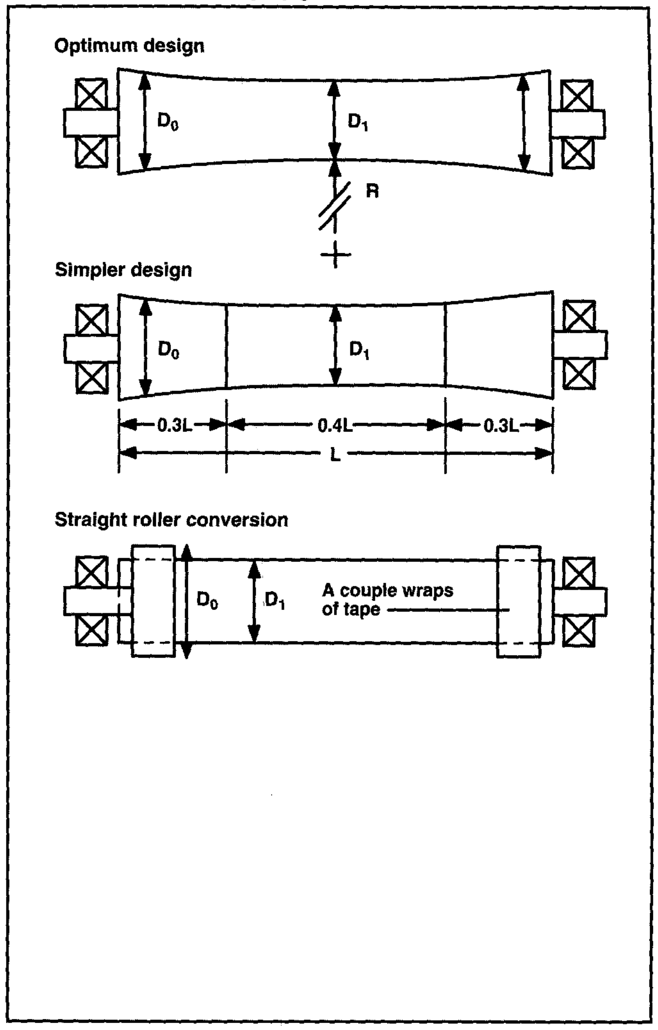
The bowed spreader roller

If numbers are any judge, the ubiquitous bowed spreader roller is a very important spreader for wide webs. As seen in **Fig. 8**, the bowed spreader has a curved stationary axle upon which a rotating sleeve(s) is mounted in numerous bearing sets. The axle may have a fixed bow, or it can be made variable through clever design arrangements such as split axles. The sleeve is typically a one-piece flexible tube of a soft synthetic composite. For high wear resistance and longer cover life, however, the sleeve may consist of numerous narrow metal rings. The "rubber" sleeve is usually grooved to reduce air entrainment and thus improve traction, and metal sleeves may be tungsten carbide-coated for abrasion resistance and traction. Finally, the bowed roller may be used in powerful dual-element spreaders which will be described in a later section.

4. Combined bending and tension: bending from spreaders or misaligned rollers, tension from line tension.



5. Concave spreader roller: this spreader is a simple roller whose diameter at the ends is slightly greater than at the center.

