Is There Any Science for D-bars and Bent Pipes?

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Introduction:

D-bars and bent pipes (non-rotating support bars with straight or curved axes) have received very little attention from web handling analysts. This is partly because their operation seems intuitively obvious. But, are they as simple as they seem? In this paper I will answer the following questions.

- Do D-bars really spread webs?
  - Do bowed D-bars produce positive CD spreading stress?
  - Do straight D-bars spread web and if so, how?
  - Are there side-effects to be avoided?
- Where should D-bars be located for best results?
- Do their effects persist very far downstream?
- How much bow is needed?

A D-bar, in its simplest form is a fixed, round bar (dead bar) or cylindrical shell (essentially a non-rotating roller). The origin of the name is unclear. The "D" may stand for first letter in dead bar or may refer to the fact that the bars can take the form of a section of a cylinder that looks like the letter D on its side.

Dead bars are sometimes used for nothing more than stabilizing the web plane upstream of a plane-sensitive device, such as an edge guide sensor. But in this paper, the focus is on their use in preventing wrinkles.

To minimize the effects of friction, a bar is usually installed with very little wrap and bow may be introduced to produce spreading. Since non-rotating bars are mechanically simple, they are often designed by users and manufactured locally. An exception is the adjustable design shown in Figure 2.

Unless specifically noted, the conclusions in this paper do not apply to web speeds high enough for air entrainment to be significant.

Throughout this paper, trough refers to a wave-shaped buckle in an unsupported web. A wrinkle refers to a buckle or crease on a roller.

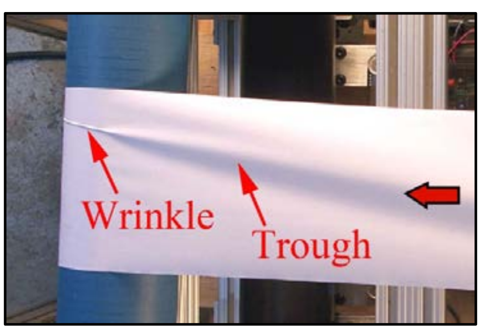


Figure 1
Definitions of wrinkle and trough

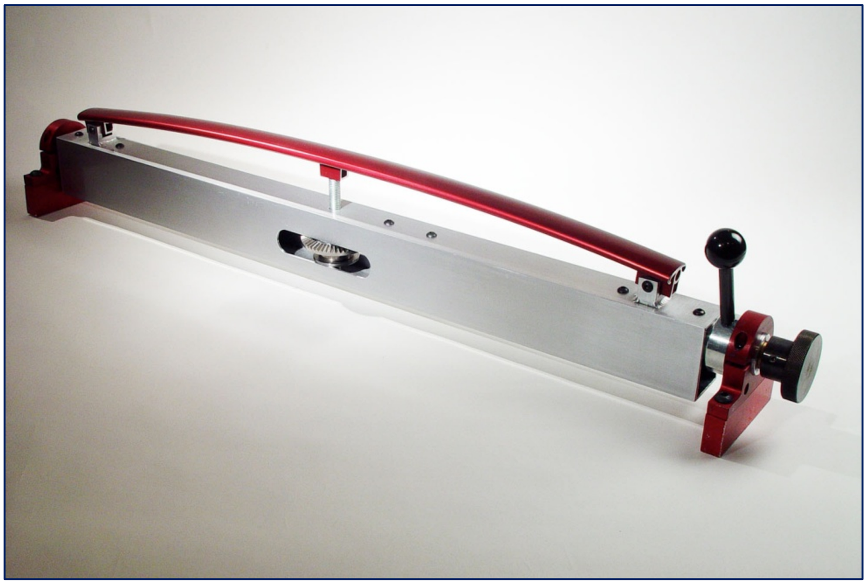


Figure 2
An adjustable D-bar

A cross section of the bar is shown below.

Figure 3
MD cross section of the bar in Figure 2

The top surface is approximately 1.5 inches wide. It has a radius of curvature of about 2 3/8 inches. The top surface transitions at the edges to a radius of about 0.31 inch. The wrap angle for the larger radius, θ is,

(1) $$\theta = 2\sin^{-1}\left(\frac{C}{2R}\right)$$

Where C is the chord of the top surface and R is the radius. So, for the bar in Figure 3 the maximum wrap angle is,

(2) $$\theta_m = 2\sin^{-1}\left(\frac{1.5in}{2(2.375in)}\right) = 36.8\,\deg$$

Wrap angles for applications are typically only a few degrees. For example, referring to Figure 5, if L1 = 66 inches, L2 = 6 inches, z = 0.5 inch and R = 3 inches, then ϕ_1 = 0.43 degrees and ϕ_2 = 4.87 degrees. So, θ = 5.20 degrees.

D-bars used in the tests described in this paper are shown in Figure 4. The top bar has 1/4 inch of bow over 12 inches of length (72 inch radius). The bottom bar is straight.

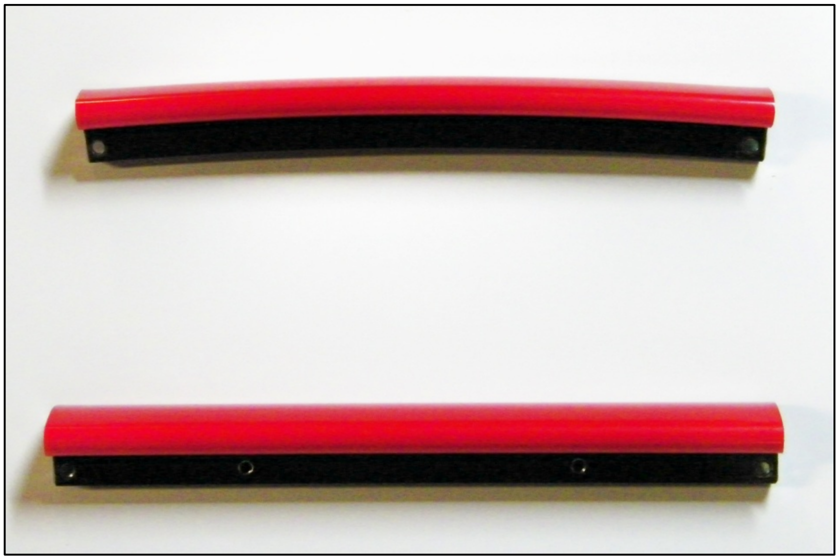


Figure 4
D-bars used in tests. Both are about 12 inches long.
The top bar has ¼ inch of bow. The bottom bar is straight

Friction and some useful relationships:

For a component that contacts the web, friction is obviously a serious concern. It should be as low as possible. For metal bars or cylinders this means that the surfaces should be polished and hardened. The bar illustrated in Figure 2 has a replaceable anti-friction polymer sleeve. In all cases the coefficient will be a function of the surface roughness of both the web and the bar.

