AIR SUPPORT CONVEYANCE OF UNIFORM AND NON-UNIFORM WEBS

by

Ronald P. Swanson

3M Company
St. Paul, Minnesota

ABSTRACT

A web span model and solution technique have been developed to determine the stresses and deflections of uniform and non-uniform webs, subject to side loading from an air support system. Formulas are given to calculate the magnitude of these side forces. An experimental air support system was used to verify the model, and serves as an example to determine the cause of lateral displacement problems.

NOMENCLATURE

Var.		Description	Units
A	=	Area	m^2 ($in.^2$)
a	=	Web Sine Wave Amplitude	m (in.)
b	=	Beam Width (Web Thickness)	m (in.)
C_0	=	Nozzle Force Coefficient (Zero)	N (lbs)
C_1	=	Nozzle Force Coefficient (Slope)	N/m (lbs/in.)
C_d	=	Drag Coefficient (Induced Drag)	Dimensionless
C_f	=	Drag Coefficient (Skin Friction)	Dimensionless
E	=	Modulus of Elasticity	KPa (psi)
e	=	Web Eccentricity	m (in.)
F	=	Shear Downstream Roller Exerts on Web	N (lbs)
g	=	Gap Between the Nozzle and Web	m (in.)
h	=	Beam Height (Web Width)	m (in.)
I	=	Moment of Inertia	m^4 ($in.^4$)
k	=	Constant from Shelton [6]	1/m (1/in.)
K_i	=	Stiffness Matrix Constant	N/m (lbs/in.)
L	=	Beam (Span) Length	m (in.)

M	=	Moment	N-m (in.-lbs)
M_0	=	Virtual Moment of Cambered Web	N-m (in.-lbs)
M_L	=	Moment Downstream Roller Exerts on Web	N-m (in.-lbs)
r	=	Radius of Cambered Web	m (in.)
Re	=	Reynolds Number	Dimensionless
T	=	Web Tension	N (lbs)
U	=	Free Stream Velocity	m/s (in./s)
V	=	Shear Force	N (lbs)
W	=	Web Width	m (in.)
w	=	Side Loading	N/m (lbs/in.)
x	=	Distance from Upstream Roller	m (in.)
y	=	Lateral Displacement	m (in.)
$[F]$	=	Force Matrix	N (lbs)
$[K]$	=	Stiffness Matrix	N/m (lbs/in.)
$[U]$	=	Displacement Matrix	m (in.)
ϕ	=	Web Tilt Angle (Crossweb)	Radians
γ	=	Tram Angle	Radians
λ	=	Web Sine Wave Length	m (in.)
θ	=	Nodal Angular Displacement	Radians
σ	=	Machine Direction Stress	KPa (psi)
ρ	=	Air Density	Kg/m^3 (Lb_m/in^3)

Subscripts

L	=	Downstream end of beam
n	=	Nozzle
y	=	Lateral or Cross Machine Direction

BACKGROUND

Air Support Uses and Types

Figure [1] shows three basic types of air flotation systems, as described by Fraser [1]. Wimberger [2] and Cohen [3] describe how drying systems have evolved from festoons in the early 1900's, to impingement in the 1960's, to flotation in the 1980's. These authors describe the advantages of air support systems, including fast uniform drying with contactless transportation.

Two of the most common nozzles used in air support systems are the pressure pad impingement and the air foil, shown in figure (2). Air impingement is defined as air that collides or strikes a surface. Impingement equipment ranges from a simple perforated plates, to impingement nozzles or pressure pads. Air foils, based on the Coanda effect, are commonly used in new designs. The Coanda effect "holds" the web at a fixed distance from the nozzle.

Problems Associated With Air Support Conveyance

Several problems are associated with air support conveyance include lateral displacement, touchdowns, touchups, roping and flutter. This paper will mainly consider lateral displacement. Lateral displacement problems occur when a web is centered going into the oven, but once inside, displaces causing the web to ride off the nozzles or into the oven wall. This type of excessive lateral displacement can be one of the causes of roping, touchdown or web breaks.

Previous Research

Previous work has been done by D.M. Kedl and H.S. Gopal [4] of 3M Company, and is presently being done by P.M. Moretti et. al. [5] at the Oklahoma State University Web Handling Research Center. The cornerstone on which this paper was built was the thesis of John Jarvis Shelton, "Lateral Dynamics of a Moving Web", July, 1968 [6]. The model developed in this paper extends Shelton's static behavior model to include non-uniform web and side loading.

UNIFORM AND NON-UNIFORM WEB SPAN MODEL

Experiments were performed to determine the possible causes of lateral displacement in air support systems. Non-uniform web, as shown in figure (3), was found to be a large contributor to the lateral displacement problem, but the air support system itself also contributes to the problem.

A web span, without air support, will follow a deflection curve described by the Shelton's static behavior model, which will be proportional to the tram error. If the oven entrance and exit are tram, the web will not deflect in this span. This is not the case with an air supported web. A tram oven can have lateral displacement problems. Therefore the air support system must have a model that is different from the Shelton static behavior model.

Uniform Web Air Support Model

A uniform web can be made to deflect in a tram air support system by unleveling the nozzles. The assumptions and boundary conditions will be identical to the Shelton's model, but the nozzles will be exerting a lateral or side force on the web. Therefore a side loading must be added to the Shelton model to more accurately model air support systems. The source and magnitude of the side load will be discussed in the "Air Support Web Model" section.

Non-Uniform Web Air Support Model

Like the uniform web air support model, the non-uniform web model must extend Shelton's model to include side loading. How does the non-uniform web change the differential equation or boundary conditions? The first boundary condition is the initial value condition $y(0) = 0$. This would not change with a non-uniform web. The third boundary condition $y'(L) = 0$ is the normal entry rule required for steady state operation, this boundary condition would not change with non-uniform web. The second boundary condition $y'(0) = 0$ is an extension of the third boundary condition. The web must enter the roller normal from the previous span, therefore it must start the next span normal. Therefore non-uniform web will not change the first three Shelton boundary conditions.

Boundary Condition Number Four. Shelton's fourth boundary stated that the moment at the down stream roller must be zero (M(L) = 0). Because the moment was zero and the web was "initially straight and uniform" equation (2) shows that the curvature at the down stream roller must also be zero. He stated that this boundary condition was formulated after experiments allowed no other conclusions.