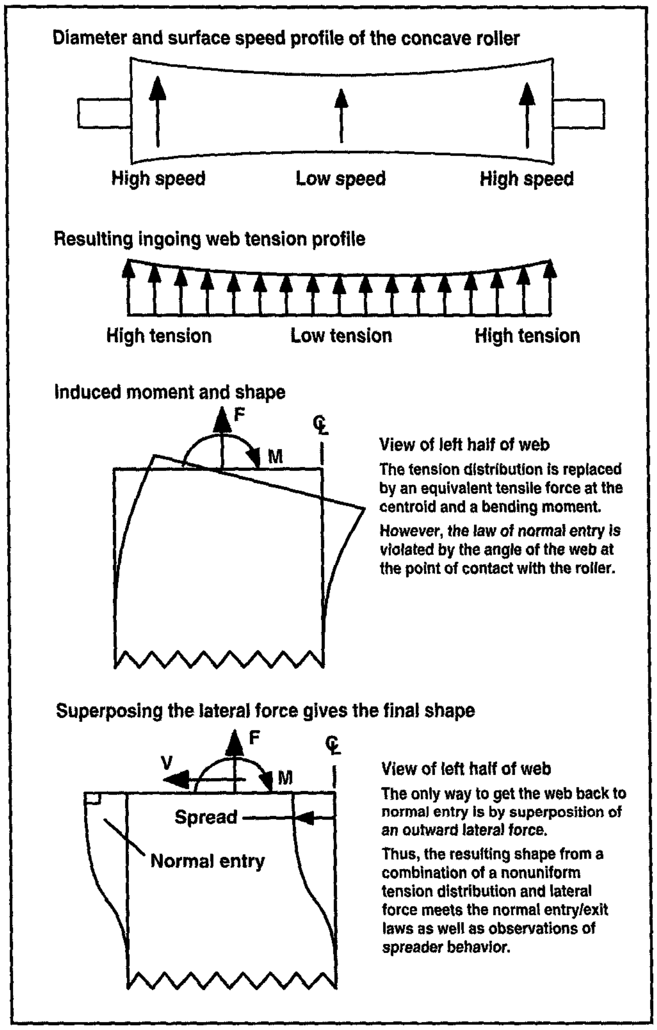


Since the bowed roller is more complex than other spreaders, there are more design considerations. For example, bearing design becomes very important on bowed rollers which may have dozens of bearing sets which are hard to replace, in contrast to conventional rollers which have only two bearings that are easy to get at. Also affecting bearing design is rpm limitations, lubrication, and the desire for minimal bearing drag. The application engineer must size the drives for motor driven spreader rollers, or size the tension upset on web-driven spreader rollers. The torque to drive the roll is composed of bearing drag and sleeve hysteresis during constant speed, with an additional acceleration component from bearing and sleeve inertia during speed changes.

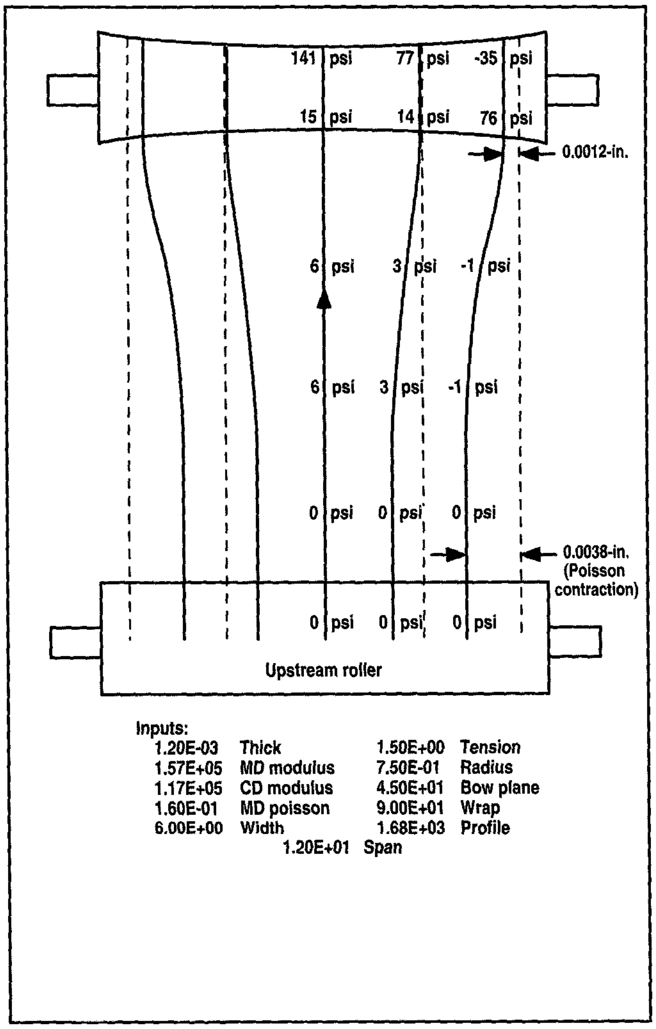
The synthetic sleeves are highly engineered composites. They must provide a reasonable tolerance to wear, bumps, cuts, and other damage which is endemic to the industrial environment. The sleeve material must also have minimal hysteresis because the continual flexing as it rotates around the curved axis can cause increased roller drag, thermal degradation, and fatigue. The sleeve must hold its shape to avoid disturbing the spreading uniformity due to diametrical variations. Also, loose sleeves are a common problem resulting from improper fits, centrifugally induced creep or thermal expansion. A loose sleeve will shift eccentrically and can cause severe spreader roller vibration. This tendency is exacerbated because spreader rollers are not dynamically balanced, and operate through resonance on high-speed winders.