Three other factors will affect the total tension drop across a bar (drag). The first is the radius of curvature of the bar surface in the MD direction. The second is the tension on the downstream side of the bar (the nominal line tension if the drag is very small). The third is the angle of wrap on the bar.

These parameters are illustrated in Figure 5 below.

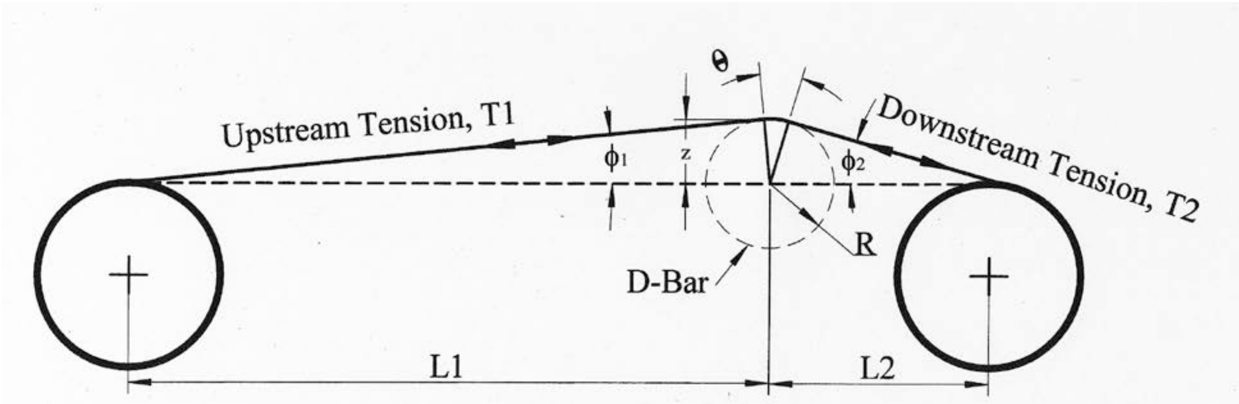


Figure 5
D-bar friction parameters

The change in MD tension across the D-bar is defined by the capstan equation, where μ is the coefficient of friction.

(3)
$$\frac{T_2}{T_1} = e^{\mu\theta}$$

There is a simple relationship between the wrap angle and the span angles ϕ_1 and ϕ_2 ,

(4)
$$\theta = \phi_1 + \phi_2$$

Pressure between the web and the bar will affect the wear rate. It is,

(5)
$$P = \frac{T}{R}$$

Note that the bar's cross sectional radius does not appear in equation (3). Also, equation (4) indicates that the wrap angle does not change with bar radius, provided that the height of its top surface in relation to the undeflected web path is not changed.

Equations (3) and (5) tell us that,

- The tension drop across the bar will increase as
  - The friction coefficient increases
  - The wrap angle (bar height in relation to the undeflected path) increases
- Wear on the bar (and scratching of the web) will increase as
  - Web tension increases
  - The radius of curvature of the bar cross section decreases.

The coefficient of friction was measured for a few materials relative to the covering material on the D-bars of Figure 4. It was measured directly by dragging piece of web material along the length of a straight bar with a weight on top of it. A thin layer of clay was placed between the weight and sample to insure that the sample conformed to the profile of the bar. Some results of this test were.

Thermal fax paper (this is the web used in Figures 6 through 8): μ = 0.19

Polyester film (An offcut from Grafix Plastics. Details such as coating unknown.): μ = 0.28

For a 30 degree wrap angle, these coefficients produce tension increases of 11 and 16 % respectively. It would be highly desirable to have lower coefficients and since coefficients vary with material combinations, a selection of bar sleeves of different materials would also be useful.

The polymer sleeves are removable. So, it was possible to measure the friction coefficients relative to the anodized aluminum surface of the bar. Results were approximately the same as with the polymer.

Tests with a curved D-bar:

Can D-bars really spread webs? The answer is, yes.

A convenient way to produce wrinkles for a test is to twist a web. Such a setup is shown in Figure 6.

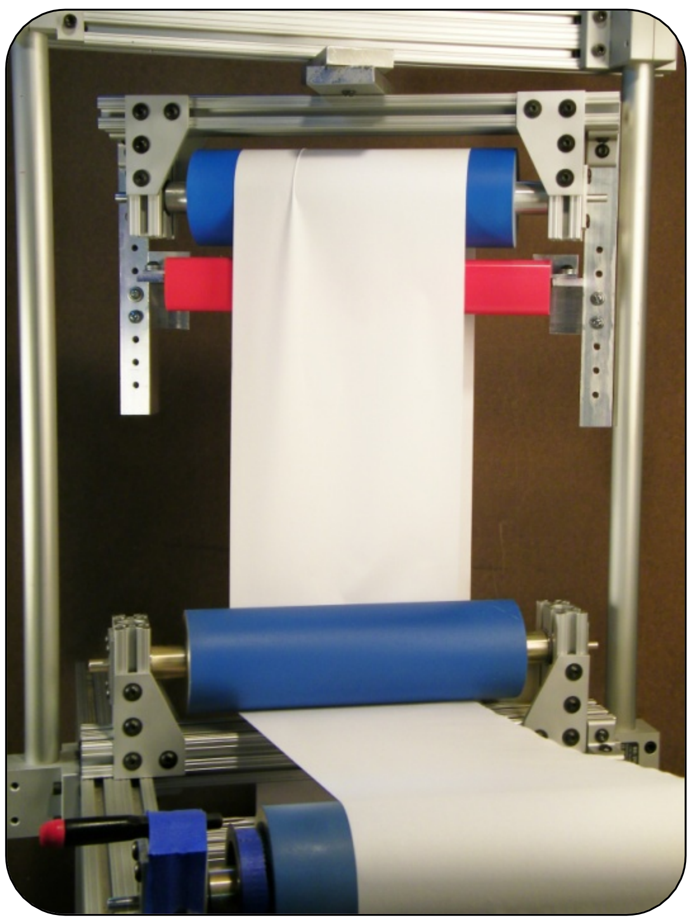
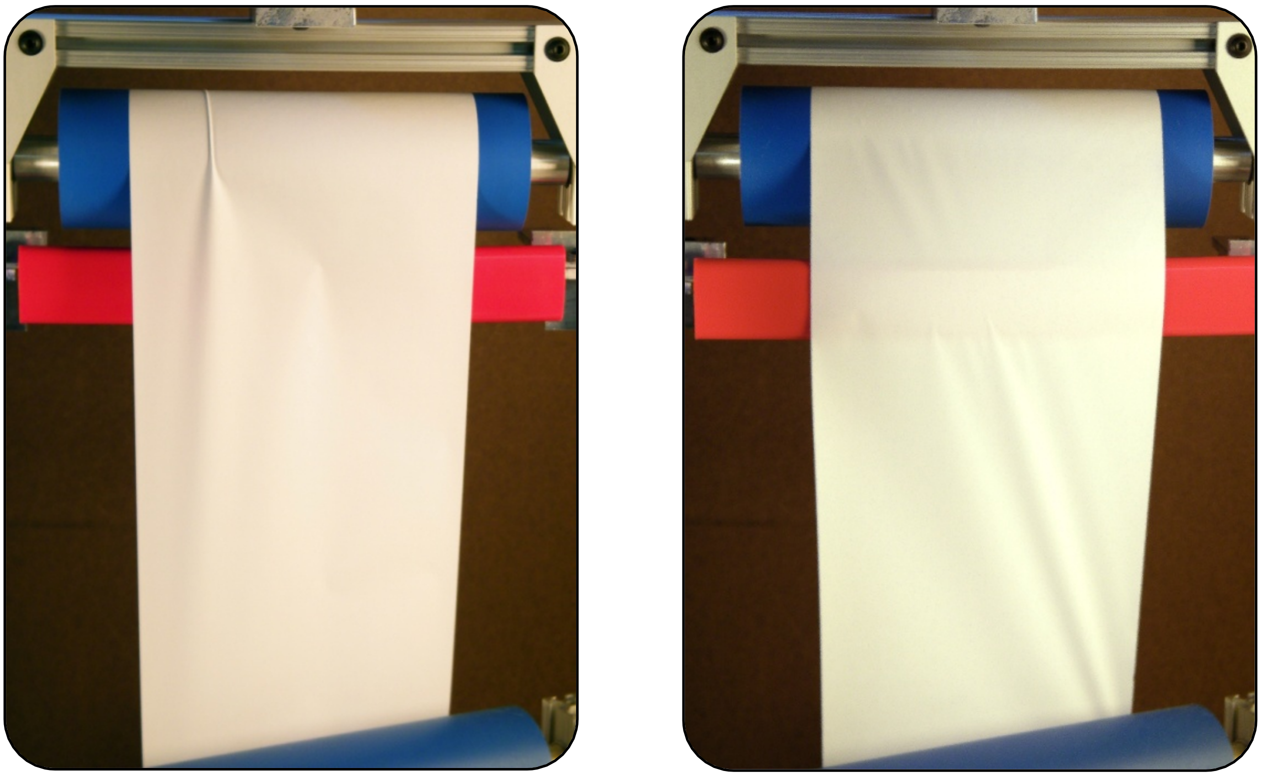


