A NONLINEAR FINITE ELEMENT MODEL FOR WEB SPREADING

by

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1. Abstract

This study concerns the modification of a commercial finite element code (ABAQUS) to efficiently model webs moving over stationary, frictional guides. This modification will allow the user to refine the mesh in areas of interest (i.e. in the contact zone) while using a coarser mesh in other areas. The model was used to investigate web spreading using three different geometries - a straight bar, a bowed in-plane bar and a bowed out of plane bar (D-Bar). The effects of the Poisson ratio of the web and friction on web spreading will be investigated.

2. Introduction

The modeling of the mechanics of continuous webs is important to a variety of industries, including paper and film manufacturing, converting applications, belt drives and magnetic tapes. Due to an almost infinite variety of imperfections in web materials, tension distributions, roller alignment, temperature and moisture uniformity, etc., wrinkles often form to relieve in plane compressive stresses. Non-flat webs lead to non-uniform coating and imaging, winding defects, web breaks and other undesirable results. Designers often employ spreading devices to remove wrinkles before critical applications such as coating or winding.

From a design point of view, it would be desirable to model the spreading process in order to compare and contrast different spreader designs. Our modeling techniques need to account for the large deflections of the web itself, along with the contact and friction interactions between the spreader bar and the web. Nonlinear finite element techniques (NFEA) have been applied to a variety of web handling applications but have lacked the ability to include the actual *motion* of the web efficiently. This paper will present a modification to the friction algorithm in ABAQUS (Hibbitt, 1997) that will allow us to model the web transport process in a more efficient way. This study will focus on stationary spreader bars, but future work will include rolling spreaders as well.

A number of other authors have investigated the mechanics of web transport with applications to wrinkle control and spreading. Roisum (1993) provides an excellent overview of a variety if spreading techniques, along with explanations for the mechanics of many different spreading devices. Delahoussaye and Good (1993a, 1993b) developed a model for spreading using rolling guides that assumed no slip occurred between the web and roller. Dobbs and Kedl (1995) investigated wrinkling in webs using linear plate theory and Benson et. al. (1993) used a specialized nonlinear finite element model to investigate wrinkling in exceedingly thin webs.

3. Eulerian versus Lagrangian Modeling Techniques

The vast majority of commercial finite element programs on the market today have been written for structural analysis. They were not intended to model continuous, i.e. "endless" belts, webs, etc. Although some of these programs can model large deflections, contact and friction, they are ill suited for situations such as web handling.

Figure 1a shows how a typical NFEA package would model a web transport problem. As the web moves over the guide, the nodes and elements of the finite element mesh will move with the web. This is called a Lagrangian reference frame, i.e. a node corresponds to a given material particle and the node itself will move with the subsequent motion of the body. For a structural analysis problem, it is a convenient description of the mechanics and one that is straightforward to implement.

For web handling problems however, this is often not the case. If our goal is to model continuous webs, the Lagrangian approach is inconvenient. In Figure 1a we see that because the mesh will move with a given material particle, two undesirable effects will occur. The first is that we will need an extraordinarily long and detailed mesh. Normally, we need to actually mesh the entire length of the web even though our area of interest (the area near the spreader in this case) is quite small when compared to the total amount of web. Therefore solution times will be quite excessive and will make the technique almost impossible to use for design purposes. The second inconvenience is that nodes will keep coming into and out of contact. This often leads to numerical chattering and will also impact solution time and robustness.

Figure 1b shows an Eulerian implementation of the same problem. Here, the mesh stays stationary and the material "flows" through it. The mathematical details of the method are beyond the scope of this paper, so only the method will be described here. The interested reader is encouraged to consult Stack (1997). For a stationary spreader bar this can be achieved by knowing that each point on the web that is in contact with the spreader bar is in a state of slip. We can compute the local direction of motion of a given point on the web by knowing the deformation gradient, i.e. the total deformation from both the rigid body rotation of the web and any straining effects that might have occurred. The details of the deformation gradient and its computation are left to the reader. Bathe (1982) The deformation gradient maps the undeformed coordinate system to the deformed coordinate system, and because we know the initial, undeformed shape of the web we can track the local direction of motion as the web deforms. As the web undergoes both rigid body motion and deformation, both of these effects on the local motion direction are account for.

From a modeling point of view this means that we can model the web without having to actually move the nodes. The nodes stay stationary while the local motion direction changes based upon the deformation of the web itself. Once the local direction of motion of the web is known, its unit vector is dotted with the local slip direction on the spreader and the appropriate friction force is applied along its direction. This method allows the user to refine the mesh around the contact zone while using a coarse mesh in areas that are not of interest. This study will assume a known back tension and the front of the web will be pinned to simulate a far fiend boundary condition. Due to symmetry we only need to model half of the web and we will assume that the bars to not deform. The results published in this study are steady state values and take approximately one hour to compute on an HP 735 Apollo workstation.