Experiments were performed, by the author, to determine the fourth boundary condition for non-uniform web. The non-uniform web was made by strategically inserting extra layers of film while tightly winding uniform PET film. These rolls were then placed in an oven at 93 C (200 F) for several hours, placing a permanent set in the web. Figure (3) shows the two non-uniform webs, one with a camber and the other with a step.

The webs were run across a tramed test stand (L/W = 3.6) and the machine direction stress was measured at three stations along the span. Figure (4) is plots of machine direction stress vs. crossweb position, for both web types. Figure (4) and the figure (5) contour plots show that the crossweb tension does not change in the down web direction. Therefore the moment must be a constant. Equation (1) shows that if the moment is a constant, the shear force must be zero. Equation (2) shows that y" must be a constant because M, E, and I are all constants. Knowing that y" is a constant and that y'(0) =0 and y'(L) = 0, the only possible constant y" could be is zero. Therefore the only solution is the trivial solution of y(x)=0.

Figure (6) is a plot of the measured lateral deflections of the two webs. The data shown in figures (4), (5) and (6) support the validity of the four boundary conditions, and shows that a non-uniform web does not significantly deflect between tramed rollers.

$$\frac{dM}{dx} = V \tag{1}$$

$$y'' = -\frac{M}{EI} \tag{2}$$

The same fourth boundary condition conclusion can be made from a kinematic point of view, similar to that done by Shelton. Figure (7) shows a kinematic or instant center drawing of a curved web and an idler. The velocity vectors of a curved web and an idler are not compatible. An idler in good traction, will not allow curvature at the incoming tangent point (y"(L) = 0).

The fourth boundary condition for non-uniform web is shown in equation (3) and in theory is only slightly different, but mathematically identical to Shelton's. Exceptions to this boundary condition will be discussed later in the section "Exceptions to Boundary Condition Four".

$$y''(L) = 0 \tag{3}$$

Differential equation. Shelton's differential equation, equation (4) could be modified for simple cases of side loading and solved closed form. This paper presents a more flexible, but possibly less elegant, numerical approach.

$$y^{iv} - k^2 y'' = 0 \tag{4}$$

Equation (2) is the differential equation of the deflection curve of a beam. It is a second order differential equation, requiring two boundary conditions. Shelton used a fourth order equation (4) with four boundary conditions. This paper will uses equation (2) with boundary conditions one and two, then treats the beam as statically indeterminate, adding boundary conditions three and four as redundant constraints.

A web under tension can't be treated as a beam, without including tension. Any deflection of the beam will couple with the tension to produce a restoring moment. Beam deflections will always be smaller if the beam is under tension. The "Finite Element Solution" section of this report will refer to this as geometric stiffness.

A web with an initial curvature (camber) traveling between two tram rollers, subject to the four boundary conditions discussed earlier, will not exhibit lateral deflection. If the overall tension is not sufficient to tighten the long side of the web, it will often be refered to as baggy web.

The curvature is always much greater than ten times the web width. Timoshenko [7] uses this as the criteria for curved beams, and therefore equation (2) is valid. Figure (8) shows that the initial curvature will be treated as a virtual moment (M_0) on the web, for the purpose of deflection calculations. Stress calculations will superimpose the bending stress, as the difference between final and initial curvatures, and the stress due to tension.

Figure (9) is a force diagram of a web span with uniform side loading. The moments about point "o", shown in figure (10) as a free body, can be summed to form equation (5). Figure (11) is a force diagram of a web span with a triangular side loading. A similar analysis can be used to determine equation (6). The reason for the triangluar loading will be discribed in the "Relative Tilt Between Web and Nozzle" section.

$$M(x) = M_0 + M_L - F(L-x) + T(y(L) - y(x)) - \frac{w}{2}(L-x)^2 \tag{5}$$

$$M(x) = M_0 + M_L - F(L-x) + T(y(L) - y(x)) - \frac{w}{6L}(L-x)^3 \tag{6}$$

Equation (2) and equation (5) can be combined to form the second order differential equation, shown in equation (7). Equation (7) can be solved numerically with several different methods. This paper will present a simple, fast and flexible solution method using the spreadsheet Microsoft Excel™.

A worksheet can be set up with the known values of T, L, E, h, b, M_0, w and γ along with the unknown redundant constraint reactions F and M_L.

A Runge-Kutta numerical solution can be set up on the worksheet. A Runge-Kutta solution is very handy in this situation because it solves initial value problems, and it automatically calculates y, y' and y" at each node. The initial values of y and y' are zero and come from the first two boundary conditions.

The normally tough job of numerically applying the extra boundary conditions and iterating for the value of y(L) is handled with the Microsoft Excel™ function "Solver". Solver is a powerful numerical optimization program, which can easily be set up to find the values for the unknowns of y(L), F and M_L, subject to the constraints of boundary conditions three and four. Figure (12) is a copy of the worksheet used to solve equation (7).

$$\frac{d^2y}{dx^2}=-\frac{\left[M_0+M_L-F(L-x)+T(y(L)-y(x))-\frac{w}{2}(L-x)^2\right]}{EI} \qquad (7)$$

Exceptions to Boundary Condition Four. Boundary condition four, equation (3), states that no curvature can exist at the downstream roller. This condition dictates that a non-uniform web does not deflect in a span between two tram rollers. Several cases of non-uniform webs, with L/W greater than 10, have been found to deflect. This could be due to several factors. First if the traction is not sufficient for the roller to produce the moment required by boundary condition four, then y"(L) will not be zero. A shear force will then be exerted on the web causing it to deflect toward the baggy side. This is similar to the case of moment transfer discussed in several papers on web wrinkling. A second possible explanation is that high L/W web spans buckle when the roller exerts the moment required to enforce the fourth boundary condition.

Several arguments can be made for and against these explanations. This is an area that requires more experimentation and research. For the purpose of modeling air support conveyance of non-uniform web, using different cases for small and large L/W ratios should be a good starting point.