Figure 6
Experimental setup. Twisted web with wrinkle. (D-bar is disengaged)

The web is thermal fax paper. The modulus wasn't measured. But, it is probably in excess of 500,000 psi. The width is 7 inches. Tension is 1 pli. The angle of twist is 21 degrees. The span is 13 ¾ inches. To get uniform wrap on the curved D-bar, the left end extends further into the web than the left. On the right side the extension is 3/4 inch beyond the normal pass line. On the left side the extension is 1 inch. The roller has a radius of 1 ½ inch. The center line of the D-bar is 3 5/16 inch below the centerline of the roller.

A wrinkle is allowed to develop and then the curved D-bar of Figure 4 is moved into the position described above. The results are shown in Figure 7.



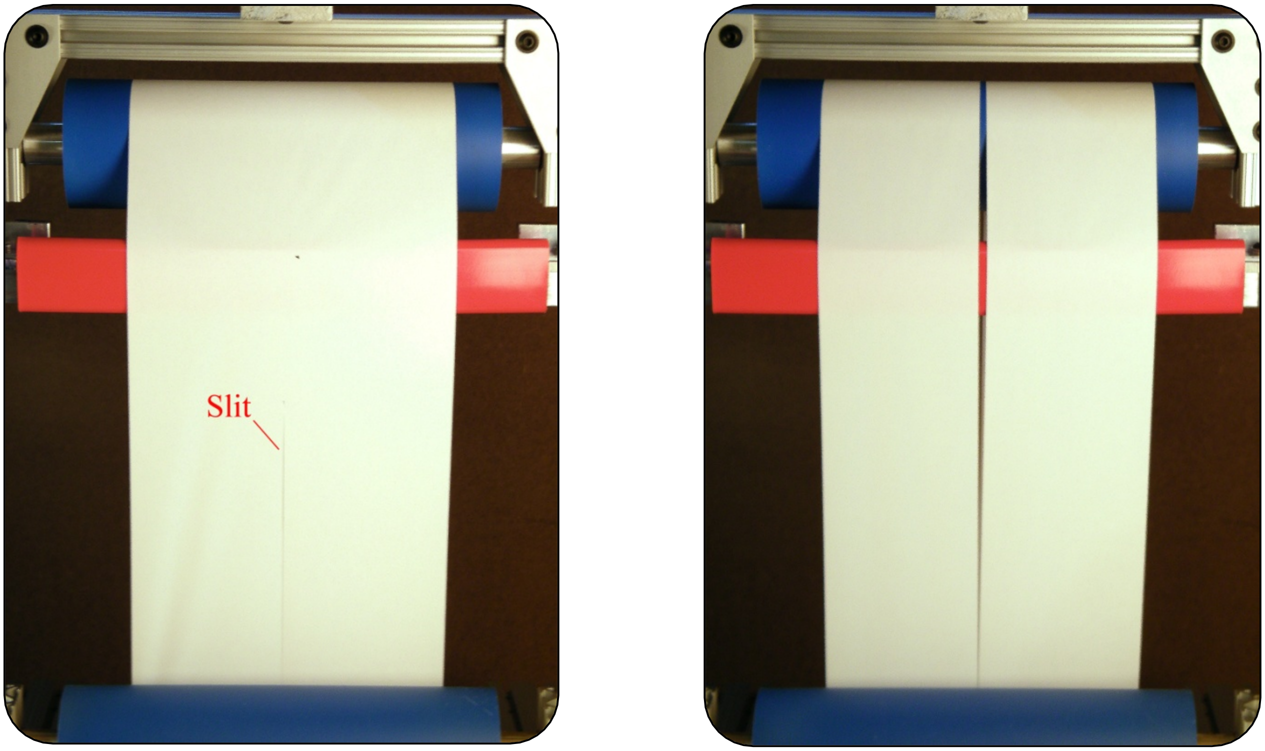
(a) (b)

Figure 7

Spreading of web by curved D-bar . (a) bar disengaged (b) bar engaged

The root cause of wrinkles is known to be compressive (negative) lateral stress. Such stresses are commonly caused by misaligned rollers. Most spreading devices (such as bowed rollers) remove wrinkles by generating positive lateral stress in the span ahead of the roller where wrinkles occur.

A classic test for spreading devices, pioneered by Ron Swanson at 3M, is to slit a web upstream of the spreader and observe whether the two halves separate. The separation is an indication that if the web had not been slit, a positive spreading stress would have been present. Such an experiment is shown in the Figure 8 using a bar with 1/4 inch of bow over 12 inches of length (72 inch radius).



(a) (b)

Figure 8

Spreading by a bowed D-bar.