4. Straight Bar

This section will detail the mechanics of an elastic web moving over a straight, frictional bar. Although we would not normally use a straight bar as a spreader roller, this section will give us insight into the interaction between a web and a stationary bar. The web is first tensioned and then wrapped over the guide using a nominal tension of 2 pli. Figure 2 shows the mesh for the web being wrapped over the guide. The mesh is extremely dense in the contact region due to the relatively small diameter of the bar when compared with the total length of the web. Figure 3 shows the machine direction (MD) tension in the web with a friction coefficient of 0.5. We see a significant increase in the tension on the upstream side of guide while the back side (downstream) tension remains at the nominal value. We know from the belt wrap equation that for a 1D "string" these tensions will be related by the equation

$$T2 = T1 * \exp(\mu\theta) \tag{1}$$

where T1 is the nominal tension, T2 is the upstream tension, μ is the friction coefficient and θ is the wrap angle.

However, from a spreading point of view we are more interested in the cross direction tension (CD) rather than the MD tension. Figure 4 shows the cross direction tension in the web. The element lines have been removed to make the plot easier to read. We see that even though the bar is straight, we in fact generate a cross direction tension. This is due to the Poisson ratio of the web material. The tension in the web will create "necking" in the material due to the Poisson effect. Because the tension will change along the length of the web, so will the local necking behavior. As a particular particle travels through the system, it's path will no longer be aligned directly with the machine direction. As particles along the web "neck in" as they approach the high tension side, the friction forces from the bar are working in the direction opposite to their motion, which in turn causes resultant spreading forces. Even though this deviation from the machine direction is quite small, it is enough to generate some CD tension.

The necking of the web causes the spreading effect on a straight bar, and therefore is controlled by the Poisson ratio of the web material. Figure 5 shows the cross direction tension for a web with a Poisson ratio of 0.45. If we compare Figure 4 with Figure 5, we see that almost twice the amount of cross direction tension is generated with a Poisson ratio of 0.45 than with 0.25. We would expect that webs that have higher Poisson ratios would be somewhat easier to spread than those with lower Poisson ratios.

Figure 6 shows the relationship between friction, Poisson's ratio and spreading force. Because we are using a symmetric model, the bar will feel a net load in the z direction. If we had modeled the entire width of the web, this force would equilibrate to zero. To compare and contract effects however, this net spreading force is quite convenient. We see that as the friction coefficient is increased from 0.0 to 0.5, the net spreading force increases quickly. If tension were increased, this spreading force would also be increased due to the increase in pressure between the web and the bar. If the Poisson ratio of the web were zero, then no spreading would occur due to the lack of necking in the web. Note also that a small amount of compression is seen on the rear edge of the bar.

5. In-Plane versus Out-of-Plane Bowed Bar (D-Bar)

The first actual spreader bar geometry we will investigate will be an in-plane bowed bar, as shown in Figure 7 . Although this geometry is normally seen as a spreader roller (i.e. the surface of the bar actually rotates) it has also used in a stationary configuration. The Poisson ratio of the web material is 0.25, the friction coefficient between the web and the bar will initially be set to zero and we will again use a tension of 2 pli. The bend radius of the bar was 500 in and the diameter was again 2.5 inches. Figure 9 shows the cross direction stresses that are developed in the web. Note that the maximum CD stress is only 19 psi. When the friction coefficient is increased to 0.5, the CD stress rises 39 psi. Figure 10 shows the total spreader force and we again see that the curve looks very similar to that of Figure 6. This small increase in CD stress over the straight bar would not warrant the use of an in-plane bent bar.

Figure 7 also shows the geometry of the out-of-plane bowed bar, or D-Bar. The D-Bar is a popular method for inducing spreading because it is not as complicated as rolling spreader devices and it's shape can be changed depending upon the particular web material. We have used a crown of 0.1 inches for this study. Figure 11 and Figure 12 shows the MD and CD stresses respectively for the D-Bar geometry given in figure with the friction coefficient being taken as 0.0. We see that the shape of the D-Bar leads to a large change in the MD stress with the higher stress occurring in the center of the web and dropping off towards the edge. The CD stress has now become 155 psi, which is an order of magnitude larger than the spreading stresses resulting from the straight or the in-plane bowed bar.

Figure 13 and Figure 14 again show the MD and CD stresses, but this time with a friction coefficient of 0.5. The MD stresses on the front side of the bar are now higher due to friction. The CD spreading stress now increases from 155 psi to 182 psi. Note also that the "spread" region has moved forward slightly due to friction.

Figure 15 shows the spreading force for the D-Bar. Note that it is much larger than that of the previous examples. The D-Bar configuration is clearly superior to that of the in-plane bowed bar and the friction coefficient, although not the dominate effect, is important in determining the CD spreading tension.

6. Conclusions

A new method for modeling the motion of webs in contact with stationary bars has been presented. The model allows or the efficient computation of such problems by using a modified friction algorithm to account for the motion of the web. Although the mesh does not actually move, the appropriate friction loads are applied to the web. The model was used to investigate web spreading using three different bars - straight, bowed in-plane and bowed out of plane bar (D-Bar). Poisson's ratio causes a small amount of spreading, even when a straight bar is used. The D-Bar was shown to be the most effective geometry for spreading, and friction was shown to have an effect on the maximum spreading stresses.

