WEB LATERAL DYNAMICS WITH BUCKLING IN SHEET METAL ROLLING

by

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ABSTRACT

The stability of web lateral motion is of importance in many engineering applications where the deviation of the web from the processing direction is highly undesirable and can cause various defects. This is especially true for sheet metal rolling, where sudden lateral deviations of the web from the rolling direction, known as strip track-off, is a serious operational problem that can lead to catastrophic consequences, such as mill crashes and damaged rolls.

The early studies of strip track-off in metal rolling showed that neither the magnitude of lateral deviations nor the catastrophic track-off observed in practice can be explained by the model of strip deformation in the span based on beam theory, common in the web handling literature. It has been suggested that strip buckling may play an important role in strip track-off phenomenon. In addition, it has also been observed in web handling literature [1,2] that the model predictions based on conventional beam bending analysis do not agree with observed web lateral motion in the situations when buckling of the web is present.

This paper presents a discussion of the recent studies of the effect of strip buckling on strip lateral dynamics in metal rolling. The analysis is based on the model of strip plastic deformation in the mill and a simplified physically based strip buckling model suggested by Benson [1]. Introduction of buckling changes the nature of the strip lateral motion, which becomes unstable once a critical level of asymmetry in rolling conditions is exceeded.

In metal rolling, the longitudinal residual stresses in the strip are usually present due to non-uniform plastic reduction. In this paper, an extension of the Benson's buckling model to include the effect of residual stress is proposed. The numerical analysis of the extended model suggests that the web with the tensile residual stress at the edges and

compressive stress in the middle is less susceptible to instability compared to the web with compressive residual stresses at the edges and the case without residual stress.

NOMENCLATURE

E	Young modulus
I	moment of inertia of strip cross-section
L	span length
M	bending moment
$M^* = \dfrac{6M}{TW}$	non-dimensional bending moment
T	tension
W	web (strip) width
d	strip deviation from central position (off-center)
h	mean strip thickness
k	curvature of strip centerline
$k^* = k\dfrac{6EI}{TW}$	non-dimensional curvature
u	strip lateral deviations
$\bar{\upsilon}$	strip average (over the width) velocity in rolling direction
x	co-ordinate across the strip width
$x^* = \dfrac{x}{W}$	non-dimensional co-ordinate across the strip width
z	co-ordinate in the direction of rolling
$\gamma = \bar{\sigma}^{(0)} / D$	non-dimensional parameter
θ	angle strip centerline forms with the roll axis
σ	longitudinal stress in the strip
$\bar{\sigma}^{(0)}$	average (over the strip width) longitudinal stress in the unbuckled strip
ω	strip in-plane rotational speed

Subscripts and superscripts

Subscripts 1 and 2 refer to entry and exit of the roll bite; Superscripts * refer to non-dimensional quantities.

INTRODUCTION

While there is an extensive literature on modelling the lateral dynamics in transport of web materials (examples include [1-9]), there are only a few published studies on the lateral dynamics in metal rolling and they are relatively recent [10-13]. A distinctive feature of lateral dynamics in metal rolling is the plastic reduction of the metal strip in the rolling mill. A cause of strip lateral motion is the asymmetry in rolling conditions that produces bending moments acting on the strip and causing the strip to tilt relative to the roll axis.

The first formulation of strip lateral dynamics model in metal rolling is due to Matsumoto and Ishii [11]. The assumptions they used are mainly similar to those adopted in web handling literature:

- The longitudinal tension is constant in the span;
- The mass of the metal strip is negligible, therefore no inertial effects or vibrations occur;
- Euler beam theory is used to describe strip deformation in the span;
- An assumption of no lateral slip between the strip and the rolls at the entry to the roll bite, which is similar to a familiar "roller climbing" equation, first derived by Shelton and Reid [3,4], is adopted

  $$\frac{dd_1}{dt} = \bar{\upsilon}_1 \theta_1 \qquad \{1\}$$

- A match of the rotational velocity of the strip imposed by the plastic reduction in the mill and by the deformation outside the roll bite at the entry of the roll bite is assumed

  $$\frac{d\theta_1}{dt} = \omega_1 + \bar{\upsilon}_1 k_1 \qquad \{2\}$$

In their experiments, Matsumoto and Ishii [11] found that the magnitude of lateral deviations cannot be explained on the basis of beam theory for strip deformation in the span, and introduced an adjustable "buckling factor" parameter into the linear beam model to fit the experimental data. However, their experimental data suggested a non-linear behaviour of lateral deviation as a function of bending moment that could not be explained on the basis of the linear beam model. Matsumoto and Ishii [11] suggested that a "theory of buckling could be effective in clarifying such non-linear nature".

The authors' earlier study [13] focused on a simpler case of lateral dynamics in a single span between the uncoiler and the rolling mill. It showed that neither the catastrophic track-off nor the effect of tension at the entry to the mill observed in practice can be explained on the basis of linear beam theory for strip deflection analysis and emphasised the importance of strip buckling.

As a rigorous description of the buckling phenomenon is too complicated to implement within the web lateral dynamics model, a simplified physically based description of strip buckling was required. Such a description has been proposed by Benson [1] who suggested that a partial buckling of the web reduces web in-plane bending rigidity. Benson's model allowed a quantification of the buckling effect through the expression for web centreline curvature under buckling.

The introduction of a simplified description of strip buckling [1] into the model of lateral dynamics in a single span of cold rolling mill [14-16] significantly changed the nature of strip lateral motion. The buckling introduced instability in strip lateral motion that may explain the sudden track-off observed in practice. The mathematical model of strip lateral dynamics with buckling, and recent results on the effect of buckling on strip lateral motion are discussed in the next section.

In metal rolling, the longitudinal residual stresses are usually present in the strip due to non-uniform plastic reduction. It is expected that the residual stresses would alter strip buckling and therefore affect the lateral dynamics. This paper presents an extension of the Benson's buckling model to accommodate the residual stresses. While the extended buckling model is rather generic, a discussion of lateral dynamics in metal rolling is based on a single span model, as in the authors' earlier study [13-16].

BACKGROUND

In this section, we briefly discuss the mathematical model of strip lateral dynamics in metal rolling and the recent results of the study of the effect of strip buckling on lateral dynamics.

Apart from the dynamical conditions (1,2), the model of lateral dynamics in metal rolling includes two additional components: 1) a model of the rolling mill, including the plastic deformation of the strip and the elastic deformation of the roll stack, and 2) a model of strip deformation in the span. They are discussed below.

Mill Model

The lateral dynamics in metal rolling is complicated by the fact that the strip is compressed and plastically deformed between the rolls as shown in Figure 1a. In steel rolling, the rolls and the strip are made of the same material, so a description of the elastic deformation of the roll stack is usually required. An approach to modeling the strip plastic deformation in the mill is similar to that in so-called "strip shape" or "strip flatness" models [17-24] and is based on the generalized two-dimensional plastic deformation theory [17]. These models, however, are not suitable for the lateral dynamics analysis as they are usually based on the assumption that the rotational component of strip velocity is absent. Matsumoto and Ishii [11] modified the mill model by introducing the in-plane rotational speed of the strip at the entry and exit of plastic reduction region.