(a) Slit approaching bowed bar, (b) Fully opened slit after running a while

It's clear that the curved D-bar spreads the web by producing positive lateral stress. FEA modeling, which will be presented further on, confirms this.

A more demanding test is to put the web in a state where wrinkling would ordinarily occur and run the same test. A convenient method for creating wrinkles is to twist the web. Results are shown in Figure 9.

This is a web that would have wrinkled without the bowed D-bar. It had been running long enough to reach a steady state and the bar still opens the slit. So, the positive lateral stress produced by the bar must have exceeded the compressive stress due to twisting.

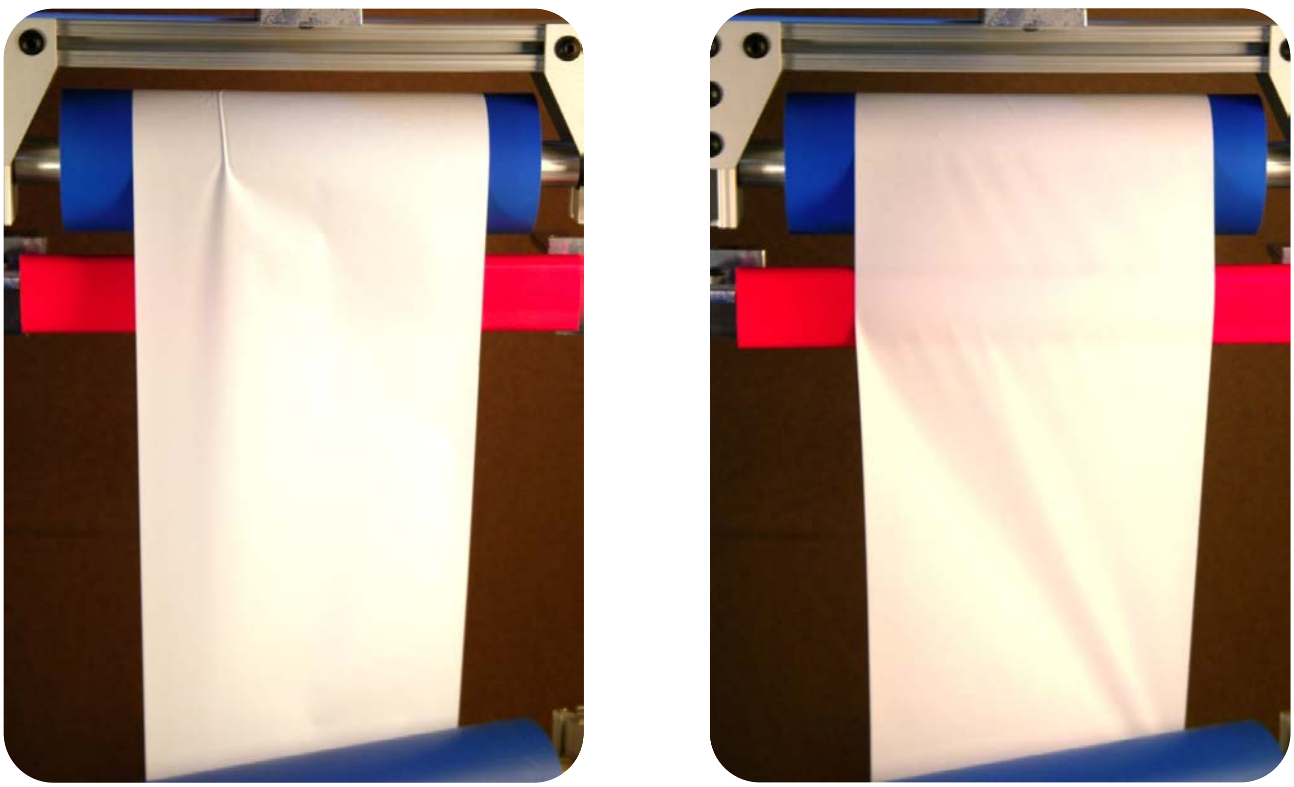
The fact that bowed bars can separate webs is not news. Bent pipes have been used in the paper industry for decades to separate slit webs at the windup of tissue machines.

Figure 9

Bowed bar engaged with a web that is twisted and slit.

Tests with a straight D-bar:

The twisted web test was duplicated for a straight bar. Results are shown in Figure 10.



(a) (b)

Figure 10

Tests with a straight bar (a) Bar disengaged (b) Bar engaged

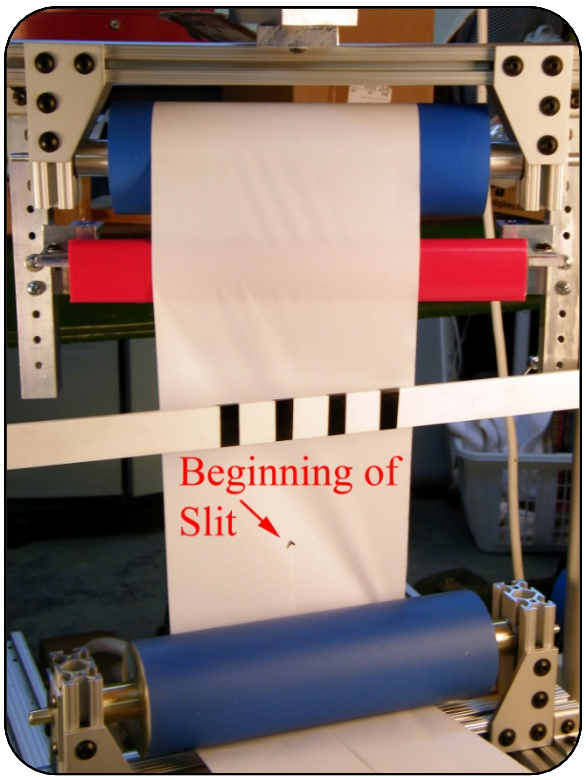
It also eliminates wrinkles.

Note that there are several troughs at the roller in Figure 10(b). But, they are not as deep as the trough in Figure 10(a) or the large trough below the bar in Figure 10(b).

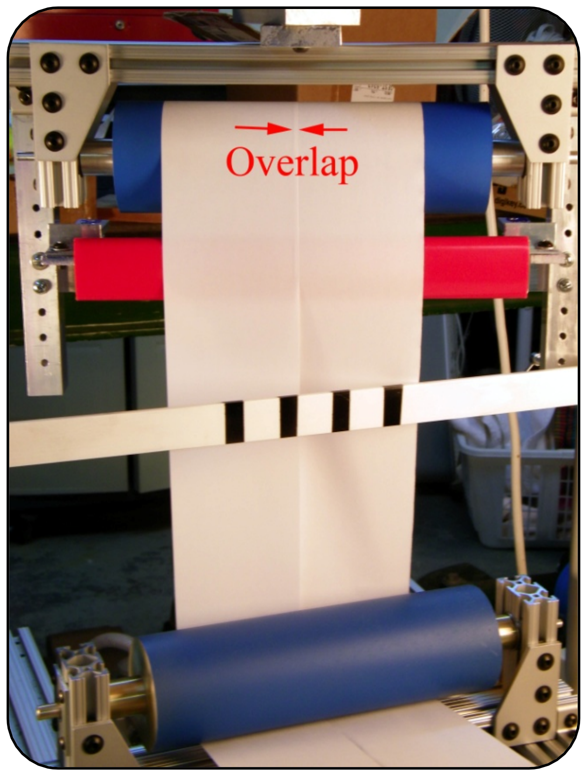
With a straight D-bar it is difficult to see how positive spreading stress would be generated. This issue deserves further investigation.