7. References

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8. Acknowledgements

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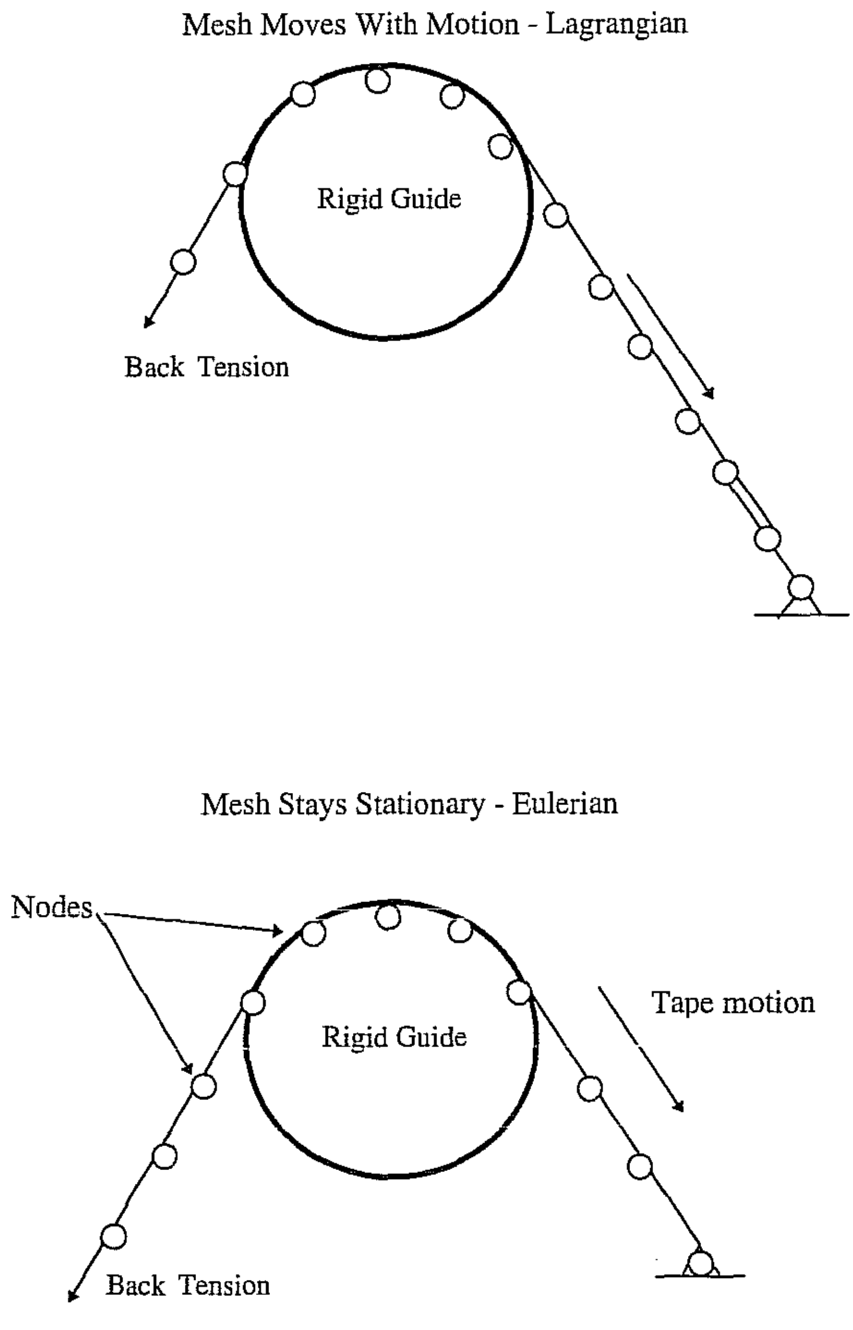