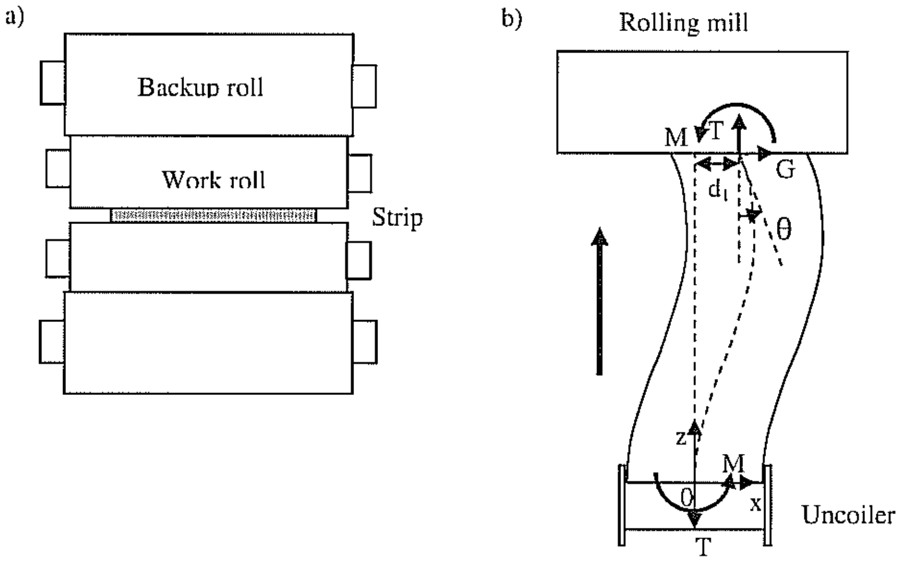

Figure 1 - Schematic of strip rolling
a) four-high mill
b) strip in a span between the uncoiler and the rolling mill.

The mill model can be used to obtain the functional relationship for the in-plane rotational speed of the strip ω_1 (angular velocity in a reference frame moving with the linear velocity of the strip) as a function of the in-plane bending moment M_1 and the off-center of the strip d_1 (lateral deviation relative to the center of the roll), both taken at the entry of the roll bite, for specified conditions at the exit of the roll bite

$$\omega_1 = \omega_1(d_1, M_1, rolling\ conditions). \qquad \{3\}$$

Strip Deformation Under Buckling in the Span

A simplified model of strip buckling proposed by Benson [1] is based on a linear stress distribution in the Euler beam and the assumption that the onset of buckling occurs at an infinitesimally small negative stress.

According to the Benson's model, the onset of strip buckling occurs at $6M/TW = 1$, and a complete loss of the bending rigidity occurs at $6M/TW = 3$. Benson [1] suggested that a partial buckling of the web reduces the web in-plane bending rigidity by reducing the effective width of the strip. Thus, bending of the strip under buckling can be viewed as bending of the Euler beam with reduced effective width and bending moment. On the basis of the Benson's model, it can be shown that the in-plane curvature of the centreline of a buckled strip is given by

$$k(M^*) = \frac{TW}{6EI}\begin{cases} M^* & if \quad |M^*| \le 1 \\ \dfrac{4}{(3-M^*)^2} & if \quad 1 < M^* < 3 \\ -\dfrac{4}{(3+M^*)^2} & if \quad -3 < M^* < -1 \end{cases} \qquad \{4\}$$

The Benson's curvature is plotted against the bending moment in Figure 2. The linear part of the curvature function describes the curvature prior to the onset of buckling. Note that the validity of the Benson's model is limited by the condition $W|k| << 1$, or, in terms of the scaled moment, $|M^*| << 3 - W\sqrt{2T/3EI}$.

On the basis of Benson's buckling model, the deflections of the strip in the span between the uncoiler and the rolling mill (Figure 1b) can be described as bending of the Euler beam with varying effective width [15] by the non-linear differential equation

$$\frac{\partial^2 u}{\partial z^2} = k(M^*(z)) = \frac{TW}{6EI}\begin{cases} M^*(z) & if \quad |M^*| \le 1 \\ \dfrac{4}{(3-M^*(z))^2} & if \quad 1 < M^* < 3 \quad ; \\ -\dfrac{4}{(3+M^*(z))^2} & if \quad -3 < M^* < -1 \end{cases} \qquad \{5\}$$

where

$$M^*(z) = \frac{6}{TW}[-M_1 + G(L-z) - T(u|_{z=L} - u)], \qquad \{6\}$$

The forces and the moments acting on the strip include the tensile force T, the bending moment M_1 and the lateral force G (see Figure 1b). The boundary conditions upstream at the uncoiler are assumed in the form:

$$u\Big|_{z=0} = \frac{\partial u}{\partial z}\Big|_{z=0} = 0 \qquad \{7\}$$

At steady-state, an additional boundary condition

$$\theta_1 = \frac{\partial u}{\partial z}\Big|_{z=L} = 0 \qquad \{8\}$$

resulting from equation (1) can be used to eliminate the unknown lateral force G. Thus, at steady-state, the off-center of the strip is a function of the entry moment for a given tension, strip dimensions and material properties

$$d_1 = u\Big|_{z=L} = d_1(M_1, T, \mathit{web\ properties}) \qquad \{9\}$$

The steady-state off-center as a function of the bending moment is a strongly non-linear function [14,15] similar in shape to Benson's curvature function (Figure 2). The buckled regions predicted by Benson's model are schematically shown in Figure 3. The location and shape of these regions resemble those that can be observed in practice when applying the bending moments to a long strip of web as depicted in Figure 1b.

Effect of Buckling on Strip Lateral Dynamics in Metal Rolling

A simplified buckling model by Benson was introduced into the strip lateral dynamics analysis in a single span between the uncoiler and the first stand of a cold rolling mill in [14-16]. Introduction of buckling into the mathematical model of lateral dynamics changed the nature of the strip lateral motion. While, in the absence of strip buckling, the lateral dynamics is inherently stable, the buckling of the strip, caused by the bending moment due to the asymmetry in rolling conditions, can lead to instability in lateral motion. The reason for this is a strongly non-linear behaviour of strip off-center as a function of bending moment that follows from equation (5), compared to an essentially linear function predicted by a conventional beam theory (this is illustrated in Figures 4a and 4b). While the buckling model used for the analysis is without doubt an oversimplified one, it is expected that the qualitative behaviour of the solution is realistic. As a result, there exists a critical level of asymmetry above which no stable lateral motion exists. Below this level, two steady-state solutions for lateral deviations of the strip are possible (see Figures 4 and 5). Numerical simulations revealed [14,15] that the smaller solution represents a stable equilibrium, while the larger one is an unstable equilibrium. It was also found that the lateral motion is sensitive to the initial off-center. Thus, the motion becomes unstable once the initial off-center reaches a critical value. The numerical simulations suggest [14,15] that the critical initial off-center is close to larger solution of the steady-state problem (that is, to the unstable equilibrium) for a given level of asymmetry in rolling conditions.