Does a straight D-bar separate a slit?

Is it possible that the straight D-bar is eliminating the wrinkle because it is somehow producing positive lateral stress? This seems counterintuitive. To answer this question, the Swanson slit test is used again.



(a)



(b)

Figure 11

Slit web test for straight D-bar.

(a) Slit approaching bar. (b) Slit after running several span lengths of web.

The horizontal bar with black markings in front of the web is a camera focusing aid

The straight D-bar failed the slit test. The overlap in Figure 11(a) was continuing to grow when the photo was taken. This indicates that the compressive stress that produced a wrinkle in the absence of the bar was still present. So, the straight bar is not eliminating wrinkles by eliminating the lateral compressive stress.

The relationship between troughs and wrinkles

The photos in Figure 10 and Figure 11 may not seem revolutionary. But, for web handling theorists who study these things in detail, there is something very important in this simple observation that goes beyond any questions about D-bars.

The root cause of wrinkles is known to be compressive lateral stress. In the case of rollers with uniform diameter, the stress develops in the free span ahead of the roller and is transported in the web onto the roller surface. It is also known that giving rollers a slippery surface (low coefficient between the web and roller), will often eliminate wrinkles. The usual explanation for the slippery roller effect is that the low friction permits the web to slip laterally and flatten out under the influence of radial pressure created by the MD tension. [The web in Figure 10, by the way, has very good traction on the roller.] This raises an obvious question. What is it about good traction (high coefficient of friction between a web and a roller) that encourages wrinkles? If it is assumed that it is lateral compressive stress that causes wrinkles in the web on the roller (and troughs in the free span), then why shouldn't the slippery roller effect work the other way around and facilitate wrinkles rather than eliminate them? The answer, which will be explained below, is that when the roller has good traction ***the lateral compressive stress that forms a wrinkle on a roller can become much higher than the rest of the web and is confined to a narrow zone at the location of the trough***. A slippery roller won't allow such nonuniform stress to exist. Without traction, the web flattens, web material is redistributed and the lateral stress falls to a lower average value.

The clue is evident in Figure 10. The bar changes the MD tension very little (based on equation (3) it would be less than 10%). Furthermore, since all the friction is being overcome by the MD motion and the bar is not bowed, there is virtually no effect on the lateral stress. In fact, the lateral compressive stress probably increased because the deep trough that was partially relieving it by buckling was replaced by several shallower troughs. But, the wrinkle on the roller went away. So, there must be a direct connection between troughs and wrinkles.

The connection between troughs and wrinkles has two parts.

In a 1997 IWEB paper titled "Shear Wrinkling in Isolated Spans" by Good, Kedl and Shelton, the authors described the first part. This idea is still discussed a bit among a few web handling experts. But, it seems to have fallen into the category of "interesting ideas that may or may not be relevant". Figure 12 illustrates the concept. This is intended to be only a schematic diagram to convey the basic idea that a trough distorts the lateral geometry of the web in a way that causes material to gather together laterally at the point where the trough and roller surface meet.

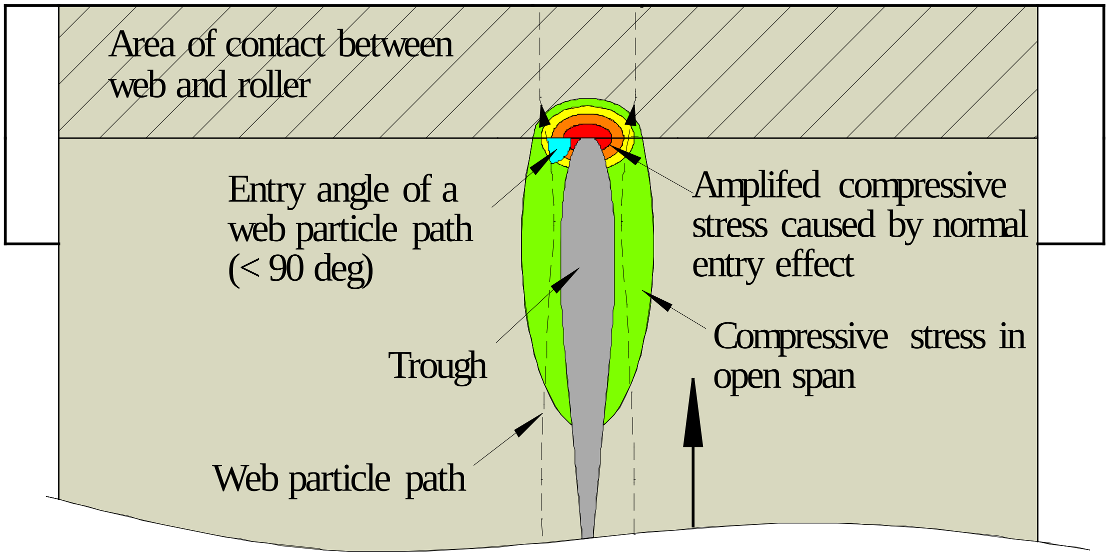


Figure 12
Conceptual illustration of normal entry effect near a trough at the moment of formation

Figure 12 shows a trough at the moment of formation (maybe right after a roller becomes misaligned). The paths followed by individual particles of the web are distorted near the trough, because the out-of-plane displacement in the trough bunches the web together laterally. The lateral distortion is greatest where the trough is deepest. Then, as the web advances onto the roller, it must compress laterally to bring those paths into parallel alignment with the motion of the roller surface (normal entry rule).