The axle serves two primary functions. First, it is the structural backbone of the spreader. Most of the effective bending stiffness of the spreader comes from the axle rather than the cover. The axle largely determines weight, deflection, and critical speed. The second function is to determine the shape of the spreader. A critical aspect in manufacturing spreader roll axles is to maintain a very uniform in-plane (no twisting) arc of a circle (constant radius of curvature). The two most common methods to form the straight axle stock into an arc is to bend (three-point, four-point, or against a template) in a brake press,

6. Concave spreader mechanics. Surface speed variations across the roller induce spreading.



7. CD web stress/strain entering a concave spreader roller—courtesy R. Delahoussaye



or to roll in a roll bender. While bending may result in less axle twisting, rolling may result in more uniform curvature.

Sizing a spreader roller involves picking a length corresponding to machine width; a diameter determined by deflection, critical speed, and bearing rpm, and finally, bow. By convention the bow shape is an arc of a circle, as shown in **Fig. 9**. A bow is often specified as the distance between the chord and the arc of the roll at its center. This is sometimes expressed as a percent bow, which is the bow distance divided by the face length. However, percent bow may not translate well for large length changes. A better non-dimensionalization of bow and length is derived by calculating the radius of curvature as:

$$r = (L_c^2 + 4b^2)/8b \qquad (1)$$

where

r = radius of curvature

L_c = cord length

b = bow magnitude.

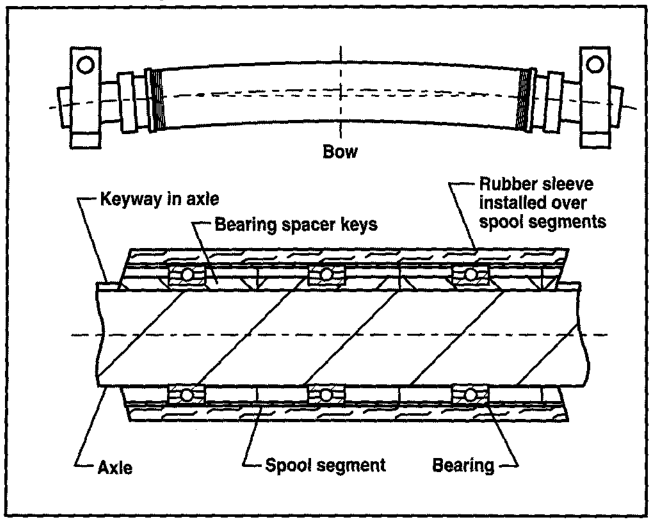
or for large radii as:

$$r \approx L_c^2/8b \qquad (2)$$

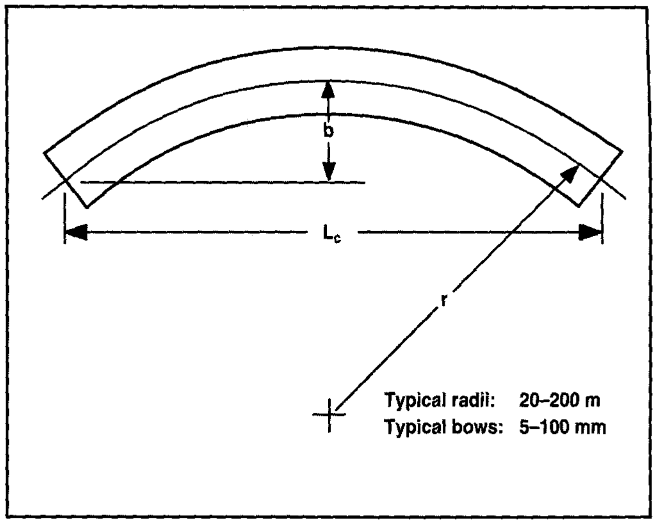
Once a selection is made for an appropriate radius of curvature for any particular application, such as unslit paper, then this value would be applicable for any width machine. However, the rub is that design guidelines for bows are almost nonexistent. Thus, one may have to use previous experience to guide bow selection. One example is a 0.125% bow for wide paper winders in the pre-slitter position and 0.5% bow for the after-slitter position. Stretchy grades could probably use more. More often than not, however, bows have erred on the excessive side, especially for stiff materials (e.g., paper) and on narrow machines (<2 m).

Perhaps the reasons bow guidelines are not widely available is because the spreading mechanism is complicated by material considerations such as anisotropic moduli, web/roller traction, and multiple slit webs. Even sophisticated computer modeling, such as in **Fig. 10**, does not currently model anisotropy and slits. However, from modeling, experiment, and experience, we know that spreading is very traction-dependent. **Figure 11** shows how spreading increases from zero at no bow to a maximum at the onset of

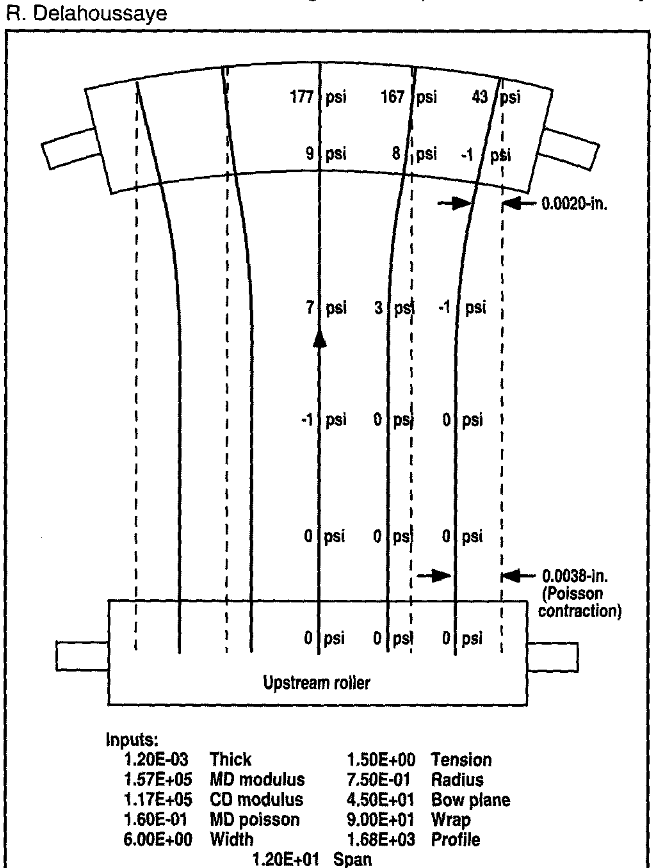
8. The bowed spreader roller is a bearing-supported cover on a curved stationary bar.