It was found [16] that the tension at the entry to the cold rolling mill is a crucial factor affecting the stability of strip lateral motion. The critical level of asymmetry is strongly dependent on the entry tension. As the entry tension increases, a higher level of asymmetry in rolling conditions is tolerable without the onset of instability. An increase in entry tension reduces, and may even completely eliminate, the strip buckling, thus

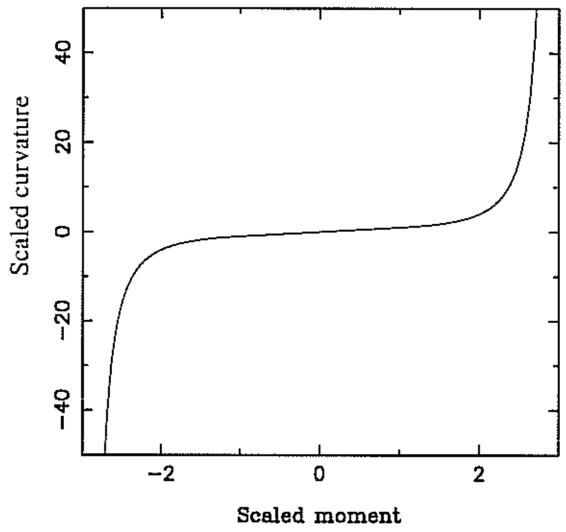

Figure 2 - Non-dimensional curvature as a function of non-dimensional moment in Benson's model

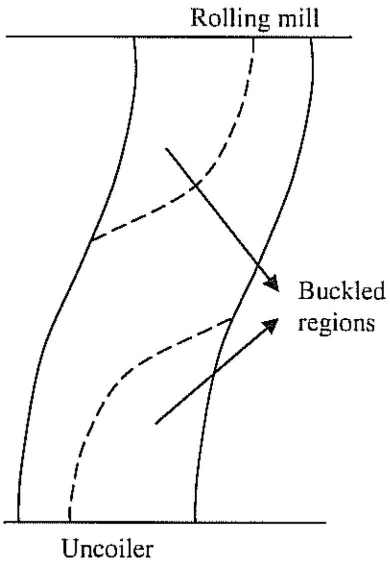

Figure 3 - Buckled regions according to Benson's model

improving the stability of strip tracking. While the stabilising effect of entry tension has long been known in rolling practice, it was not predicted by the previous models.

EFFECT OF RESIDUAL STRESSES IN THE STRIP ON STRIP LATERAL MOTION

In metal rolling, the longitudinal tensile stress variation across the strip width is usually present due to non-uniform plastic reduction resulting from mismatch in the work roll and strip crowns. It is expected that the presence of such residual stresses would alter strip deformation under buckling. However, such cases cannot be analysed using the original Benson's buckling model, as it is based on the assumption of linear tensile stress distribution across the strip width. In this section, an extension of the Benson's buckling model for the case when the residual stress variation exists within the strip is proposed.

A simplified discussion of the effect of residual stresses on strip lateral motion at the end of this section is based on the observation that the bending moment generated in the roll bite is little affected by the symmetric residual stress in the strip (a detailed analysis will be presented elsewhere). Thus, the curves (1a) and (1b) in Figures 4a and 4b remain unchanged. Then, the effect of residual stress on strip lateral motion can be studied by comparing the lateral deviations of the strip under the same bending moment and tension but different residual stresses. Under simplifying assumptions [14], the lateral deviation at the entry to the roll bite is proportional to the curvature of strip centerline at the entry. Thus, the effect of residual stresses on lateral motion is discussed by comparing the entry curvature.

Extension of Benson's Buckling Model for the Case of Residual Stresses in the Strip

Typical residual stresses in metal rolling include:

- A compressive stress at the edges of the strip (Figure 6a), resulting in strip with "wavy edges";
- A compressive stress in the middle of the strip (Figure 6b), resulting in strip with "full center".

In this section, we propose an extension of Benson's model for these two types of residual stress.

The residual stress in the strip $\sigma^r(x)$ is assumed to be quadratic

$$\sigma^r(x) = a + bx^2 \qquad \{10\}$$

and satisfies the condition

$$\int_{-W/2}^{W/2} \sigma^r(x)dx = 0\,. \qquad \{11\}$$

It is also assumed that the residual stress is independent of the bending moment acting on the strip. Then, the total stress distribution across the strip width under the bending moment M and tensile force T takes the form

$$\sigma(x) = \overline{\sigma}^{(0)} + \sigma^r(x) + cx \qquad \{12\}$$

where $\overline{\sigma}^{(0)}$ is the average stress in the unbuckled strip. Using the conditions

$$h\int_{-W/2}^{W/2} \sigma(x)dx = \overline{\sigma}^{(0)}hW = T, \quad h\int_{-W/2}^{W/2} \sigma(x)xdx = M\,, \qquad \{13\}$$

expression (12) can be re-written as

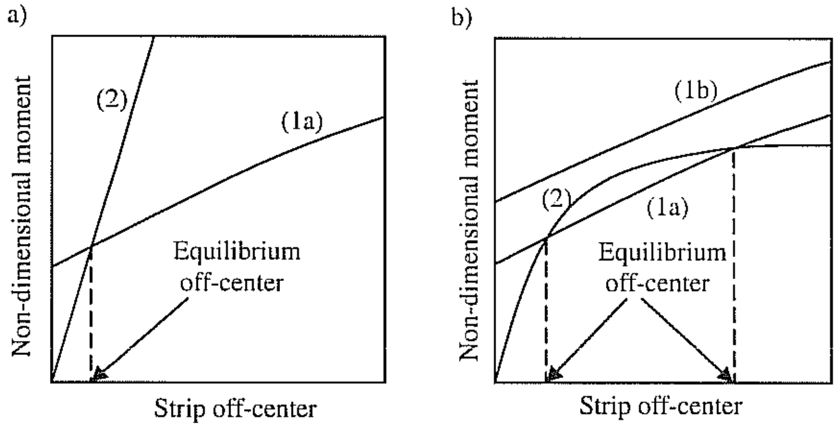

Figure 4 - Graphical solution for steady-state lateral deviations
(a) solution without buckling
(b) solution with buckling
Curves (1a) and (1b) show the solutions of the mill model for different levels of asymmetry in rolling conditions, curve (2) shows the solution for strip deformation in the span.

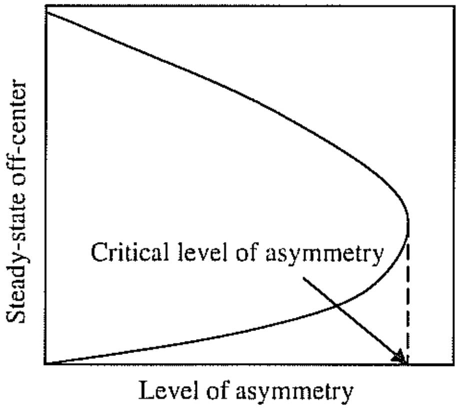

Figure 5 - Steady-state strip lateral deviation at the entry of the roll bite as a function of asymmetry in rolling conditions.

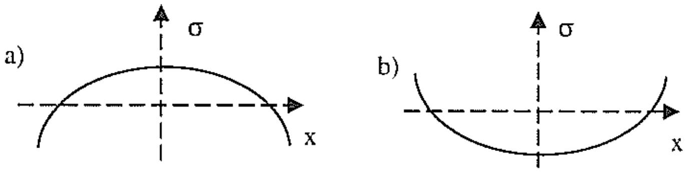

Figure 6 - Typical residual stresses in metal rolling
a) "wavy edges" type of residual stress
b) "full center" type of residual stress

$$\sigma(x^*) = \bar{\sigma}^{(0)} - \frac{D}{2} + 6Dx^{*2} + \frac{12M}{hW^2}x^* \qquad \{14\}$$

where $D = \sigma^{(0)}\big|_{x^*=\pm 0.5}$, $\sigma^{(0)}$ is the symmetric stress distribution for $M = 0$.