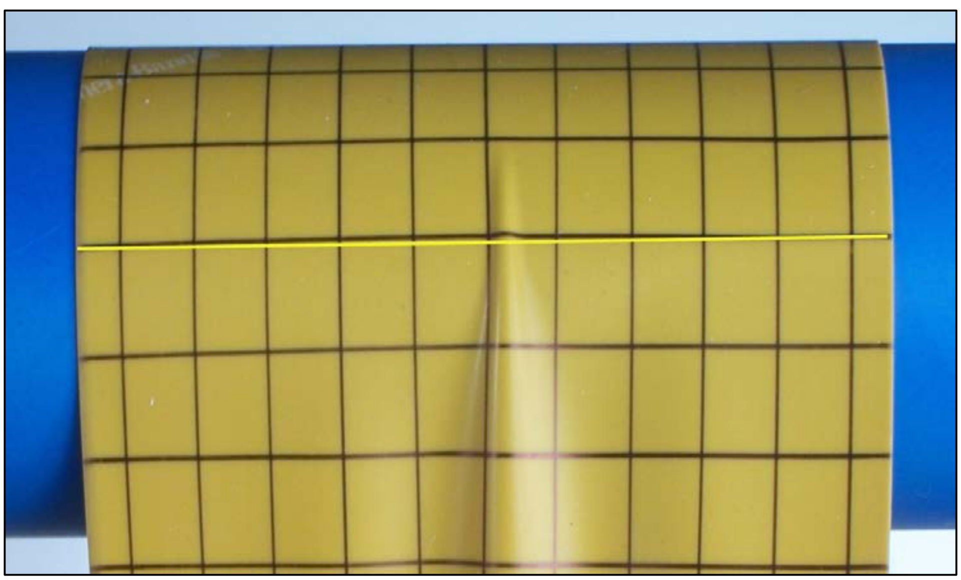


Figure 13
The normal entry effect in the vicinity of a wrinkle (from 2008 AWEB paper)

Evidence of the normal entry effect in wrinkle formation was demonstrated in an experiment with a latex web presented in one of the author's 2008 AWEB papers. One of the photos is reproduced in Figure 13. It shows a web on a roller that was twisted shortly before the picture was taken. A wrinkle is beginning to develop and the horizontal grid lines that were previously parallel with the yellow reference line are curving downward in a triangular pattern with its peak at the wrinkle, as they respond to the normal entry effect.

This phenomenon is only half of the story, though. There is something else happening that is just as significant. It is illustrated in Figure 14.

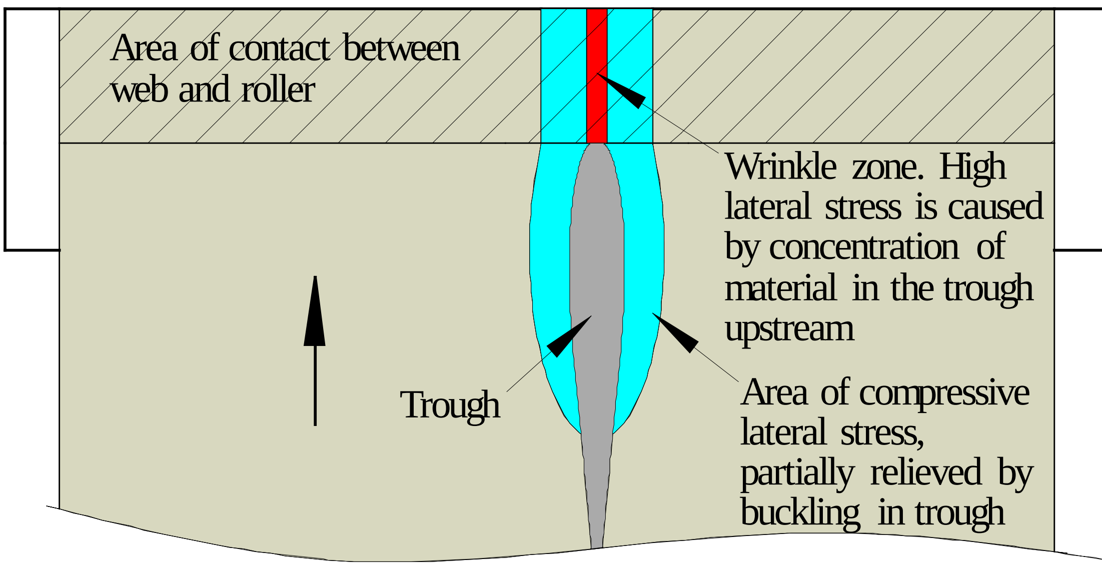


Figure 14

Conceptual illustration of stress concentration on roller caused by gathering of web material into a trough

When a web buckles in a free span, the lateral distribution of web material is altered. If you imagine the mass of a buckled web projected onto a flat surface, the mass per unit width in the troughed areas will be greater than in those that are flat. Then, if there is good traction at the point of entry onto the roller, there is no way for the extra mass in a trough to redistribute itself laterally before it moves onto the roller surface. Furthermore, the normal entry effect, illustrated in Figure 12, concentrates the mass further. So, the lateral compressive stress on the roller, downstream of the trough increases. If the trough is shallow, the pressure of the MD tension may be adequate to keep the web pressed against the roller. But, a deeper trough may channel so much material into the wrinkle zone that the lateral stress increases to the point where the web can't maintain its flat shape. It overcomes the pressure of the MD tension and pops up off the surface. When you observe a trough at the point of entry onto a roller, as shown in Figure 13, the web is clearly in an unstable state just prior to wrinkle formation. It will be seen to be popping up and down on the roller surface.

So, the reason a straight D-bar like that in Figure 10 eliminates wrinkles is that it reduces the lateral concentration of material in troughs by keeping them shallow.

Where should D-bars be located for best results?

For a straight bar that is being used to flatten troughs, it is obvious that the bar should be in close proximity to the roller where the wrinkles are to be eliminated. The only restriction is that it should not be so close that the angle, ϕ_2, in Figure 5 becomes greater than half the maximum angle of wrap, 18.4˚.

For curved bars, FEA analysis is a good way to provide insight. Two cases will be examined. One will place a bowed D-bar close to the downstream roller. The other will place the bowed D-bar half way down the span. The application parameters are,