Figure 1 Lagrangian versus Eulerian Motion

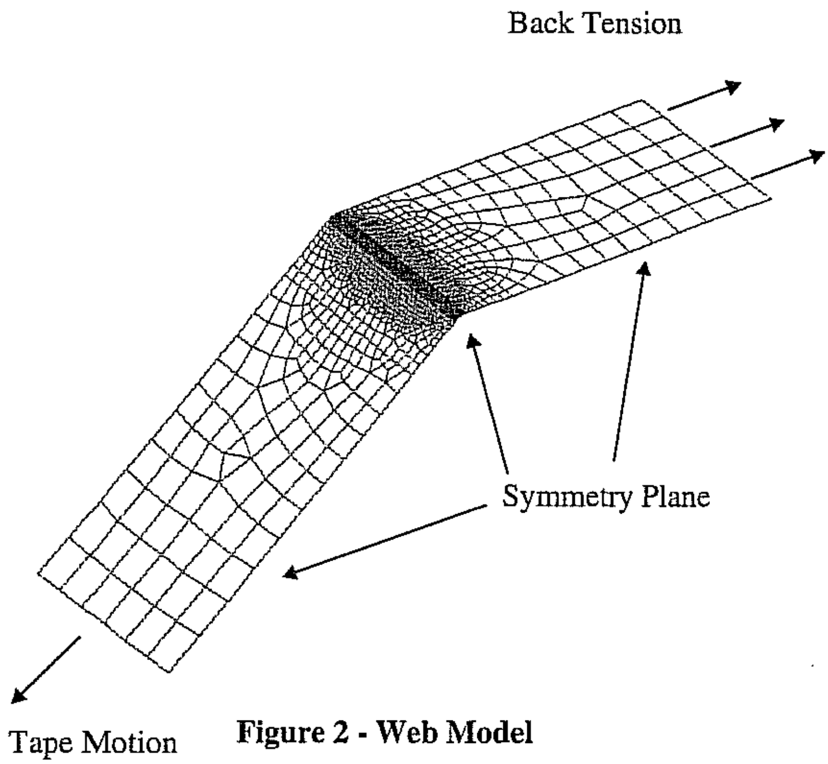

Figure 2 - Web Model

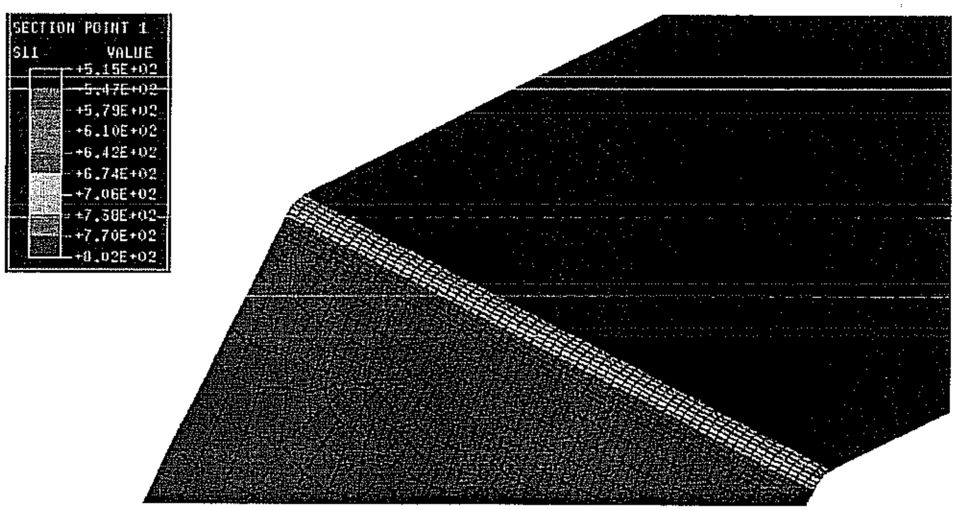

Figure 3 - MD Stress Increase Due to Friction

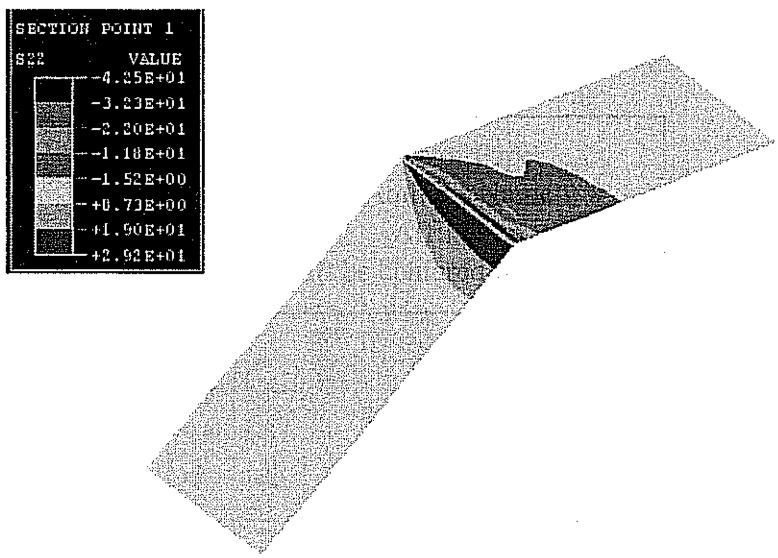

Figure 4 - CD Stresses - Straight Bar Poisson Ratio = 0.25

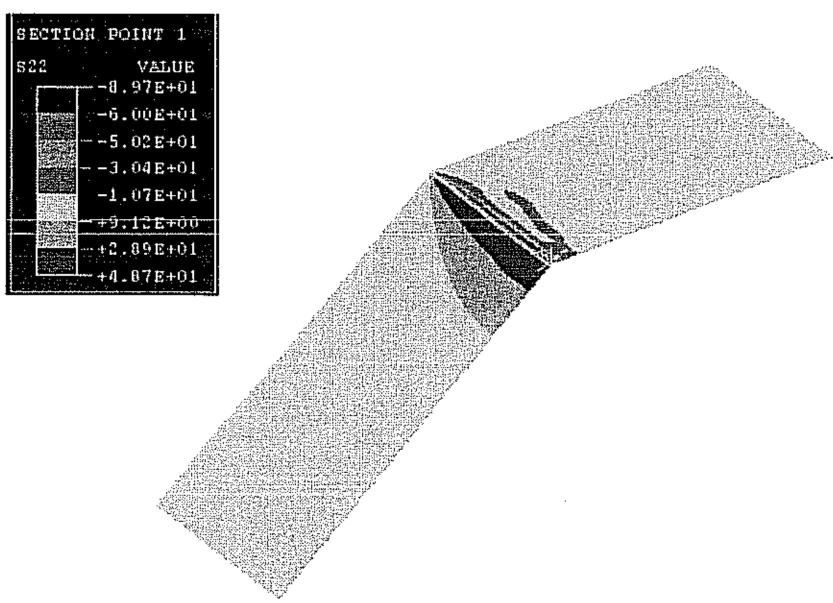

Figure 5 CD Stresses - Straight Bar - Poisson Ratio = 0.45

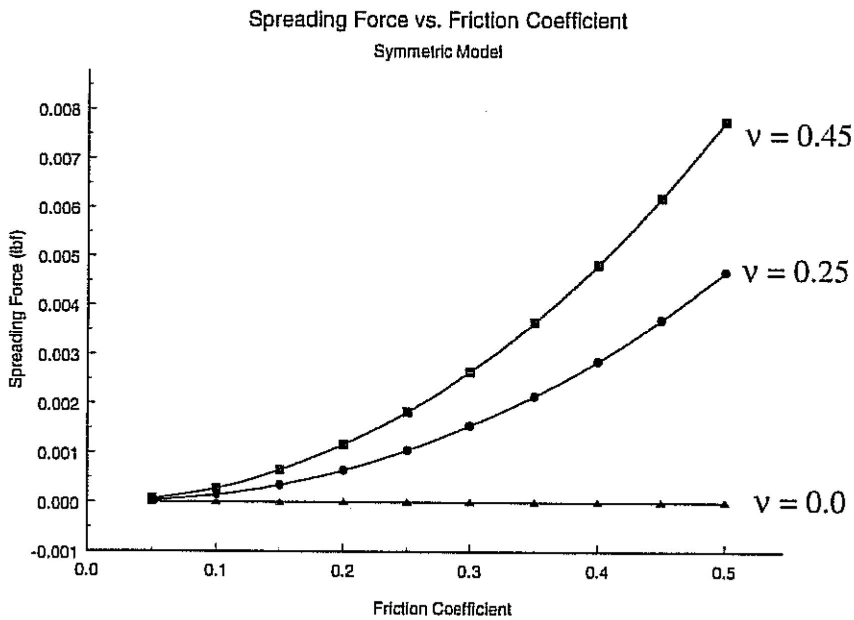

Figure 6 - Spreading Force - Straight Bar

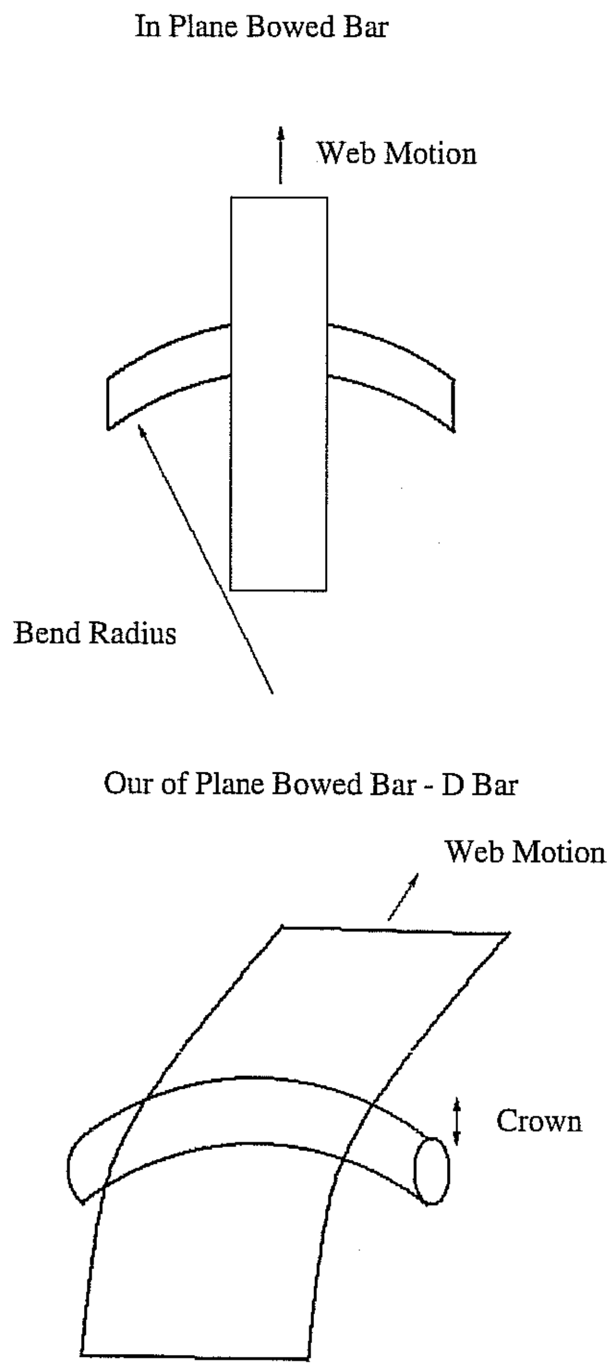

Figure 7 - Spreader Geometries

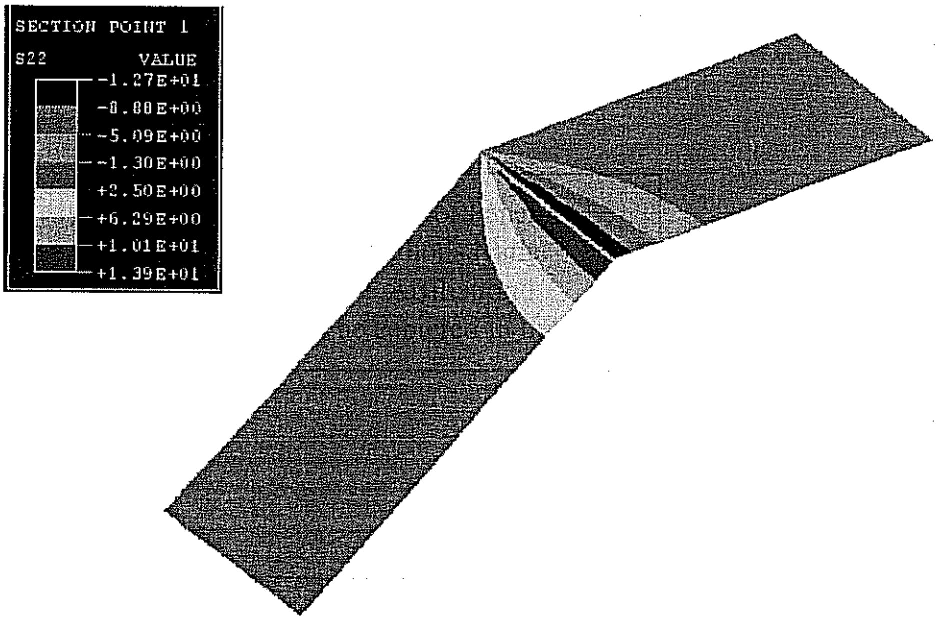

Figure 8 CD Stresses - In Plane Bowed Bar- Friction = 0.0