It is convenient to introduce a parameter $\gamma = \bar{\sigma}^{(0)}/D$, so that $\gamma > 0$ for the "full center" type of residual stress and $\gamma < 0$ for the "wavy edges" type of residual stress. Then, expression (14) takes the form

$$\sigma(x^*) = D(6x^{*2} + 2M^*\gamma x^* + \gamma - \frac{1}{2}) \qquad \{15\}$$

We now assume, as in Benson's buckling model, that the strip cannot sustain compressive stress. The modified stress distribution in the strip after buckling takes place is assumed to be of the form

$$\sigma^{(m)}(x^*) = D\begin{cases} \gamma - \frac{1}{2} + 6x^{*2} + b_1^* + b_2^* x^* & \text{if} \quad \sigma^{(m)}(x^*) \geq 0 \\ 0 \quad \text{if} \quad \sigma^{(m)}(x^*) < 0 \end{cases} \qquad \{16\}$$

where $b_1^* = b_1/D$; $b_2^* = b_2/D$, b_1 and b_2 are unknown constants. If we denote by x_a^* and x_b^* the roots of the quadratic equation $\sigma^{(m)}(x^*) = 0$ so that $x_a^* \leq x_b^*$, a condition $\sigma^{(m)}(x_a^*) = 0$ yields

$$b_1^* = -b_2^* x_a^* - 6x_a^{*2} + \frac{1}{2} - \gamma \qquad \{17\}$$

Thus, the expression for the modified stress becomes

$$\sigma^{(m)}(x^*) = D\begin{cases} 6x^{*2} + b_2^* x^* - b_2^* x_a^* - 6x_a^{*2} & \text{if} \quad \sigma^{(m)}(x^*) \geq 0 \\ 0 \quad \text{if} \quad \sigma^{(m)}(x^*) < 0 \end{cases} \qquad \{18\}$$

This expression contains two unknowns x_a^* and b_2^* that can be found from the conditions

$$\int_{-0.5}^{0.5} \sigma^{(m)}(x^*)dx^* = \frac{T}{hW},$$
$$\int_{-0.5}^{0.5} \sigma^{(m)}(x^*)x^*dx^* = \frac{M}{hW^2} \qquad \{19\}$$

The non-dimensional curvature of the strip centreline can be calculated as

$$k^* = k\frac{6EI}{TW} = \frac{b_2^*}{2\gamma} \qquad \{20\}$$

We now analyse the cases with $\gamma < 0$ and $\gamma > 0$ separately.

"**Full Center**" **Type of Residual Stress**

Firstly, consider the case $\gamma > 0$, that is, when the residual stress distribution under the symmetric loading has compressive stress at the center of the strip and tensile stress at the edges.

When bending moment is applied, the following conditions define the existence of the compressive stress in the strip:

1. For $0 < \gamma \le 0.5$, there is a region of negative stress within the strip width for any M^*. For $M^* < 1 + \frac{1}{\gamma}$, the region of negative stress is isolated from the strip edge, while for $M^* \ge 1 + \frac{1}{\gamma}$ the region of negative stress becomes connected to the strip edge;
2. For $0.5 < \gamma < 2$, the stress is positive everywhere if $M^* < \frac{\sqrt{3(2\gamma - 1)}}{\gamma}$. An isolated region of negative stress appears if $\frac{\sqrt{3(2\gamma-1)}}{\gamma} < M^* < 1 + \frac{1}{\gamma}$. This region becomes connected to the strip edge if $M^* \ge 1 + \frac{1}{\gamma}$;
3. For $\gamma \ge 2$, the region of negative stress exists at the strip edge if $M^* \ge 1 + \frac{1}{\gamma}$.

After manipulations, equations (18,19) can be reduced to the following system of non-linear algebraic equations in x_a^* and b_2^*:

1. For $\gamma \ge 2$ and $M^* \ge 1 + \frac{1}{\gamma}$ and also for $0 < \gamma < 2$ and $x_a^* > -0.5$ we have

$$\begin{cases} -(b_2^* x_a^* + 6x_a^{*2})(0.5 - x_b^*) + 2(\frac{1}{8} - x_b^{*3}) + \frac{b_2^*}{2}(\frac{1}{4} - x_b^{*2}) - \gamma = 0; \\ -3(b_2^* x_a^* + 6x_a^{*2})(0.25 - x_b^{*2}) + 9(\frac{1}{16} - x_b^{*4}) + 2b_2^*(\frac{1}{8} - x_b^{*3}) - \gamma M^* = 0 \end{cases} \qquad \{21\}$$

where $x_b^* = -x_a^* - \frac{b_2^*}{6}$.

2. For $0.5 < \gamma < 2$ and $\frac{\sqrt{3(2\gamma - 1)}}{\gamma} < M^* < 1 + \frac{1}{\gamma}$ and also for $0 < \gamma \le 0.5$ and $M^* < 1 + \frac{1}{\gamma}$ we have the following non-linear equations to determine x_a^* and b_2^*:

$$\begin{cases} -(b_2^* x_a^* + 6x_a^{*2})(2x_a^* + \frac{b_2^*}{6} + 1) + 2(x_a^{*3} - x_b^{*3} + 0.25) + \frac{b_2^*}{2}(x_a^{*2} - x_b^{*2}) - \gamma = 0; \\ -3(b_2^* x_a^* + 6x_a^{*2})(x_a^{*2} - x_b^{*2}) + 9(x_a^{*4} - x_b^{*4}) + 2b_2^*(x_a^{*3} - x_b^{*3} + 0.25) - \gamma M^* = 0 \end{cases} \quad \{22\}$$

The results of the calculations are shown in Figures 7-9, where the non-dimensional curvature is plotted versus the non-dimensional bending moment for different values of γ. The non-dimensional curvature from the Benson's buckling model is also shown in these Figures by solid curve. One can see that the non-dimensional curvature in case of "full center" type of residual stress approaches the non-dimensional curvature of the original Benson's model as γ increases.

As illustrated in Figure 4, instability is associated with non-linear behaviour of the strip centreline curvature and the strip lateral deviation functions, while the linear behaviour is usually associated with stable motion. Figures 7-9 show that in case of "full center" type of residual stresses the linear part of curvature function is extended for larger interval of bending moments compared to the curvature from the original Benson's model. Also, the curvature of the non-linear part of curvature function is smaller than the Benson's curvature. This suggests that the "full center" type of residual stress makes strip more resistant to lateral deviations and instability during rolling. While in case $\gamma < 0.5$ the curvature can be larger in the presence of residual stresses compared to the case without residual stresses, this occurs at the values of bending moment where the curvature function is linear and so no instability is expected.

"Wavy-Edges" Type of Residual Stress

Consider now the case γ < 0, that is, when the residual stress distribution under the symmetric loading has compressive stress at the edges of the strip. When the bending moment is applied, two situations can be distinguished: 1) the regions with the compressive stress exist near both edges of the strip; 2) the region of compressive stress exists only at one edge of the strip. These two cases will be considered separately.