Figure (13) shows the deflection in a case of high L/W ratio. In this case the fourth boundary condition y"(L) is not zero. The actual deflection curve can be closely modeled by solving equation (7) with the moment applied to the web by the roller (M_L.) as zero. This is equivalent to saying that boundary condition number four, for high L/W web, is given by equation (8).

$$y''(L)=-\frac{M_0}{EI} \qquad (8)$$

This boundary condition would create a very different machine direction stress profile, which would now be uniform across the downstream roller, but non-uniform at the upstream roller, as shown in figure (14). A shear force would now be exerted on the web, which would deflect toward the initially long (baggy) side of the web until there was normal entry.

The deflection curve of a bad web, using equation (8) as a fourth boundary, can be solve closed form, for the case of tram rollers, in terms of the web eccentricity[1] "e", which is described in figure (15). The closed form solution is shown in equation (10).

$$e = \frac{M_0}{T} \tag{9}$$

$$y = -e\left(1\text{-}\cosh(kx) + \frac{(\sinh(kL))}{(1\text{-}\cosh(kL))}(kx\text{-}\sinh(kx))\right) \tag{10}$$

The cambered web shown in figures (4), (5) and (6) had an e = 0.0095 m (0.375 in.), M_0 = 1.0 N/m (9.0 in.-lbs), L = 0.91 m (36 in.), W = 0.254 m (10 in.), T = 107 N (24 lbs), b = 0.0000254 m (.001 in.), E = 3.5 X 10^6 KPa (500,000 psi). Equation (10) or the solution of equation (7) with equation (8) as a fourth boundary condition yields a displacement of y(L) = 0.00117 m (.046 in.). Which is more then was measured in figure (6). This difference was more pronounced at lower tensions. The shear force F, would have been F = 2.4 N (0.53 lbs). This shear force would have easily been detectable in figures (4) and (5).

Finite Element Solution. The Runge-Kutta solution is fast and flexible, but can't solve point loading problems, that could be used to model discrete nozzles. This type of modeling must be done with finite element methods. A two node, two degree of freedom beam element, as shown in figure (16) was used. The standard beam element formulation would decouple the tension from the lateral deflection. This would not be an accurate model of the web. H.S. Gopalakrishna (Gopal) of 3M Company, formulated a beam element stiffness matrix [K] that accounts for geometric stiffness[2]. Equations (11 - 15) comprise the FEM model. An assembled four node, six degree of freedom, model is shown in equation (16).

$$K_1 = \frac{12EI}{L^3} + \left\{\frac{6}{5}\frac{T}{L}\right\}^* \tag{11}$$

$$K_2 = \frac{6EI}{L^2} + \left\{\frac{T}{10}\right\}^* \tag{12}$$

---

[1] Eccentricity is a term used by D.M. Kedl to describe non-uniform web.

[2] $\{\ \}^*$Geometric Stiffness Terms by H.S. Gopal

$$K_3 = \frac{4EI}{L} + \left\{\frac{2TL}{15}\right\}^* \tag{13}$$

$$K_4 = \frac{2EI}{L} - \left\{\frac{TL}{30}\right\}^* \tag{14}$$

$$\begin{bmatrix} K_1 & K_2 & -K_1 & K_2 \\ K_2 & K_3 & -K_2 & K_4 \\ -K_1 & -K_2 & K_1 & -K_2 \\ K_2 & K_4 & -K_2 & K_3 \end{bmatrix} \begin{bmatrix} V_1 \\ \theta_1 \\ V_2 \\ \theta_2 \end{bmatrix} = \begin{bmatrix} F_{y1} \\ M_1 \\ F_{y2} \\ M_2 \end{bmatrix} \tag{15}$$

$$\begin{bmatrix} 2K_1 & 0 & -K_1 & K_2 & 0 & 0 \\ 0 & 2K_3 & -K_2 & K_4 & 0 & 0 \\ -K_1 & -K_2 & 2K_1 & 0 & -K_1 & K_2 \\ K_2 & K_4 & 0 & 2K_3 & -K_2 & K_4 \\ 0 & 0 & -K_1 & -K_2 & K_1 & -K_2 \\ 0 & 0 & K_2 & K_4 & -K_2 & K_3 \end{bmatrix} \begin{bmatrix} V_{y1} \\ \theta_1 \\ V_{y2} \\ \theta_2 \\ V_{y3} \\ \theta_3 \end{bmatrix} = \begin{bmatrix} F_{y1} \\ M_1 \\ F_{y2} \\ M_2 \\ F_{y3} \\ M_3 \end{bmatrix} \tag{16}$$

$$[U] = [K]^{-1}[F] \tag{17}$$

Equation (17) can easily be expanded and programmed or solved using Microsoft Excel™. The spread sheet matrix functions "minverse()" and "mmult()" will minimize programming time and the "Solver" function can handle the boundary condition constraints. This model can be slow, and with the addition of iteration, can be extremely slow.

AIR SUPPORT WEB SPAN MODEL

Sources of Side Force

An experimental web line was used for analysis and experimentation. The R-K model was used to determine the magnitude of a lateral force that would cause the web to make contact with the side of the oven. The web line was 9.144 m (360 in.) long, the web was 0.305 m (12 in.) wide and 0.0000254 m (.001 in.) thick. The web was made of PET with a modulus of 3.5 X 10^6 KPa (500,000 psi). The web tension was 53.4 N (12 lbs.). The maximum tolerable deflection was 0.064 m (2.5 in.). Under these conditions the side force required to push the web to the side of the oven was found to be 0.23 N/m (0.0013 pli) or 0.04 N/nozzle (0.0092 lbs/nozzle), for the small L/W model.

The large L/W model found a maximum of 0.60 N/m (0.0034 pli) or 0.11 N/nozzle (0.024 lbs/nozzle). This is a very small force, and the question becomes where does this force originate? The two obvious sources would be the oven or the web. The source of these effects can easily be determined by flipping the web. If the problem was caused by the web, the deflection would be opposite, the oven caused problems would not.

The oven caused problems could come from at least three sources: non-level nozzles, non-uniform crossweb nozzle air flow or cross flow in the return air system. Web caused problems would result from a difference in web to nozzle gap height due to web bag or cross web tension differences. The nozzle level, non-uniform nozzle air flow and difference in web to nozzle gap height due to web bag, produce a similar effect. The result is a relative "tilt" between the web and nozzle.