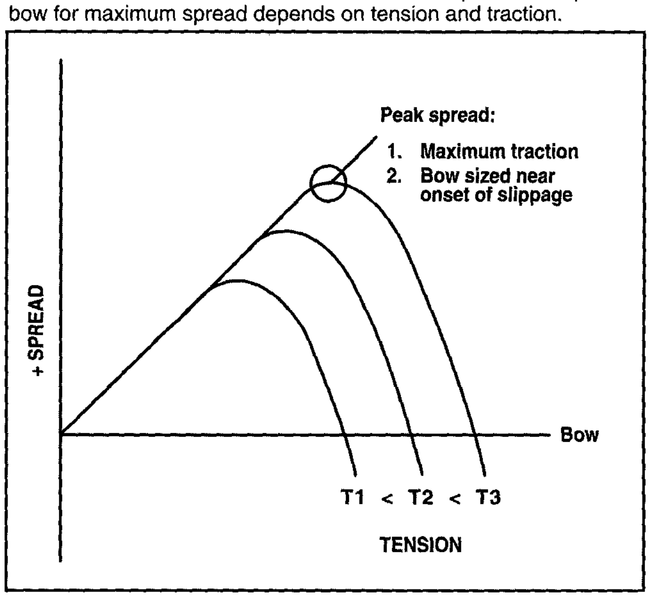
9. Bow shape: the axle of a bowed roller is usually bent into an arc of a circle.



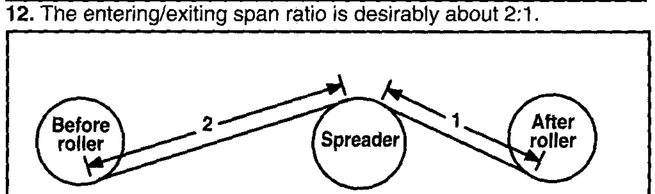
10. CD web stress/strain entering a bowed spreader roller—courtesy R. Delahoussaye



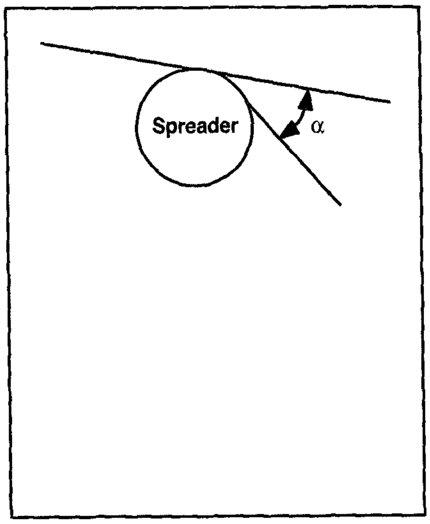
11. Effect of bow and traction on the amount of spread: the optimum bow for maximum spread depends on tension and traction.



12. The entering/exiting span ratio is desirably about 2:1.



13. Spreader roll wrap angle: the bowed roller wrap angle is typically about 30°.



slippage. After which, further bow increases will reduce spreading, and may even contract the web *(8)*. Thus, it may be better to err on the side of too little bow rather than too much. Unfortunately, small bows are much more difficult to manufacture to an accurate profile.

Setting up a bowed spreader roll can be even more controversial than selecting a bow. Conventional teaching is to place the spreader such that the entering/exiting span length ratio is about 2:1, as shown in **Fig. 12**. Later we will see that the reason for placing a spreader closer to the downstream roller is to retain more of the hard fought spread. Another area of controversy is the desirable wrap angle, as seen in **Fig. 13**, which is normally taught to be 15° to 45°, with at least one author claiming up to 180° is even better *(9)*.

The final area of setup controversy is the desirable bow orientation. Experience teaches us that the bow should be pointed downstream in a direction perpendicular to the bisector of the wrap. However, adjustments from this nominal orientation can be used to compensate for a baggy center or slack edges. As seen in **Figs. 14 and 15**, a baggy center can be tightened by rotating the bow into the web. As the bow orientation is turned more into the sheet, the path that the center of the web must take is longer than the edges, and consequently tighter. Since the web tension/draw control sets the average tension across the width, the edges will loosen at the same time the center tightens in order to maintain that average tension. Conversely, slack edges can be tightened by rotating the bow out of the web, but care must be used in this direction to avoid edge wrinkling.