1. For $-0.5 < x_a^* < 0.5$; $-0.5 < x_b^* < 0.5$, equations (18,19) yield the following system of non-linear algebraic equations in unknown parameters x_a^* and b_2^*:

$$\begin{cases} x_a^*(b_2^* + 6x_a^*)(2x_a^* + \frac{b_2^*}{6}) - 2\left[2x_a^{*3} + \left(\frac{b_2^*}{6}\right)^3 + \frac{b_2^* x_a^{*2}}{2} + \frac{x_a^* b_2^{*2}}{12}\right] + \frac{b_2^{*2}}{2}\left(\frac{x_a^*}{3} + \frac{b_2^*}{36}\right) = \gamma \\ -b_2^* x_a^*(\frac{b^{*}{}_2}{12} + x_a^*)(6x_a^* + b_2^*) + 9[(x_a^* + \frac{b_2^*}{6})^4 - x_a^{*4}] - 2b_2^*[(x_a^* + \frac{b_2^*}{6})^3 + x_a^{*3}] = \gamma M^* \end{cases}$$

{23}

2. For $-0.5 < x_a^* < 0.5$; $0.5 < x_b^*$, equations (18,19) yield the system of non-linear equations

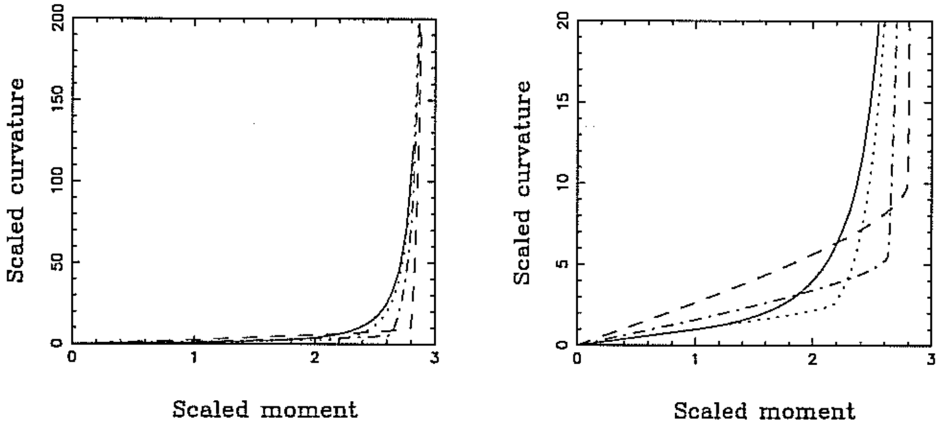

Figure 7: Non-dimensional curvature as a function of non-dimensional moment
_ _ _ $\gamma = 0.03$; _ . _ . _ $\gamma = 0.1$; ...... $\gamma = 0.5$. Solid curve shows the curvature from Benson's model.

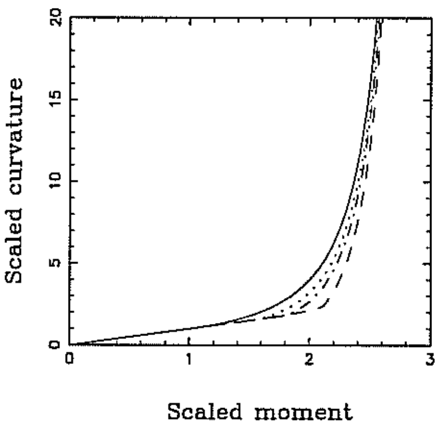

Figure 8 - Non-dimensional curvature as a function of non-dimensional moment
_ _ _ $\gamma = 0.6$; _ . _ . _ $\gamma = 1.1$; ...... $\gamma = 1.9$. Solid curve shows curvature from Benson's model.

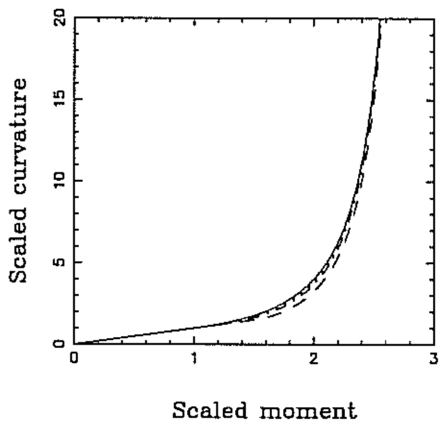

Figure 9: Non-dimensional curvature as a function of non-dimensional moment
___ $\gamma = 2$; _ . _ . _ $\gamma = 5$; ...... $\gamma = 10$
Solid curve shows the curvature from Benson's model

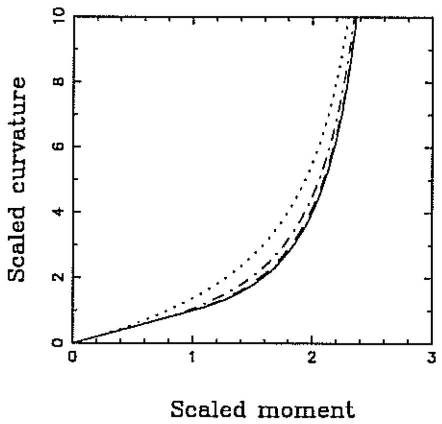

Figure 10: Non-dimensional curvature as a function of non-dimensional moment
___ $\gamma = -10$; .... $\gamma = -3$; _._._._ $\gamma = -1.01$
Solid line shows the curvature from Benson's model.

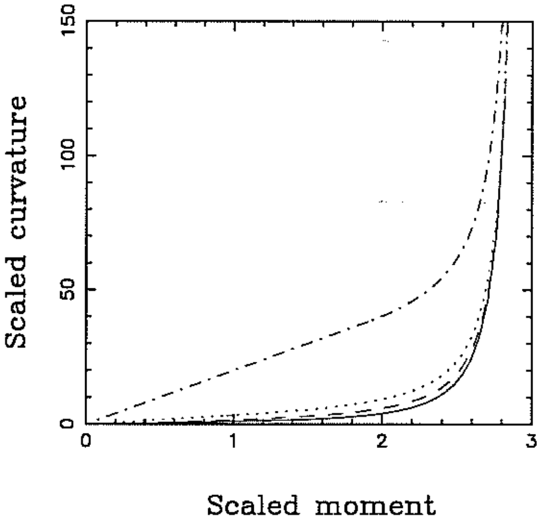

Figure 11: Non-dimensional curvature as a function of non-dimensional moment
___ $\gamma = -0.8$; .... $\gamma = -0.3$; _._._._ $\gamma = -0.05$
Solid line shows the curvature from Benson's model

$$\begin{cases} x_a^*(b_2^* + 6x_a^*)(x_a^* - 0.5) + 2(\frac{1}{8} - x_a^{*3}) + \frac{b_2^*}{2}(0.25 - x_a^{*2}) - \gamma = 0; \\ 3x_a^*(6x_a^* + b_2^*)(x_a^{*2} - 0.25) + 9(\frac{1}{16} - x_a^{*4}) + 2b_2^*(\frac{1}{8} - x_a^{*3}) - \gamma M^* = 0 \end{cases} \quad \{24\}$$

The numerical solution for the non-dimensional curvature as a function of non-dimensional moment is presented in Figures 10 and 11 for wavy-edge type of residual stress distribution and for different values of γ. The curvature from the Benson's buckling model is also shown in this Figure by solid curve. One can see that for "wavy-edges" type of residual stress, the non-dimensional curvature is larger than for the original Benson's model without residual stresses. It approaches the Benson's curvature as the absolute value of γ increases. For $\gamma < -1$, the linear part of curvature function coincides with the linear part of the Benson's curvature function. However, in this case the linear behaviour of the curvature function extends for shorter interval of non-dimensional bending moment, which means that the onset of instability occurs at smaller level of asymmetry in rolling conditions. For $-1 < \gamma < 0$, the slope of the linear part of non-dimensional curvature function is larger than in case of the Benson's model. The smaller the absolute value of γ, the larger the values of curvature. Thus, the "wavy edges" type of residual stress makes strip more susceptible to instability in lateral motion.