Cross Flow of Return Air. The cross flow of return air is a source of side force that does not come from a tilt in the web, although a tilted web in a cross flow could act as a wing with an induced drag. The web can be modeled as a flat plate in a cross flow. This cross flow will cause skin friction and induced drag forces on the web. Equations (18-20), from Houghton and Brock [8] can be used to calculate the lateral force on a flat plate wing.

The model showed that side force of 0.23 N/m (0.0013 pli) would be required in order to push the web into the side of the oven. If the air was flowing straight across the web, the required 0.23 N/m would be produced by a velocity of 17 m/s (3350 ft/min, 38 mph). If the air was flowing across a slightly tilted web (5 deg), the required 0.23 N/m side force would be produced by a velocity of 14 m/s (2800 ft/min, 32 mph). If the air was flowing in the bottom of one side of the oven, and out on the top of the opposite side (45 deg), the required 0.23 N/m side force would be produced by a velocity of 3.5 m/s (700 ft/min, 8 mph).

These values are actually quite large. If this is the cause of the lateral displacement problems, the problem could easily be detected. Tools such as an anemometer, smoke bomb or simple tell-tail made from cassette tape, should quickly determine if cross flow is the source of the lateral displacement problems.

$$F_y = (C_f + C_d)\left(\frac{A\rho U^2}{2}\right) \tag{18}$$

$$C_f = \frac{1.326}{\sqrt{Re}} \tag{19}$$

$$C_d = \frac{(2\pi\phi)^2}{\pi\frac{L}{W}} \tag{20}$$

Relative "Tilt" Between Web and Nozzle. Nozzle level, non-uniform nozzle air flow and difference in web to nozzle gap height due to web bag, produce a similar effect, a relative "tilt" between the web and nozzle. If the nozzles force the web into a sine wave pattern, as shown in figure (1), a simple triangular model could be used to analyze the magnitude of this force F_n, as shown in figure (17). The magnitude of F_n can be calculated with equation (21). The magnitude of F_n can also be modeled as a linear function of the gap between the web and the nozzle, as shown in equation (22). Figure (18) shows that if there is a relative tilt between the nozzle and the web, F_n has a lateral component F_y, which can be calculated with equation (23).

$$F_n = \frac{8Ta}{\lambda} \tag{21}$$

$$F_n = C_0 + C_1 g \tag{22}$$

$$F_y = F_n \phi \tag{23}$$

Equations (21) and (22) can be combined and solved for the amplitude "a". Then the derivative of both sides with respect to y was taken. Tension is a function of y, and the derivative of the amplitude with respect to y is the angle ϕ. The result can be combined with equation (23), resulting in equation (24). The values of "a" and "T" are functions of y, but average constant values will only introduce small errors. The tension differential can be calculated from equation (25), using the web edge stresses found using the web span models. Note that in the large L/W case the differential crossweb tension approches zero at the down stream roller, as shown in figure (14). Equation (24) shows that if the differential tension is zero the side force must also be zero. This is the reason that a triangluar side loading was used for large L/W spans, in figure (11) and equation (6). The simple case of small L/W spans between tram rollers can use equation (26).

$$F_y = -\frac{a}{T}(C_0 + C_1 g)\frac{dT}{dy} \tag{24}$$

$$\frac{dT}{dy} = h(\sigma_2 - \sigma_1) \tag{25}$$

$$\frac{dT}{dy} = \frac{M_0 W h}{I} \tag{26}$$

The oven discussed previously, set to factory specifications, and using the same film and tension would have an F_n of 6.7 N (1.5 lbs). The model showed that side force F_y of 0.23 N/m (0.0013 pli) would be required in order to push the web into the side of the oven. Equation (23) shows that a tilt angle ϕ is .0061 radians (0.35 deg, 73 mils/ft). This is a very small angle and suggests that a very small relative tilt between the web and the nozzle can create lateral displacement problems.

The same analysis can be done to determine the degree of non-uniformity that can be run through this example oven. Equation (24) and (26) can be used to calculate the M_0 or the web eccentricity "e" that would be required to produce .04 N/nozzle (.0092 lbs/nozzle). The previous conditions remain the same, and the following values were used; a = .0053 m (.21 in.), C_0= 15.5 N (3.5 lbs), C_1 = -1100 N/m (-6.25 lbs/in.), and g = .0081 m (.32 in.). M_0 was found to be .47 N-m (4.2 in.-lbs) and "e" was found to be .009 m (0.35 in.), which is equivalent to a web with a radius of curvature of 435 m. A web, with a noticeable crossweb hardness difference, that had an "e" value of .0031 m (0.124 in.), could be run through the air support system, under these conditions. A web with a manufactured "e" value of 0.014 m (0.54 in.) would quickly move away from the baggy edge and hit the oven wall.

CONCLUSIONS

1. Non-Uniform web, in a small L/W span and good traction, will not exhibit lateral deflection. The crossweb stresses, and side forces required to create lateral displacement problems can be modeled by solving equations (2) and (5), with the added constraints of normal entry (y'(L)=0) and no curvature at the down stream roller (y"(L)=0).
2. Non-uniform web, in a large L/W span and/or poor traction, will exhibit lateral deflection toward the baggy side. The deflection, crossweb stresses, and side forces required to create lateral displacement problems can be modeled by solving equations (2) and (6), with the added constraints of normal entry (y'(L)=0) and no applied moment (M_L) at the down stream roller (y"(L)= -M_0/EI).
3. The side forces required to create lateral displacement problems could possibly come from the cross flow of air, but the flow velocities and angles are large and easily measurable.
4. The side forces required to create lateral displacement problems could come from a very small relative "tilt" between the web and nozzle. This "tilt" could come from unleveled nozzles, uneven air flow, or non-uniform web. The magnitude of these forces can be calculated with equation (23) or (24).
5. The down web sine wave may be required in an air support system for lateral stiffness to prevent such problems as wrinkling, roping and flutter. Large amplitudes reduce the lateral stiffness of the web, increasing lateral displacement problems, and reduces web steering efficiency. The magnitude of the side forces on the web are also directly proportional the sine wave amplitude. Therefore the optmual sine wave amplitude is a compromise between problems such as wrinkling, roping and flutter verses problems of lateral displacement.