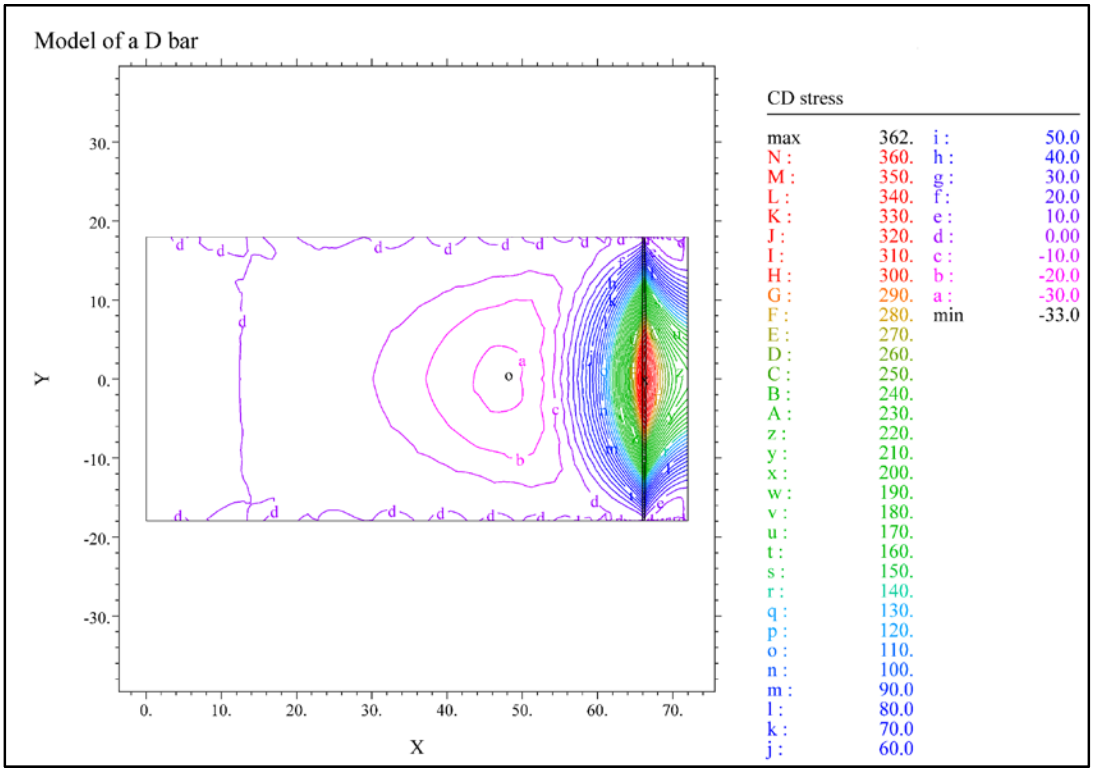
Span length: 72 inches	Web width: 36 inches
Web thickness: 0.001 inch	Web modulus: 500,000 psi
Tension: 1 PLI	Bar height at ends: 0.5 inch
Bar height in center: 0.75 inch	Coefficient of friction: 0.2

The plot in Figure 15 shows, as expected from the photo in Figure 9, that a bowed D-bar near a downstream roller can produce positive (spreading) CD stress at the roller.

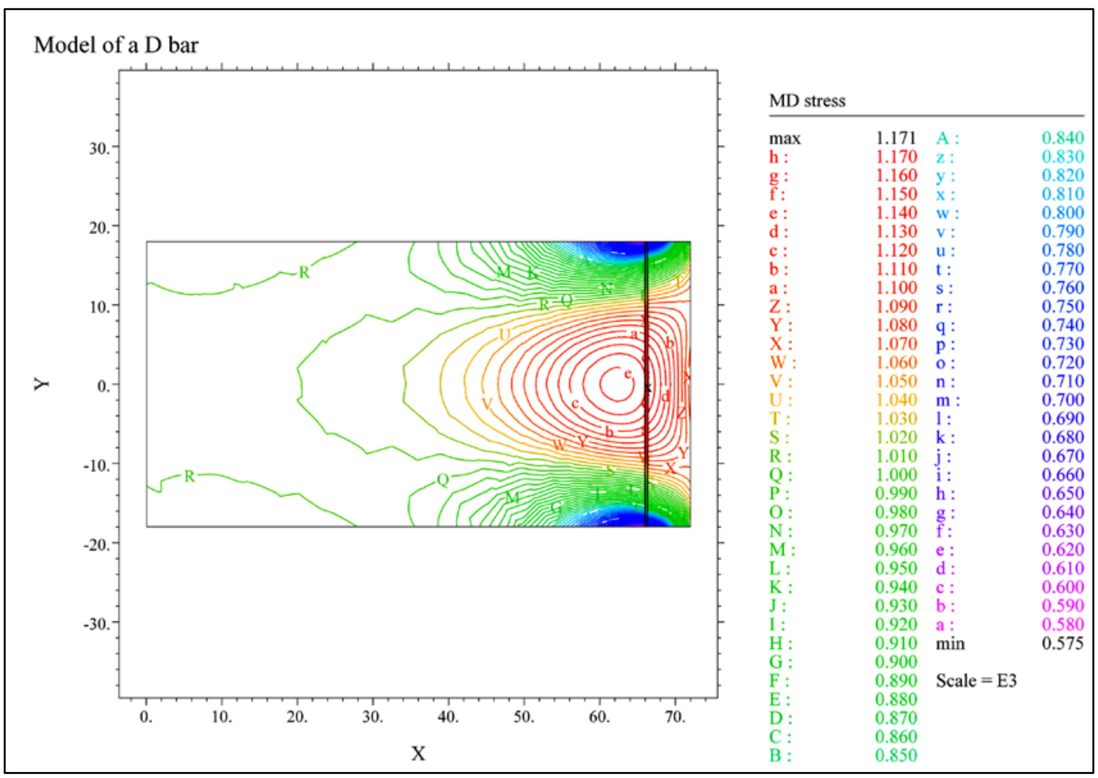
In Figure 16, with the bar half way down the span, the spreading stress dissipates after the bar and a small negative (compressive) CD stress has developed at the downstream roller.

In both cases, the MD stress has behaved as expected – increased in the center of the web and decreased at the edges.

So if wrinkle removal is the objective, a D-bar, flat or bowed, should be positioned close to the roller where the results are desired.



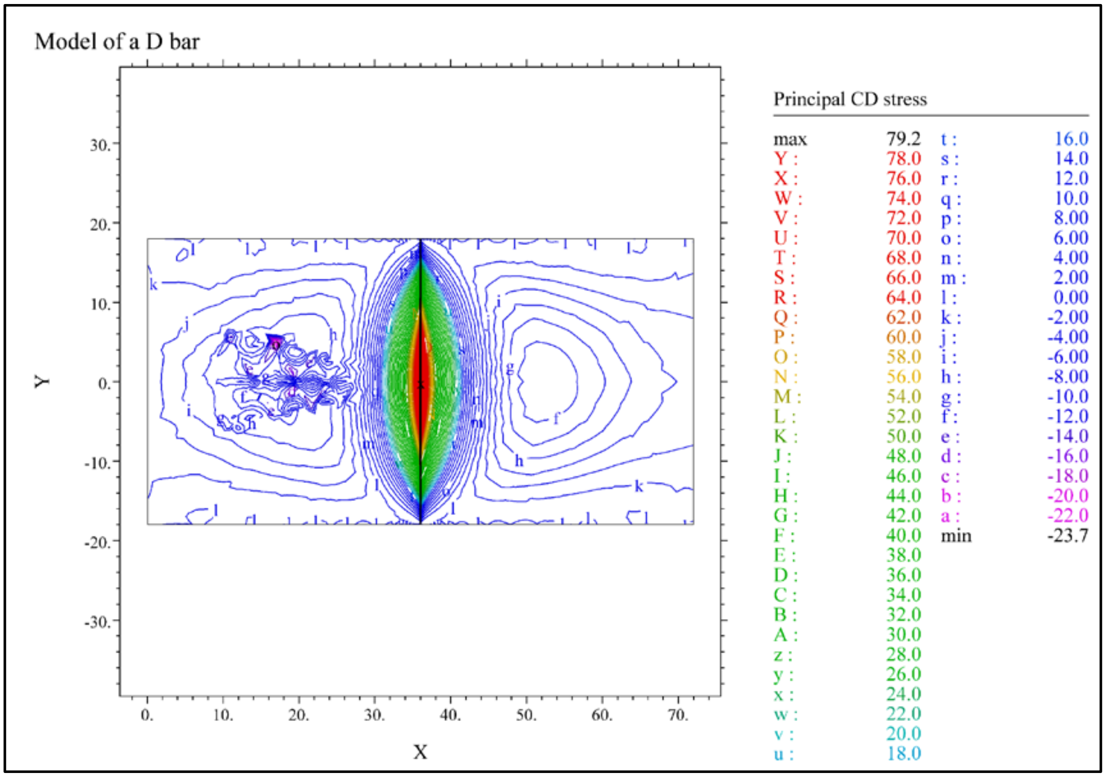
(a)