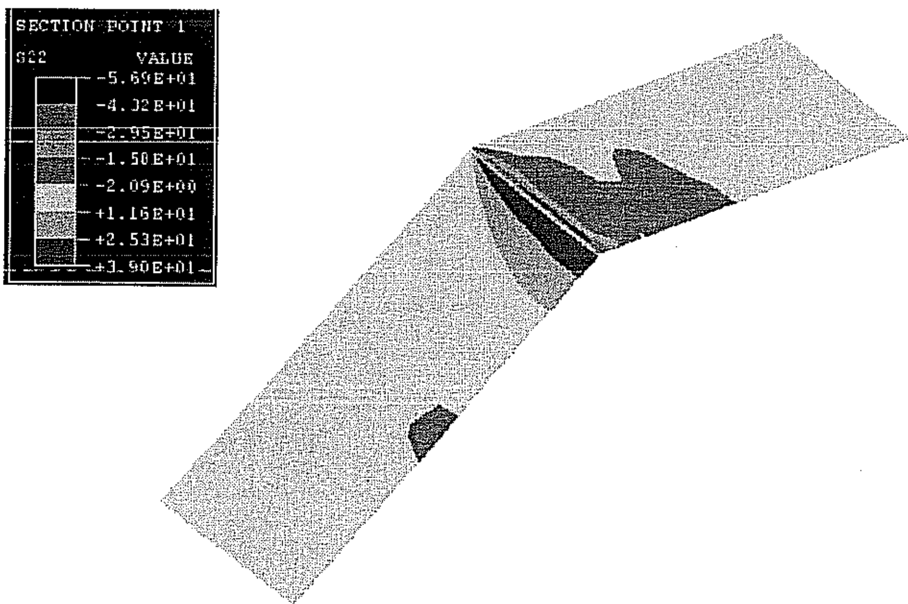

Figure 9 - CD Stresses - In Plane Bowed Bar - Friction = 0.5

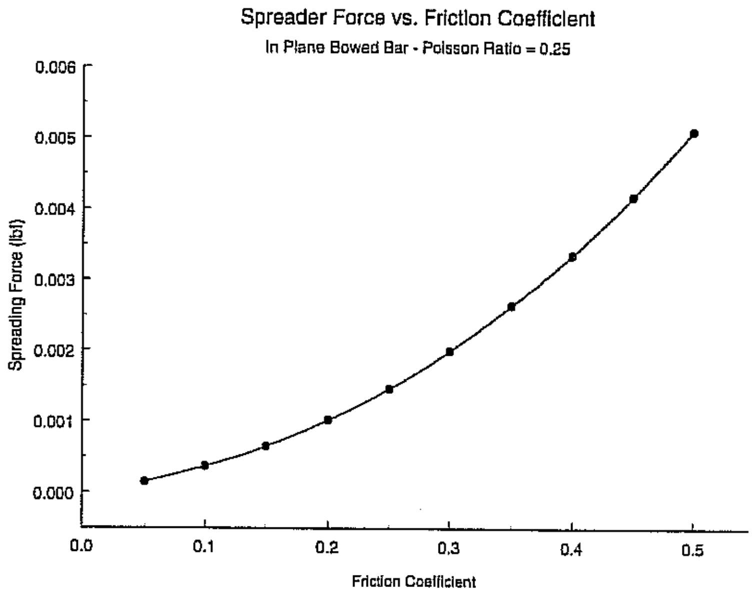

Figure 10 - Spreader Force In Plane Bowed Bar

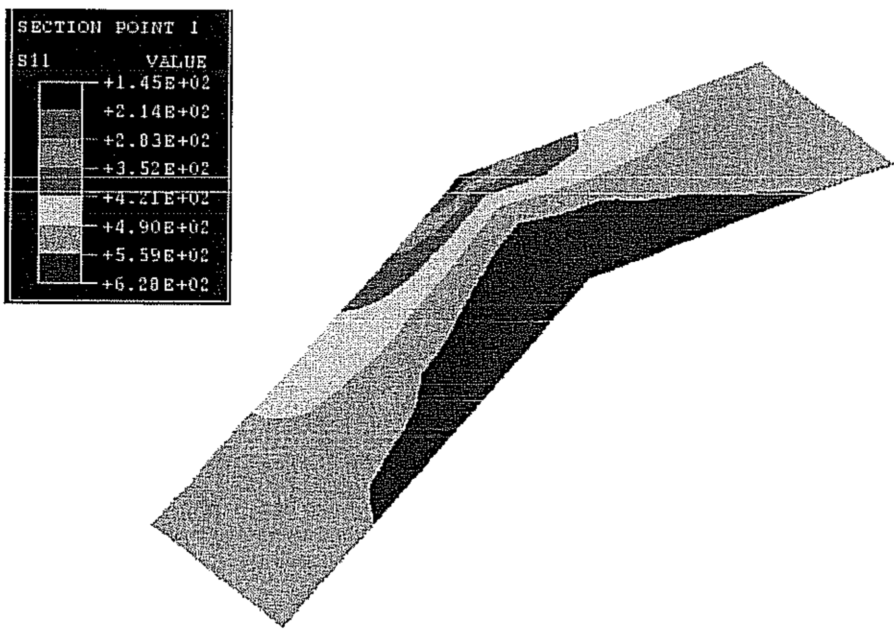

Figure 11 - MD Stresses - D-Bar - Friction =0.0

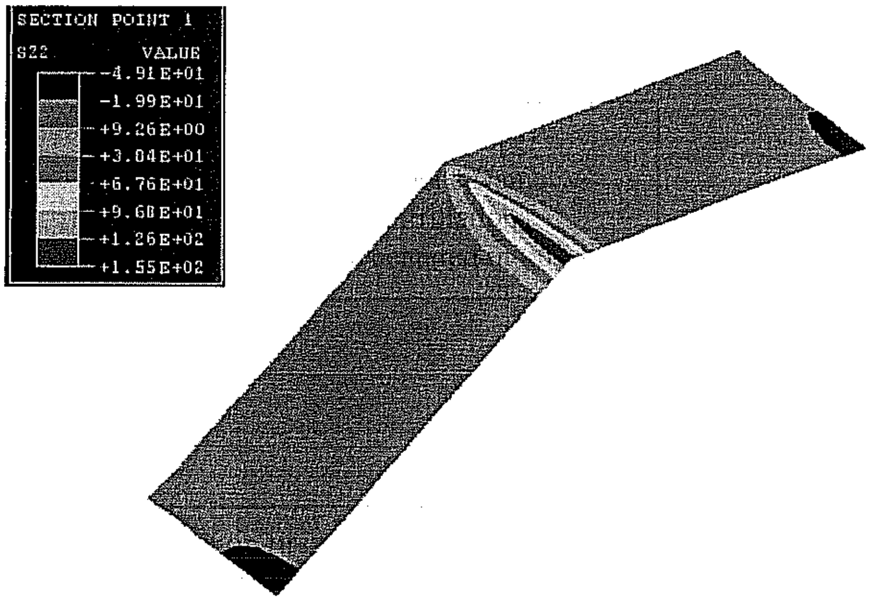

Figure 12 CD Stresses - D-Bar - Friction = 0.0

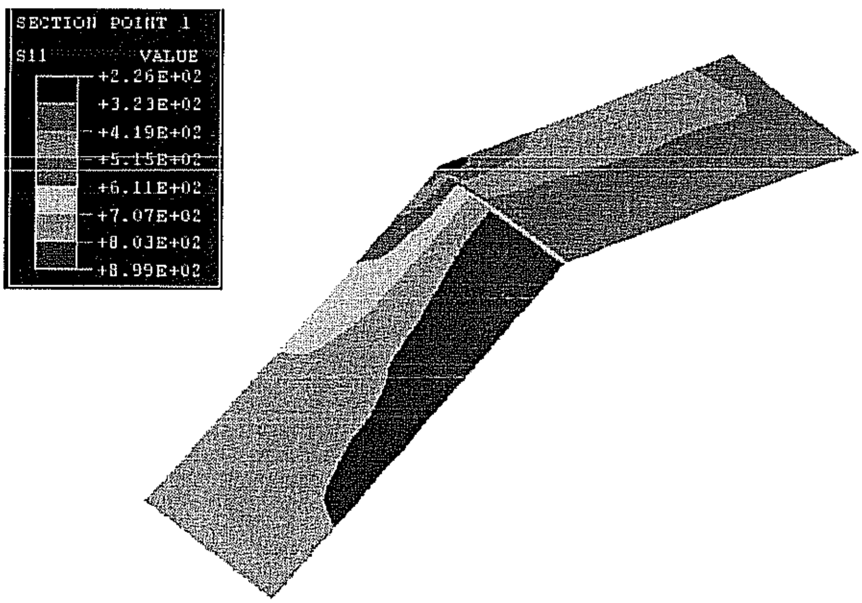

Figure 13 - MD Stresses - D-Bar - Friction = 0.5

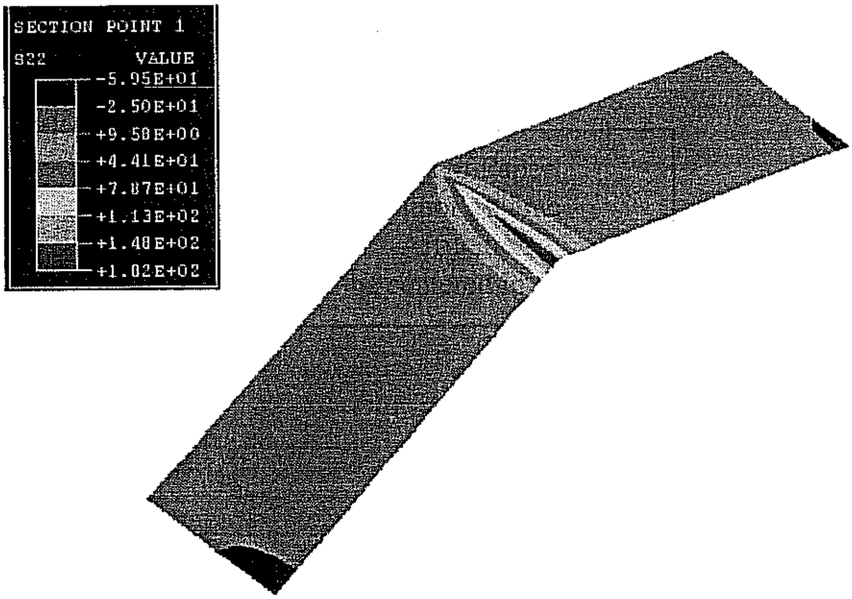

Figure 14 - CD Stresses - D-Bar - Friction = 0.5

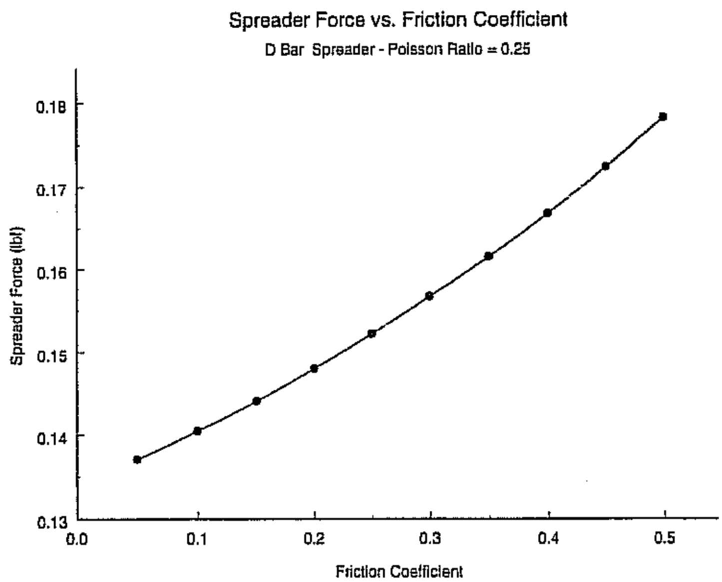