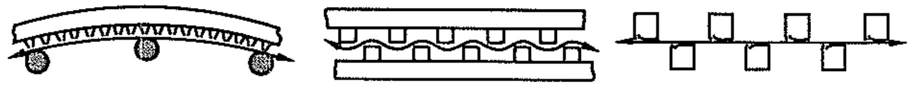
ACKNOWLEDGMENTS

I would like to thank 3M Company for supporting this research. I would also like to individually thank D. M. Kedl, Dr. H.S. Gopalakrishna and Dr. Grant Tiefenbruck for technical insight and assistance. I would also like to thank Dr. J. J. Shelton, whose 1968 Ph.D. thesis formed the foundation on which this work was built.

REFERENCES

1. W. A. R. Fraser, "Air Flotation Systems: Theoretical Considerations and Practical Applications", Paper, Film and Foil Converter, May, June 1983.
2. Wimberger, R. J., "New Flotation Drying Techniques", The International Review for the Pulp and Paper Industry, 1991
3. Cohen, E. D., Gutoff, E. B., Modern Coating and Drying Technology, VCH Publishers, Inc., New York, 1992
4. D. M. Kedl, H. S. Gopal, Internal 3M Correspondences, 1991-1993
5. P. M. Moretti, et al.,Web Handling Research Center Internal Correspondences.
6. J. J. Shelton, "Lateral Dynamics of a Moving Web", Ph.D. thesis, Oklahoma State University, July, 1968
7. S. Timoshenko, Strength of Materials Part I and II, 3rd ed., Krieger Publishing, Malabar, Florida, 1976
8. E. L. Houghton, A. E. Brock, Aerodynamics for Engineering Students, Arnold Publishers, London

FIGURES

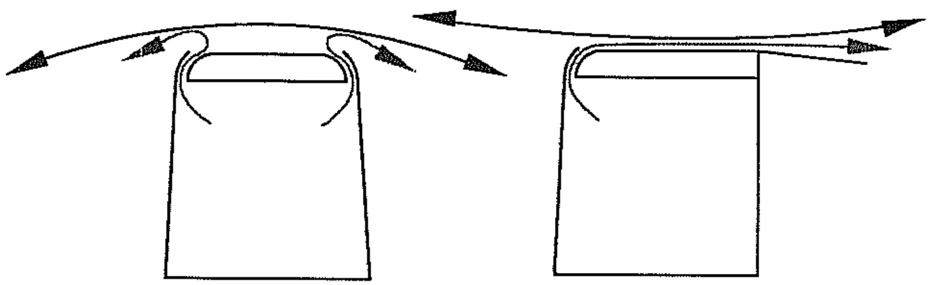


A) Conventional air impingement nozzles of an arch dryer.

B) Sinusoidal web path pressure-pad or cushion air tubes on each side of web.

C) Air foil tubes on each side of web.

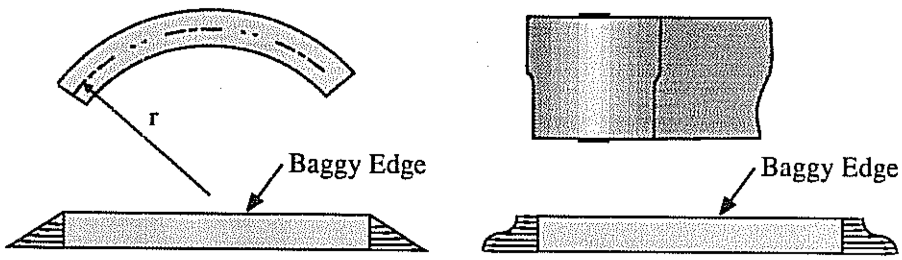
Figure 1 Fraser's Three Air Support Systems.



Impingement Nozzle or Pressure Pad

Air Foil

Figure 2 Impingement Nozzle and Air Foil.

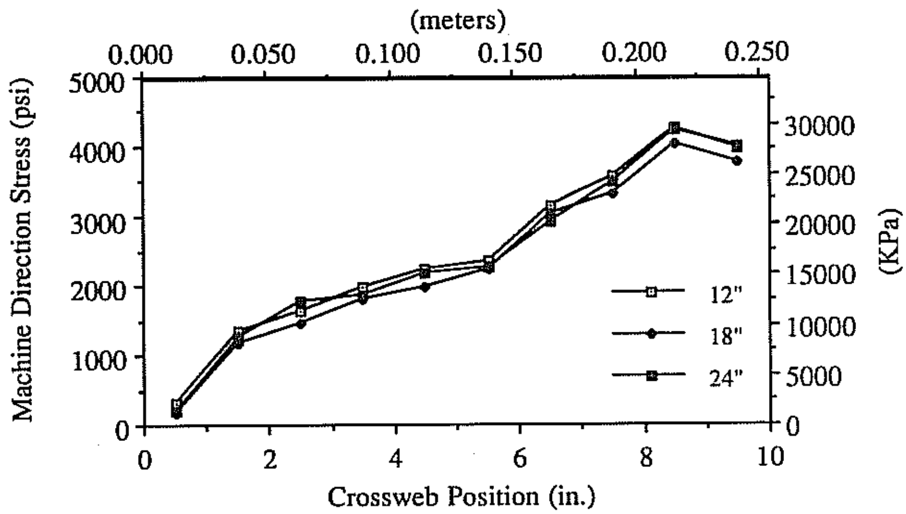


Cambered Web

Stepped Web

Figure 3 Non-Uniform Web.

Data from "Cambered Web"



Data from "Stepped Web"

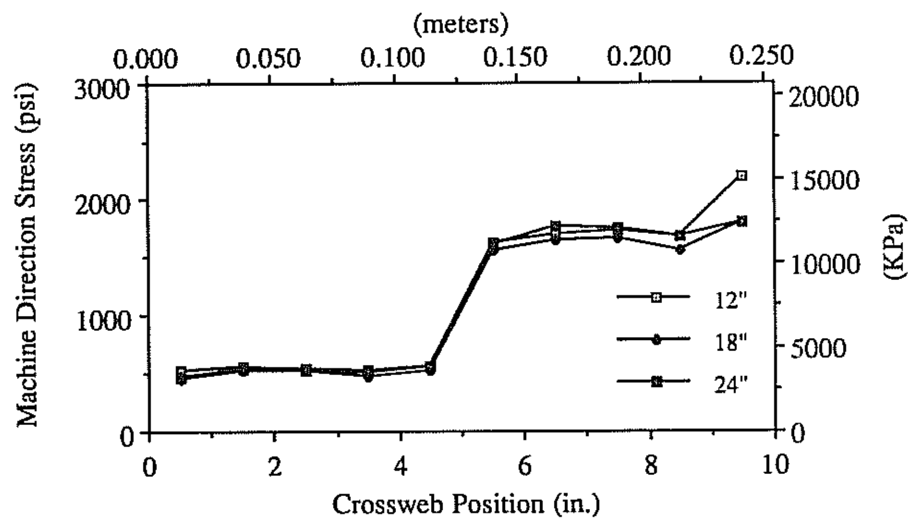


Figure 4 Machine Direction Stress Graphs for Two Types of Non-Uniform Web Between Parallel Rollers.