It is important to note that the web sees a different bow magnitude and a different bow direction than the specified bow and pointer direction that the spreader manufacturer provides. This is because web tension and gravity deflection both modify the bow's direction and magnitude. For example, a spreader pointing upward will see a net bow which is the pre-bow minus gravity deflection, while the same spreader pointing down will see a net bow which is the pre-bow plus gravity deflection. To determine what pre-bow should be supplied to achieve a desired net bow, and to determine what direction to aim the pointer to result in a desired bow direction requires simple vector math. This is a little more complicated for split axle designs which are less stiff in the bow direction than perpendicular to the bow.

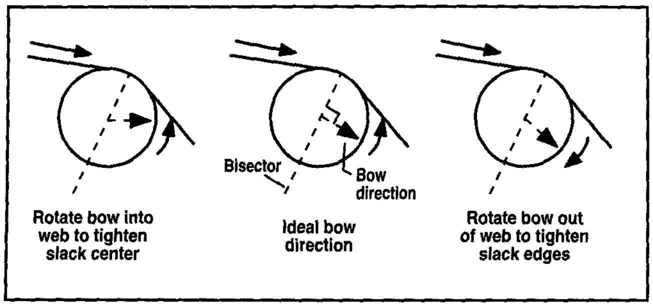
The mechanics of bowed roller spreading follow the same web-handling principles as do all other rollers, including the Normal Entry Law for the non-slipping case. As seen in **Fig. 16**, the center of the web travels exactly in the MD, while the edges travel perpendicular to the axis of the roller at the edges. While the surface *speeds* are uniform across the web (for a uniform diameter roller), the surface *velocities* are not. The velocity vector at any position has both an MD tension component and a lateral CD tension component. The MD velocity distribution is maximum at the machine centerline and steadily decreases toward the edges, which causes an outward rotation of the web. The CD velocity is zero at the machine centerline and increases as one progresses outward, which causes an outward lateral displacement of the web. Thus, while rotation fights displacement in the case of the concave roller, rotation works with displacement in the case of the bowed roller.

In addition to rotation and displacement, there is also a carry-out effect that increases bowed roller spreading with increased wrap angle. As seen in **Fig. 17**, the web exits a point further outward than where it entered. The carry-out effect increases from zero at no wrap to a maximum at 180° wrap, but is reduced very slightly with bow orientations away from the ideal. From simple trigonometry, the magnitude of this effect can be quite easily calculated. For the somewhat extreme example of a 180° wrap on a 25-cm roller with a 50-m radius of curvature on a 5-m wide machine, the carry-out effect would be an increase of width of about 0.5%. Thus, spreading can be improved by increasing the wrap angle, which increases both traction and carry out.

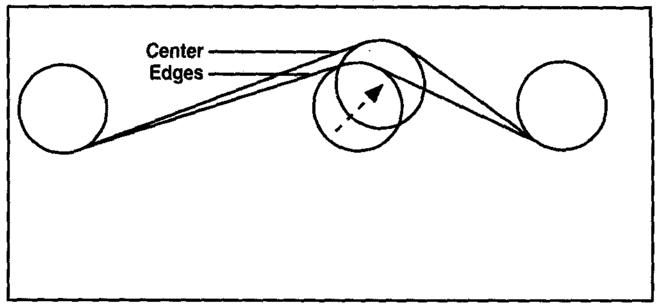
Putting it all together, we can draw the path of the web through a machine as shown in **Fig. 18**. The web exits normally from the upstream roller at a width W_0 which is known, bends outward and enters the spreader at a right angle at all positions, and finally rotates inward to become perpendicular to the downstream roller. Intuitively, one might conclude that the amount of spreading is determined by the width at the spreader (W_1). However, it is the width at the downstream roller (W_2) that actually determines the amount of spread that will be carried downstream.