Figure 15 - DBar Spreading Force - Poisson Ratio = 0.25

Question - What kind of elements did you use for the web model?

Answer - Good Question, we used both S4r and S4r5 for those of you who don't know, cause there are a lot of shell elements. The hardest part of this simulation isn't doing the motion mechanics which is actually wrapping the web over a nonstraight guide. For those of you who have tried it, know that it is quit a challenge sometimes. Depending upon the simulation of the tension levels we can use S4r or S4r5 we can reduce, which are a little more robust, but you have to watch the lower tolerances on the hour glass differences. If you can get these to work they are a little more efficient.

Question - Are you comptiplating in the near future or looking at materials that are highly orthotropic like paper?

Answer - Most of the work we do is on polymer web or magnetic tapes. We do a lot of work for thermo printers which are not orthotropic but doing orthotropic webs is a 10 minute work change.

Question - In your nonrotating bars of the web do you allow it to displace?

Answer - Absolutely.

Question - Do the numbers agree with some of the theories that are available

Answer - We verified the model, using a laser sensor and tape guide and measured how far it moved. For stationary guides the tape doesn't move as far as the rolling guides. I don't know that we ever correlated the "D" non rolling guide displacement, but we did correlate the moving guide. That it worked out very well.

Question – What's the influence of the elastic or plastic properties (stiffness) of the web? Did you calculate that?

Answer - In terms of running different materials for a given tension or something like that, no we didn't have time to do that. The biggest effect would be in softer webs, this would be easier to spread cause they could strain more. But I haven't tried that.