CONCLUSIONS

This paper shows that the introduction of a simplified description of buckling into the lateral dynamics model changes the nature of lateral motion and introduces instability in the situations that otherwise would be identified as stable. The buckling may explain the sudden strip track-off observed in metal rolling. The effect of the tension at the entry to the rolling mill on stability of strip lateral motion, which has long been observed in practice, can also be explained by strip buckling.

In this paper, the original Benson's buckling model is extended to the situations when residual stress is present in the web, which is a common situation in metal rolling. The extended model reveals that the web with the tensile stress at the edges and the compressive stress in the middle is less susceptible to instability compared to the web with compressive residual stresses at the edges and the case without residual stress.

Clearly, strip buckling effect, even with the simplified model used, produces significant changes in the lateral dynamics. This issue calls for further investigation. A validation and improvements of a simplified treatment of strip buckling is also required.

ACKNOWLEDGEMENTS

The authors thank the management of BlueScope Steel Research for permission to publish the information in this paper.

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Web Lateral Dynamics with Buckling in Sheet Metal Rolling	**T. Tanopolskaya[1], W. Y. D. Yuen[2], D. Gates[1], & F. R. deHoog[1]**, [1]CSIRO Mathematical & Information Sciences & [2]BlueScope Steel Research, AUSTRALIA
Name & Affiliation	**Question**
Mike Muncy Goodyear	You have developed a better strategy for either control or guiding the material. You now avoid this track-off problem and you have reduced the number of roll crashes dramatically. Is that correct?
Name & Affiliation	**Answer**
Daniel Yuen BlueScope Steel Research	I wish I could say that. The answer is not yet. I regard it as fairly early stage of the research into track-off for the steel industry. In some sense, we are trying to implement methods that the paper industry has deployed for many years. In the steel industry as you can see the first analysis was found in 2002, so 3 years ago. Certainly with the knowledge and insight we gained from this research we would be able to quantify some parameters. I would not say we can define the operating window yet. We know that, for example, increasing entry tension would help. We know that avoiding wavy edges coming out of the rolls would help, but like I said before we still need to do a bit more work.
Name & Affiliation	**Question**
David Pfeiffer JDP Innovations Inc.	Is a lubricant applied to the strip during rolling in the reversing mill?
Name & Affiliation	**Answer**
Daniel Yuen BlueScope Steel Research	Yes, certainly a lubricant is applied. In the video if you watch carefully you would see the water oil emulsion in the roll bite which tries to spread out. Actually a lot of lubricant is being applied.
Name & Affiliation	**Comment**
David Pfeiffer JDP Innovations Inc.	I would think you would need lubricant and perhaps it would help to experiment with the nature of the oil in the oil/water emulsion or some soap or other additives.
Name & Affiliation	**Question**
Daniel Yuen BlueScope Steel Research	To increase the traction?
Name & Affiliation	**Answer**
David Pfeiffer JDP Innovations In.	To increase the traction or decrease the traction. To get some more slip.

Name & Affiliation Daniel Yuen BlueScope Steel Research	**Answer** One of the problems in the rolling process is if we have too little traction the strip will not go through the roll bite. That also causes mill crashes as well. We're really treading on a fine line here.
Name & Affiliation David Pfeiffer JDP Innovations Inc.	**Comment** As I was watching your video I noted that if you had some noncontacting rolls top and bottom of the strip (making a gap for the strip to pass through) it would eliminate or reduce the out-of-plain motion of the strip and would help to straighten the strip entering the nip.
Name & Affiliation Daniel Yuen BlueScope Steel Research	**Answer** Yes, that certainly is an important factor. Any restraining point that we can have upstream of the roll bite is still very far away because of the diameter of the rolls. For that deflector roll you saw in the video, it was something like 2 meters to 2 ½ meters from the roll bite.
Name & Affiliation David Pfeiffer JDP Innovations Inc.	**Question** Is it really necessary to have that much free span of web at the entry to the nip?
Name & Affiliation Daniel Yuen BlueScope Steel Research	**Answer** We don't want to. The design makes it difficult to constrain close to the gap. If you look at the geometry, the angle is really very small. The roll is ½ meter in diameter. The strip is something like 2 mm or 1 mm.
Name & Affiliation Bob Lucas GL&V USA, Inc.	**Question** Relative to the angle of attack of the nip rolls. What sort of angle to the web do you have going in?
Name & Affiliation Daniel Yuen BlueScope Steel Research	**Answer** For cold rolling in the range of 1 to 3 degrees.
Name & Affiliation Bob Lucas GL&V USA, Inc.	**Comment** In the paper industry it's not uncommon to have the web wrap one of the rollers to have that wrap help lay out any potential wrinkles. Obviously paper is different than steel strip.
Name & Affiliation Daniel Yuen BlueScope Steel Research	**Answer** Yes, we also sometimes do that in a process called temper rolling where we have a very small thickness reduction. That would be more similar to paper industry. With high reduction we tend not to do that. We need to achieve the plastic deformation and to achieve symmetry on top and bottom. But I agree with you in the case of temper rolling. We use what we call an anti-crimping roll. That would tend to prevent any wrinkles or looseness going into the roll bite, which could cause roll pinches or mill wrecks.

DISCUSSION I

Leaders: **B. Feiertag & J. J. Shelton**, Oklahoma State University, USA

Name & Affiliation	Comment
Bruce Feiertag Oklahoma State University	First of all, let me add my welcome to that of all the other people who have been up here. It is great to see all of you and I hope that you will be able to go back with some solutions to your problems. Hopefully, the idea here is that you might have some suggestions on things for the future which we would be glad to entertain, but if there are other questions, other comments or that sort of thing that have brought up from any of the presentations that have been made this morning or this afternoon, this is a good time for you to get answers to your questions. Does anyone care to make any comments on any of the presentations? A discussion topic I would like to throw out has to do with the subject that John Shelton talked about – the relationship of spans and tracking – that is to say a situation in which you have a short span preceded by a much longer span. This can be a very sensitive system. We have referred to it for years as pre-entry span steering – that is to say, you have a span coming into a roll which would be of some length. You have a much longer span preceding that. Now once you start, for instance in steering, laterally deflecting the path of the short span, you are going to propagate bending moments back up across the roller that is the upstream roll of the short span into the long span. This creates many tracking and guiding problems. It can come in many, many ways, but it is absolute. So I throw this out as a discussion item: The pre-entry span problem is a big problem. It is very common in steering systems, because you may be deliberately bending the span in order to steer that short span. Once you propagate that lateral bending up into the upstream span which is longer, then you have a real catastrophe on your hands.