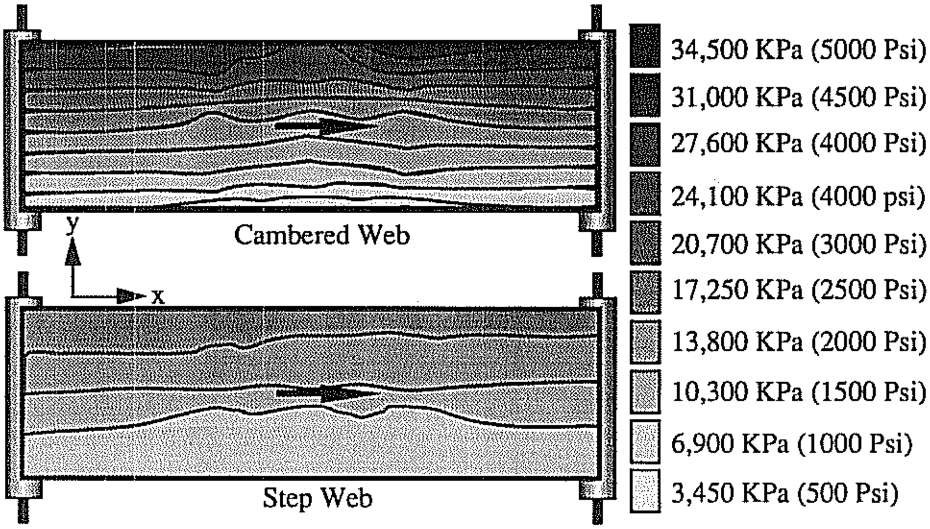
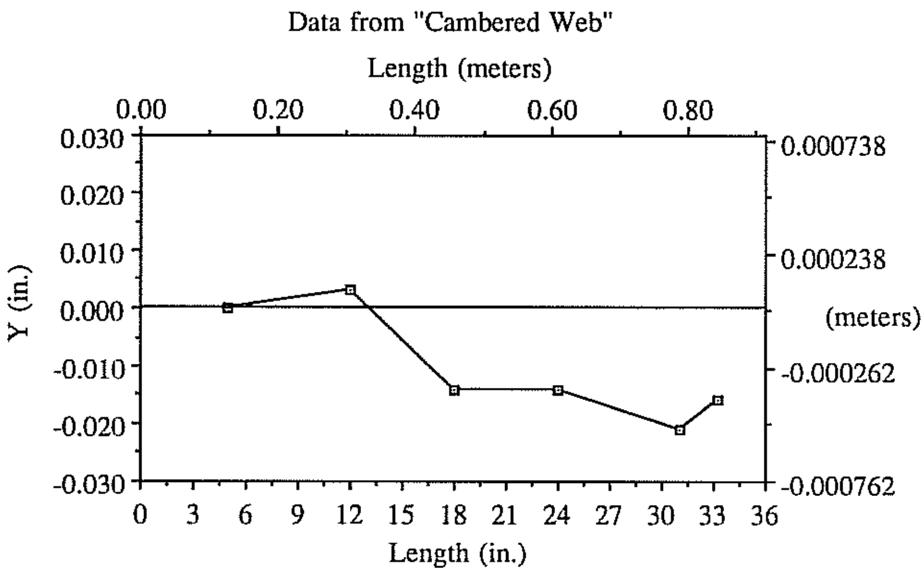


Figure 5 Machine Direction Stress Contour Plots for Two Types of Non-Uniform Web Between Parallel Rollers.



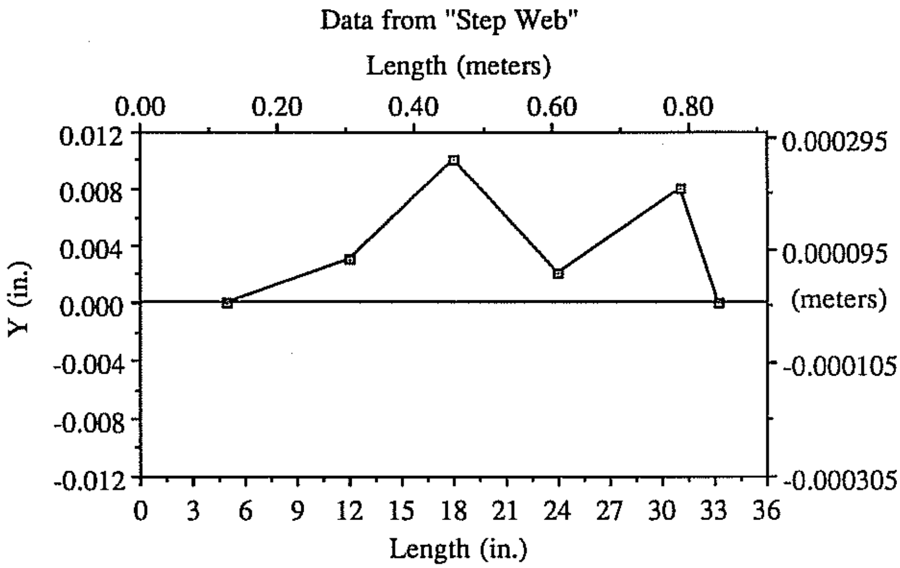


Figure 6 Plots of Measured Deflections.