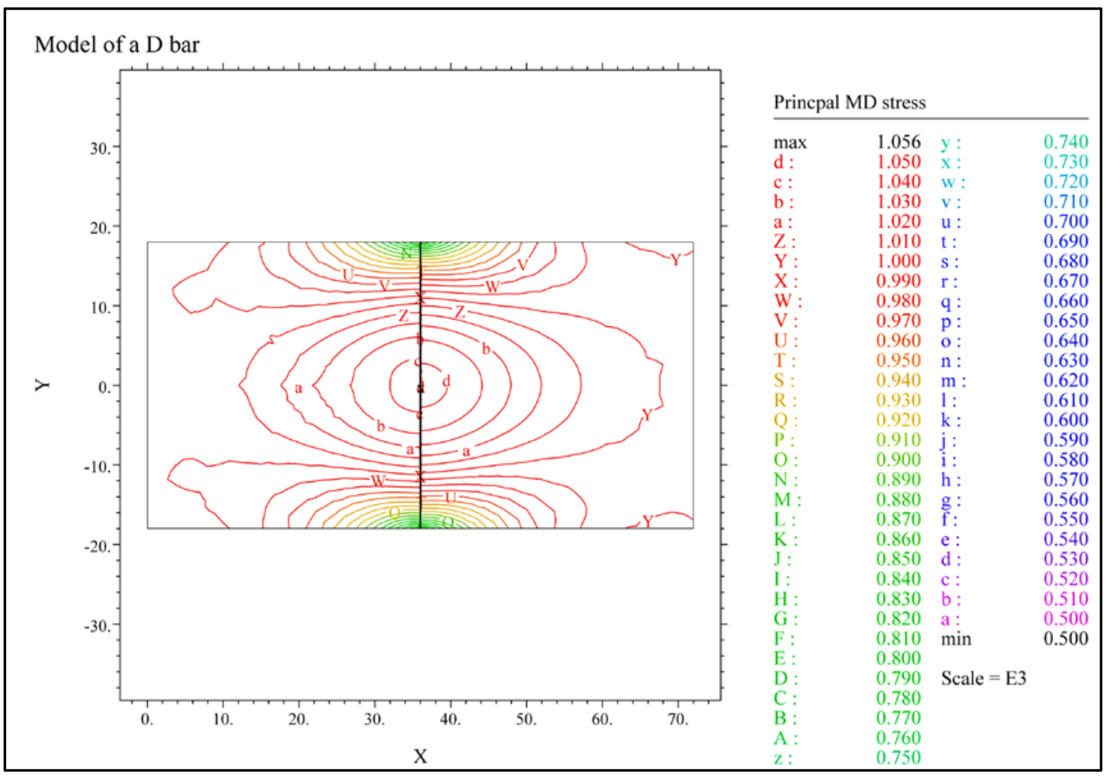
(b)

Figure 15

Stress contours with bowed D-bar positioned 6 inches from downstream roller



(a)



(b)

Figure 16

Stress contours with bowed D-bar positioned mid-span
(a) CD stress (b) MD stress

Bowed rollers as D-bars:

Anyone who has been in converting plants has probably seen bowed rollers with the bow oriented so that they cannot be functioning as intended (they may not even be rotating). This could be helping to solve a baggy web problem. But, based on the forgoing discussion, it is quite possible that the line operator has discovered through trial and error that a non-rotating or slipping bowed roller can be used as a D-bar spreader.

S-Wrapped rollers as wrinkle preventers:

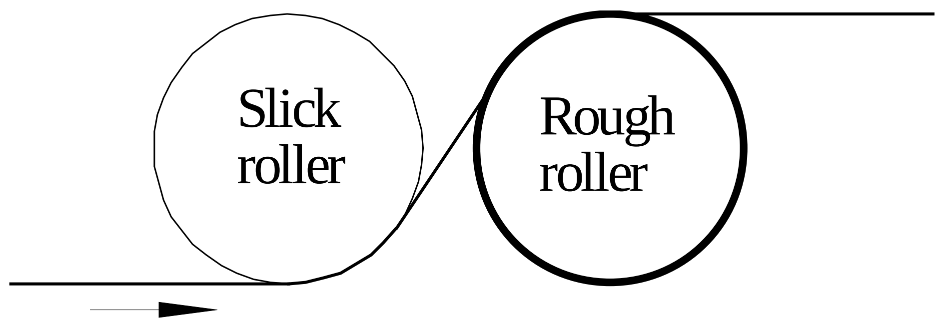


Figure 17
Using a slick roller to prevent wrinkles.

An arrangement like Figure 17, where two rollers are close together may occur for reasons having nothing to do with wrinkling. But, it is useful to bear in mind that the risk of wrinkles can be minimized by reducing traction on the one upstream. An S-wrap will minimize the span length available for trough formation.

The effects of air entrainment:

It is possible that at high speeds, where air entrainment is a factor, that a D-bar could used ahead of a vented roller with good results. The D-bar would have the benefit of air lubrication. However, there are two caveats to this suggestion. One is that it must be remembered that the velocity term in the foil bearing equation will be half that for a roller that is turning. The other is that the air film on the bar may get thick enough that troughs are not flattened effectively.

Venting and air lubrication for D-bars is an area that deserves investigation.

Conclusions:

1. Do D-bars really spread webs? Yes
2. Do bowed D-bars produce positive CD spreading stress? Yes
3. Do straight D-bars spread webs and if so, how? Yes, they reduce the depth of troughs.
4. Are there side-effects to be avoided? Drag and scratching. Vendors should explore better materials and the possibility of air lubrication.
5. Where should D-bars be located for best results? Near the roller where results are desired.
6. Do their effects persist very far downstream? No.

7. How much bow is needed? Very little. In fact, you may not need any at all to eliminate wrinkles. Adding bow may make it possible to have a smaller wrap angle (smaller z in Figure 5) and thus less drag. Bow is, of course, also useful for helping with a baggy center.