Name & Affiliation	Comment
Claude Faulkner DuPont	In the previous paper they were talking about the concave roller. It was very interesting to see how poorly it performed in that configuration. I am wondering if the configuration and the web feeding directly into the nip where the nip is hourglass in shape and is limiting the ability of the concave roll to spread the web.

Name & Affiliation	Comment
Bruce Feiertag Oklahoma State University	One of the things you must keep in mind concerning concave rolls: If the span is short, then the span is stiff and

	if the span is that stiff, you can't shape it. Thus you don't have the capacity to get the spreading you need. It is pointless in many cases to put a concave roll at the exit of a very short span simply because that span is not shapeable to the extent that it would be if the span were much longer. Short entry spans really limit the spreading ability of concave rolls. If you have longer entry spans you can eliminate this problem and get the spreading you require.
Name & Affiliation	**Comment**
Jim Dobbs 3M	In response to the topic that Bruce Feiertag led with concerning the pre-entry span problem: The last two papers we had some discussions about getting the entry roller in close to a nip, that opens up a distinct possibility of having a long pre-entry span. A nip doesn't have to be misaligned, it is perfectly capable of steering a web on its own. If the entry roller is not really pinning the lateral position of the web it can cause an upstream instability feeding right into the nip.
Name & Affiliation	**Comment**
John Shelton Oklahoma State University	There was a term that Doug Kedl of 3M, used for the friction on the first roller upstream from a misaligned roller, web guide or whatever, he called it friction cache. We have had a qualitative understanding of this for a long time. The paper I presented today was the first successful effort that I am aware of in getting this quantified in what really happens when you have interaction of spans and how the friction is really shared. Some of the assumptions such as Coulomb friction that doesn't invalidate the analysis. The fact that you never have perfectly definable friction whether it be viscous, Coulomb, stick/slip or whatever, the analysis is still to a great extent, applicable. The results do deviate a little bit from it, but the problem results are still largely the same.
Name & Affiliation	**Question**
	The nip roll is always driven, but do some of these phenomena vary depending on whether the roll is driven or nondriven?
Name & Affiliation	**Answer**
John Shelton Oklahoma State University	Yes. There is always some tension difference across a roller that is not driven. This difference probably becomes worse if it is driven, if it's not synchronized perfectly. The moment transfer can be applied to driven or nondriven rollers.
Name & Affiliation	**Question**
	Is there a difference of the propagation effect from entry span to pre-entry span that would change based upon a driven versus a non-driven roller?
Name & Affiliation	**Answer**
John Shelton Oklahoma State University	The primary phenomenon is the moment. With span ratios (L/W) less than .25 lateral breakaway occurs before

	moment breakaway. The primary phenomenon is moment breakaway. The web is going faster than the roller on one side than the other. So the moment is transferred into the upstream span. The effect of the roller being driven or nondriven is very minor in comparison to the amount of misalignment versus the amount of friction that is available at the roller that separates the two spans.
Name & Affiliation Keith Good Oklahoma State University	**Question** This is a question directed to Prof. Hashimoto: We listened to John Shelton's discussion this afternoon on moment interaction. This morning, you displayed a slide for a misaligned roller and you showed the shear force due to misaligning in the upstream span. You also showed a frictional force on the roller. Since your angle of wrap was 60 degrees instead of 90, there was a shear force in the exiting span as well. How might that affect your results?
Name & Affiliation Hiromu Hashimoto Tokai University	**Answer** I fixed the wrap angle in my tests at 60 degrees. In my calculations, I changed the angle from 20 to 100 degrees. I got similar results, but these results are not verified experimentally. I will do this in the near future.
Name & Affiliation Neal Michal Kimberly-Clark	**Comment** First I would like to make a comment on one then a challenge to the group. A comment on Mr. Rice's presentation – it's nice to see some empirical work. I think that the air entrainment splashing off the entry is the driver of the issue here. I think that if he was to have a chance to redo this, to consider the wrap angle of the final nip would be an intriguing area to study compared to the nonuniform nip with no wrap. A challenge: We've had a lot of great presentations on how a web tracks in a web line. Typically, we focus on a single roll or possibly two spans. It would be interesting if someone could do some empirical work or some mathematical modeling of multiple spans, or festoons where span length to width ratios vary.
Name & Affiliation David Roisum Finishing Technologies, Inc.	**Question** This is kind of a follow-up on the earlier discussion of critical angles for misalignment in wrinkling, and critical angles for pre-entry span problems. We've had models for about a decade now – some really good models, starting with work Keith Good had done. And even continuing today. We are really able to calculate an acceptable misalignment angle. My question is why isn't the industry using these models? We can define alignment needs with these models and the industry bases alignment tolerances based on their capabilities or lack of capability. They have not made any use of this whatsoever of these models, except maybe the guiding people, but no one else has. Why aren't the machine builders and machine owners making use of these models? Do we need another decade?

Name & Affiliation	Comment
Keith Good Oklahoma State University	When I first got involved in that work, Dave, I was attacking the problem opposite of your description. When I went out and visited web companies, I saw them going to great lengths and spending lots of money aligning every roll in a machine.

Name & Affiliation	Comment
David Roisum Finishing Technologies, Inc.	Needless alignment, which they were performing just because they were capable of doing that.

Name & Affiliation	Comment
Keith Good Oklahoma State University	You are correct. The reason for developing the theory was to determine how much misalignment could be tolerated before a trough or wrinkle resulted. The point is that you don't need to spend as much money aligning some rolls as you do others. These equations help you decide which ones are the important ones.

Name & Affiliation	Comment
David Roisum Finishing Technologies, Inc.	Thus the theory has been developed for ten years. It's the most important thing you guys have provided the machine builders, why are they not using it?

Name & Affiliation	Comment
Ron Swanson 3M	I have a change of subject: Two years ago we had a vote on which way the cambered web tracks in a web line. Can we vote again and see if the results have changed?

Name & Affiliation	Comment
Stuart Critchley Dofasco	A comment in response to Dave Roisum's question on why we don't do what we should do. Technically, I think it goes back to the keynote presentation we heard this morning. We don't do a good job, dare I say, of explaining to business and technical management what we ought to be doing. We don't explain the value of what we need to do. Now a comment on the cold rolling: There were a couple of good suggestions for us. The paper we saw on reversing where the strip has to go both directions in a symmetrical manner, and so we have to keep it flat. We run an operation where the strip goes through continuously. We have learned some lessons today thanks to you folks. We have actually followed the pattern of the industry where we have taken out a roll which from the presentations seen earlier put the lengths of spans in logical manner. This is a challenge for the group: What we see in our product quite often is what is referred to as the other half of the problem. It's not the asymmetry in the machine; it's the asymmetry in the web. So we have some new materials that are coming through our mills where we might have a 10 meter length that is a little asymmetrical that causes a whole lot of problems. This is a challenge for the modeling. If we do not have a nice simple camber but have a camber that varies over a 10 meter length and maybe repeats. So we

are introducing time into our analysis rather than analyzing the steady state position of a web with constant camber. We've done an awful lot of good work and it is real interesting. The good news is that there will be material for conferences for 25 years.