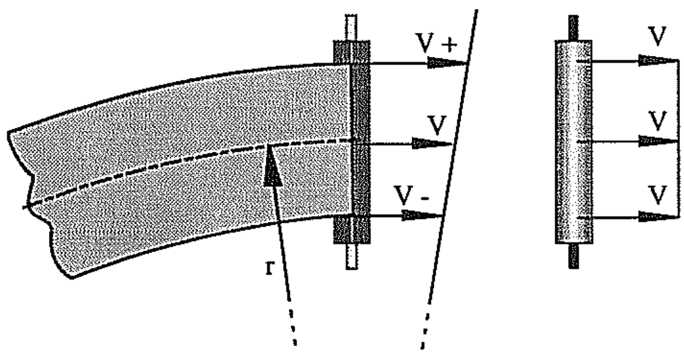


Figure 7 Kinematic Analysis of Curved Web and Roller.

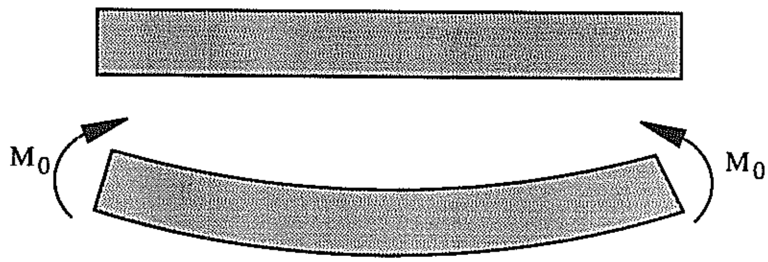


Figure 8 Virtual Moment of Cambered Web.

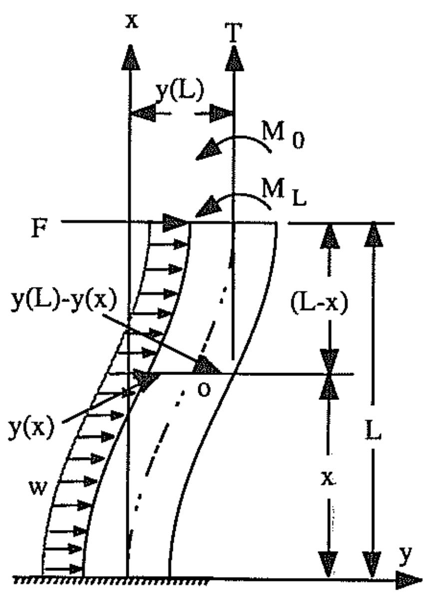


Figure 9 Force Diagram of a Web Span with Uniform Side Loading.

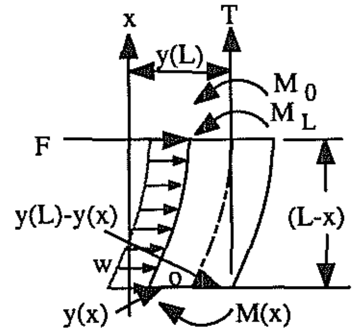


Figure 10 Free Body Diagram of a Web Span with Side Loading.

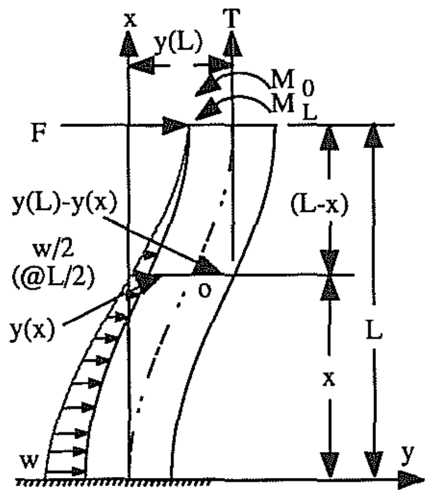
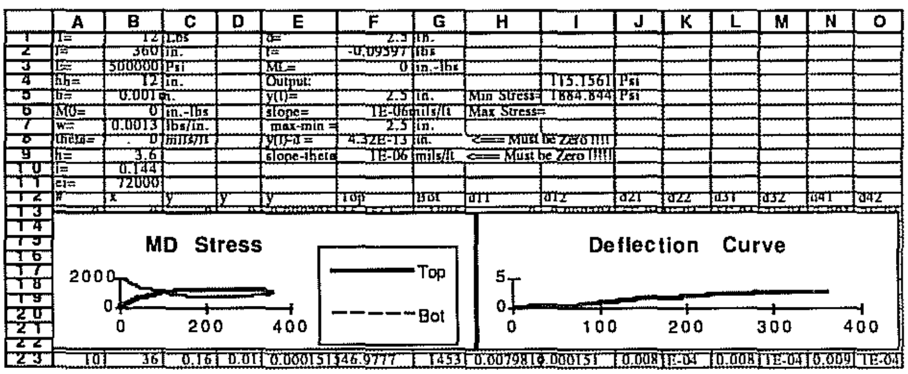


Figure 11 Web Span with Triangular Side Loading.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	T=	12	Lbs		d=	2.5	in.								
2	l=	360	in.		f=	-0.09597	lbs								
3	E=	500000	Psi		ML=	0	in.-lbs								
4	hh=	12	in.		Output:				115.1561	Psi					
5	b=	0.001	in.		y(l)=	2.5	in.	Min Stress=	1884.844	Psi					
6	M0=	0	in.-lbs		slope=	1E-06	mils/ft	Max Stress=							
7	w=	0.0013	lbs/in.		max-min =	2.5	in.								
8	theta=	0	mils/ft		y(l)-d =	4.32E-13	in.	<=== Must be Zero !!!!							
9	h=	3.6			slope-theta	1E-06	mils/ft	<=== Must be Zero !!!!							
10	i=	0.144													
11	ei=	72000													
12	#	x	y	y	y	Top	Bot	d11	d12	d21	d22	d31	d32	d41	d42
13															
14															
15															
16															
17															
18															
19															
20															
21															
22															
23	10	36	0.16	0.01	0.000151	346.9777	1453	0.007981	0.000151	0.008	1E-04	0.008	1E-04	0.009	1E-04

Figure 12 Worksheet Used to Solve Equation (6).