Unfortunately, only a few conclusions can be made about width relationships without analytical models or experimental measurements. First, $W_1 \geq W_0$ because of the combined effects of rotation, displacement and carry out at the spreader. Second, $W_2 \geq W_0$ because a portion of the spread will survive to the downstream roller, depending mostly on the proximity of the spreader to the downstream roller. For spreaders placed very close to the downstream roller, $W_2 \geq W_1 \geq W0_2$. A note of caution is needed here. If the spreader is placed too close to the downstream roller, wrinkling can re-

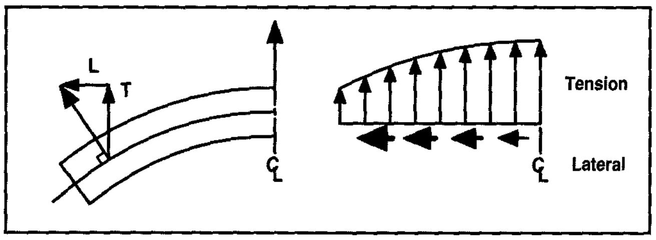
14. Bowed spreader roll bow orientation: the bow is pointed downstream on the perpendicular bisector of the wrap.



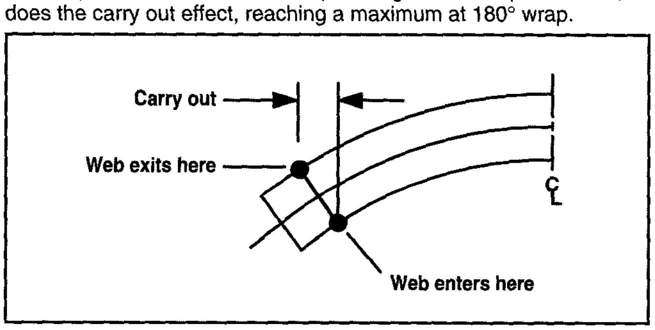
15. Bow orientation changes span lengths: a bow turned into the sheet makes the center span length longer/tighter.



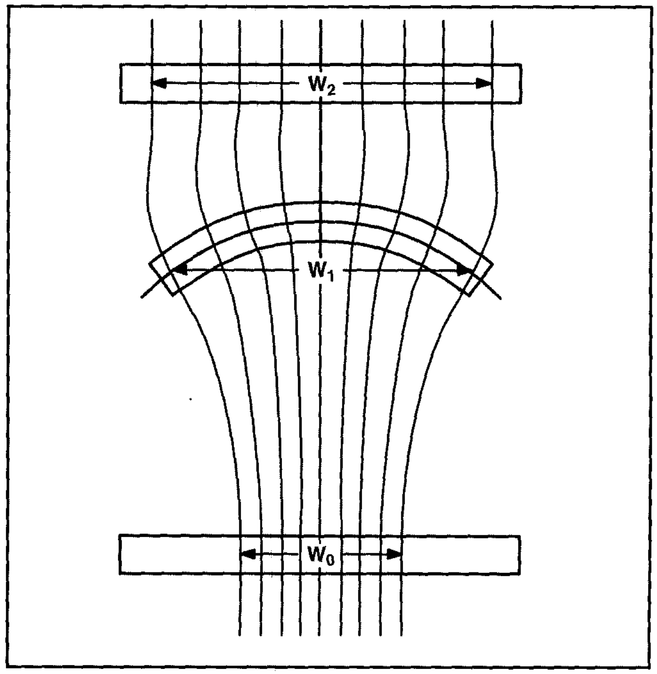
16. Stresses at a bowed roller: lateral and bending forces both contribute to move the web outward.



17. Wrap effects on bowed roller spreading: as the wrap increases, so does the carry out effect, reaching a maximum at 180° wrap.



18. Bowed roller web path: web streamlines for various deckle positions



sult from the severe stress gradients. For spreaders placed quite far from the downstream roller, $W_2 \approx W_0$. In other words, all spreading effects can (and will) be lost given enough distance downstream for reasons which will be discussed in Part 2.

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