Name & Affiliation	**Question**
Tim Walker TJWalker & Associates	This may not be a new topic, but related to bad web or baggy web. One of the most difficult challenges is where people are trying to push the limits of getting bad web through their machine, especially the film products that have a lot of bagginess coming from caliper variations. How bad can the product be and still get through your process and how do you design a process that allows that bad web to get through? The top issue is nip rollers. I'd like to get rid of nip rollers in web handling, I think you can do that, but we don't get paid to handle the web from point A to point B, we are paid to process the web. We are usually extruding or coating or laminating or embossing or calendaring that requires a nip. So besides getting above the critical tension where all the web has some tension and appears flat, how do you handle webs where it is not possible to get above that critical tension and yet get these webs through these web processes?

Name & Affiliation	**Answer**
John Shelton Oklahoma State University	In some cases the answer may lie in plastically deforming the web to make it more uniform. The steel and aluminum industries have series of several rollers called levelers where the web wraps small diameter rollers that are backed up with a stack or pyramid of other rollers. The intent is by plastically deforming the web in reversed bending that web length variation can be minimized. I'm sure there are other things done in other industries in heating a web under tension to reduce the length variation. It is a difficult problem to improve a web.

Name & Affiliation	**Comment**
David Pfeiffer JDP Innovations	Regarding Tim Walker's and Dave Roisum's comments on machine alignment: This insight comes from the audio industry. If you have a piece of machinery and you've built it and you don't know if it's aligned, you can buy an alignment tape that has the audio tracks totally perpendicular to the web so you can run the alignment tape through the machine and make sure you are tuned up for the highest frequency possible. Some of the enterprising mills should make an alignment film for winding machinery so you can run this perfect film through the winding machinery and make sure it's aligned and you can handle cambered webs.

Name & Affiliation	**Comment**
Bruce Feiertag Oklahoma State University	You can just run a cable through the machine and see how it tracks.

Name & Affiliation	**Comment**
David Landskron Quad Graphics Printing	Regarding the previous comments: As far as the alignment tape, I think the gentleman that had the square grid on his web introduced a helpful method because you could see with a camera the change in the square to a rhombus or a trapezoid as a means of measuring non-uniformity. In regards to Bruce Feiertag's and John Shelton's comments: Conditioning webs is done in the Gravier printing processes, they have web conditioners. They deal primarily with heat, but I think there is a tension effect too. So some industries do that. A comment regarding bagginess: In printing, we try to run a lot of baggy webs. If it's too bad, you reject the roll. It's time for some of the material suppliers to set up a set of specifications and the people using the product to set a set of specifications. If they are not met, it's time to reject the roll.

Name & Affiliation	**Comment**
	I would like to add to that as a teacher who always gets a question about how to handle a baggy web, I just say just run and hide. You have few choices, pull hard or pull loose, try a spreader, but I doubt if any of that would ever work. So I give them the same piece of advice: Give it back to the supplier. The first time you send a roll and a complaint, the second time you send back a truckload and you start catching their attention that way. We really can't solve it or handle it after the fact. Maybe our machinery is tolerant, but it's very hard to make tolerant. The easiest thing to do is to remove rollers starting with nips. So get rid of your printing nips, your holding nips, your widening nips and you'll make your machine a whole lot more tolerant for bagginess. Is that what you want? I think we had better put it back on the suppliers.

Name & Affiliation	**Comment**
Tim Walker TJWalker & Associates	I think brings us to a future topic on winding: What are the characteristics in winding and material properties that promote the length variations that create bagginess? It is not just caliper; but variation in radial modulus, etc. I think we should consider designing film products to be windable and provide high yield in the next process. I don't know that I've seen that presented very well.

Name & Affiliation	**Comment**
Jerry Brown Essex Systems	Addressing the issue of why we don't make better use of the things we have learned: An observation, first of all, the things we do are kind of complicated. You know some of the math is complex and if you want to make these calculations, you've got some things to learn. Then you aren't sure you have it right, right? Then you're going to spend a lot of money building a line. Some of the most important things are invisible to an observer on the process line except in terms of the consequences. We can't see the

stresses. So that brings you back to the issue of instrumentation.

One other comment: In my past life, I worked with beta gauges a lot (i.e. a thickness gage). You would go into a customer's plant and show them the profile of their product thickness. Invariably after we put the beta gauge on line, and you could actually see the thickness profile, they were dumbfounded. They never dreamed it was as it is. I think that is doubly true of stresses and deformations in webs.

Name & Affiliation	**Question**
Ron Lynch Procter & Gamble	This is somewhat related to some of the comments around baggy webs and nips and other types of imperfections. We always say that a perfect web on a perfect machine always runs straight and never wrinkles. We know we have neither, generally. Whatever the problem is, be it baggy webs or any other defect in the material, we are always trying to run the cheapest web that we can as fast as we physically can. So whatever the barriers are, if we can overcome them, we just go up and bump into the next one. So really, if it's not one problem, it's another. To that extent, I know there are a couple of real physical speed limits where the inertia to get a web around a roller exceeds the tensile strength capabilities of the web. That can be 10's of 1,000's of feet per minute in some cases, so it's not really a problem. You did see the Pringle's product this morning; a very doughy sheet that weighs a lot. In this case you can start to calculate an upper speed limit for making Pringles type products. But for most webs, it's not a problem. Are there any other practical barriers that we run into? How baggy can it be before you can get through a nip or is there just zero tolerance for that? Are there other types of limits? Obviously, cheaper and cheaper webs means thin and thinner, so zero tension is another obvious limit, but not necessarily because you can run webs on conveyors at zero tension.

Name & Affiliation	**Comment**
Bruce Feiertag Oklahoma State University	Coming back to the two spans we talked about at the beginning of this session, where we have a short span preceded by a long span and you may have a misalignment in the downstream roll of that tri-roll set, for instance. So you have a bending moment in that short span which is propagating across the preceding roller into the long span. There is a good way to diagnose this problem if you suspect that is what it is and can afford to do this. That is to stop the roller that is between the two spans so that it doesn't rotate or steer. If the lateral behavior becomes more tame and you don't have a tracking effect, you can say that you have identified that it's that one roller. So

	there is an easy way to diagnose that.
Name & Affiliation	**Comment**
John Shelton Oklahoma State University	Another aspect of what Bruce Feiertag is talking about is a bowed roller installed after a fairly short span. It shouldn't be too short or it won't do a good spreading job, but with a long pre-entering span and a wrinkle coming right down it, the Bow roller may take that crease out, but it was responsible for the crease in the first place. Another way of explaining this is to consider your web as two half webs. The thought that each side was a web and it steered each one of them into the pre-entering span to where they overlapped and caused wrinkles.
Name & Affiliation	**Comment**
David Pfeiffer JDP Innovations	I have a comment before we adjourn, and the comment is look how far we have come. I think the credit is due to OSU and the Web Handling Research Center. If you just look at the rack of books out there on the table from all the years' publications, you'll see a fantastic knowledge base and I'm thinking back to the years when John Shelton published his thesis; the years back when Bob Lucas and I worked at Beloit Research Center in Downingtown. We are going to talk about that tomorrow. Forty years ago how little we really knew; we didn't know what we were getting into at that point and how quickly it has become a knowledge explosion and a knowledge base. I think many of you here are loaded with that knowledge and we appreciate everyone coming to share that in a meeting of this sort.
Name & Affiliation	**Comment**
Bruce Feiertag Oklahoma State University	Thank you very much, Dave. We appreciate that. There are many people in this room we can thank.