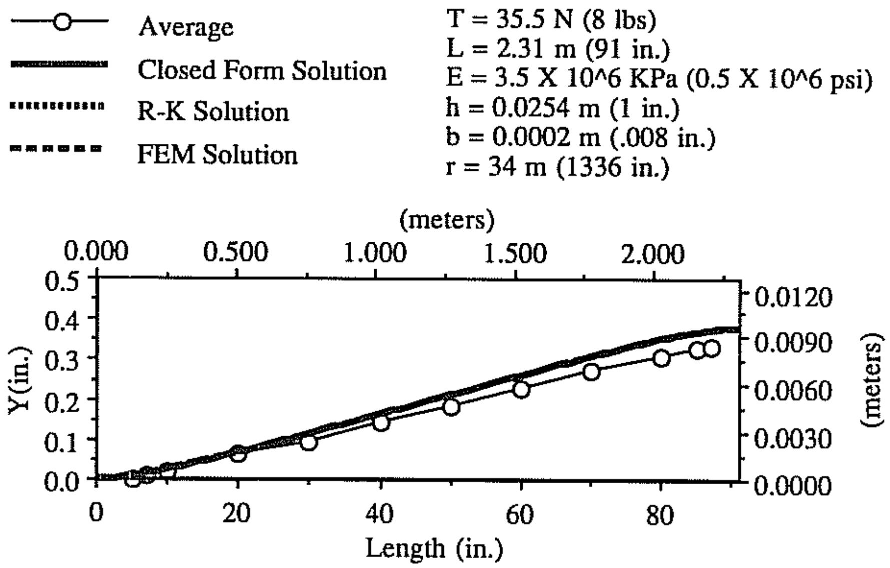


Figure 13 Measured Deflection of High L/W Web Span.

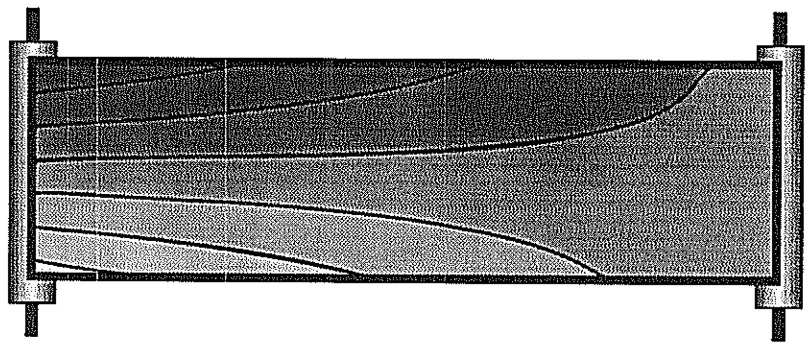


Figure 14 Machine Direction Stress Contour Plot of Large L/W Non-Uniform Web Between Parallel Rollers (Theoretical).

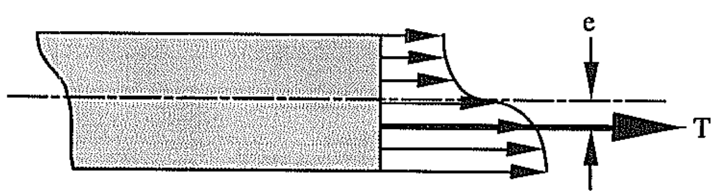


Figure 15 Definition of Web Eccentricity[1].

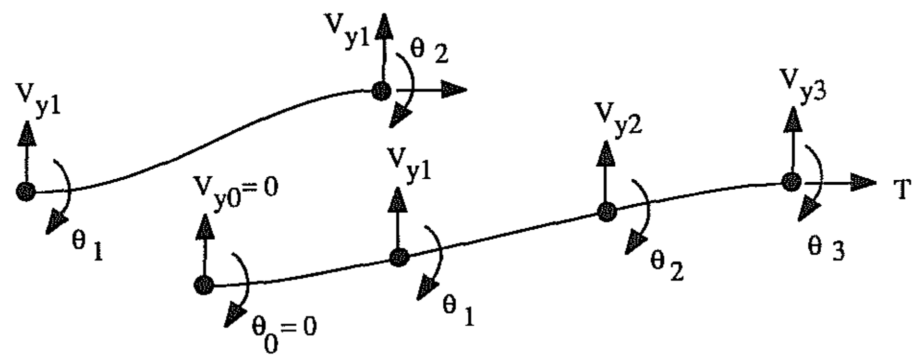


Figure 16 A Two Node, Two Degree of Freedom Beam Element and Assembled Model.

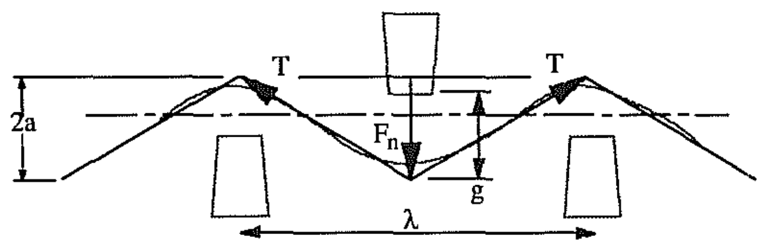


Figure 17 Simplified Sine Wave Model.

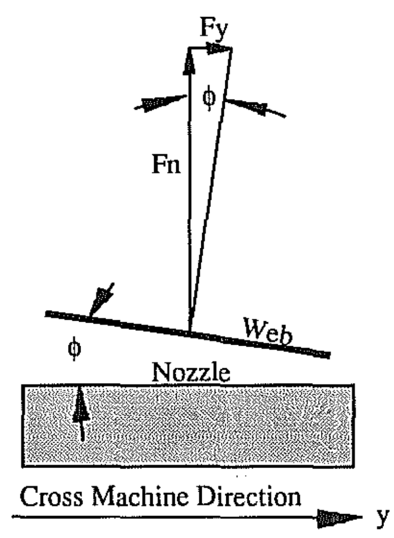


Figure 18 Cross Web View of Tilted Web.

QUESTIONS AND ANSWERS

Q. Would you please elaborate on what you meant by tilt of the nozzles?

A. Yes, I assumed it was like one big long nozzle. You'd have to use a finite element approach to handle the analysis for the tilt of discrete nozzles.

Q. Well, doesn't the web immediately twist? Why doesn't the web tilt?

A. Yes, the web does tilt. Now the nozzle produces a force on to the tilted web which has a component in the lateral direction.

Q. Did you study skew of the nozzles?

A. I didn't look at skew of the nozzle. My thoughts are, it's not as big a factor. I did not look at that.