GAUGE OPTIMIZATION OF THE REFERENCE TENSION IN WINDING SYSTEMS USING WOUND INTERNAL STRESSES CALCULATION

by

M. Boutaous,[1] D. Knittel[2] & P. Bourgin[3]
[1]Centre de Thermique de Lyon
[2]Louis Pasteur Université
[3] Ecole Centrale de Lyon
FRANCE

ABSTRACT

In winding process, the quality of the roll is directly connected to its stress state. The winding tension is the most significant parameter which plays an important role in the stresses generated within a roll, during winding. If the stresses exceed a critical value, defects can appear in the roll and make the web non usable.

This work concerns the estimation and optimization of the maximal dispersion of the reference tension, so that the tangential and radial stresses values remain in a gauge. It aims to find automatically the maximum and minimum limits for the reference tension, so that all curves ranging between these two limits or thresholds, generate radial and tangential stresses, theirs selves included in a gauge fixed in advance. The results lead to a practical gauge optimization of the reference tension for industrial applications.

INTRODUCTION

A web is defined as a continuous, thin and flexible material, which is transported under tension through various processes [1]. Disturbances can affect this tension and the quality of the formed roll. The winding tension reference is generally determined experimentally with respect to the desired quality of the roll. This tension value can be constant or function of the radius, according to any linear or non linear function.

It is well known that the reference tension value, which *a priori* guarantees a good quality roll, is based on the stress generated within the roll. So, it is possible to optimize this reference tension by optimizing the calculated stresses within a roll. Indeed, the model of stress computation makes it possible to define a criterion J given by the sum of the weighted quadratic errors between the obtained stresses and the desired stresses. The reference tension which minimizes criterion J can be optimized using, for example, an algorithm based on the principle of the simplex [2]. To insure a good quality of a roll during winding, it is necessary to maintain the stresses values in gauge. This gauge is defined by the extreme values which the mechanical behavior of the web can accept. In a previous paper [3], the criterion for tension adjustment was the tangential stress. A method for offline reference adjustment and online control based on predictioncorrection using the simplex algorithm was presented. This method was tested numerically. In [4-5], the criterion of tension reference optimization was generalized by considering both the tangential and the radial stress within the roll during winding. The same optimization algorithm was used, taking into account the dynamic tension model. In this previous works, the aim was the calculation of the reference tension which minimizes a criteria J calculated by means of the wound internal stresses model.

In this paper the approach is different: this time it aims to calculate the maximum dispersion which can have an optimal winding tension so that the tension located within this dispersion produces tangential and radial stresses also within a gauges defined preliminary. Thus, the industrials can calculate by advance the acceptable dispersions for the reference tension or for the measured tension. Several examples are then presented concerning how to optimize the variations of the reference tension in order to keep the roll in a stress state which guarantees its quality.

EFFECT OF THE REFERENCE TENSION VARIATIONS RATE DURING WINDING

Usually, the concept of an optimum reference tension for controlling the web tension resort of industrial know-how: see for instance Reid et al. [6], Wolfermann et al [7-8] or Knittel at al. [9]. The control of winding systems is generally based on practical experience and the tension reference does not change or decreases according to a more or less complicated function of the radius.

In this paper, for didactics reason, we assume that the winding tension decrease linearly versus the radius: this curve thus depends on two parameters, i.e. the position and the slope or rate of decrease. It is clear that the approach described in this paper can be applied to more complex functions. In our example, we will show that the slope plays also an important role.

The optimum tension is that which guarantees that the stresses within the roll still confined in a desired gauge. But for industrials, the important and practical question is to know the limits of variations of the reference tension.

In other words, the idea is how to find the maximum and minimum gauge for the reference tension, so that all curves ranging between these two limits (thresholds) generate radial and tangential stresses, theirs selves included in a gauge fixed in advance. The problem is illustrated in the following example, Figure1:

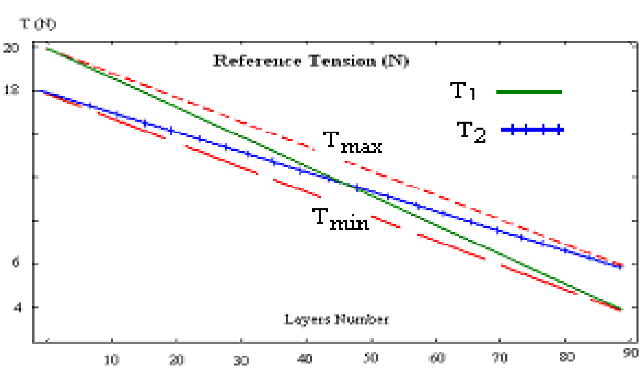

Figure 1 – Evolution of the different linear reference tensions

One wounds a roll with a reference tension which decreases linearly versus the radius. This linear tension is optimised. As example, for the minimal roll radius, near the core, this tension is worth 19N, while for the maximum radius it is worth 5N. It is represented by this line equation: $T_{opt} = a.R + b$. where a and b have been optimized so that a criterion J is minimum, see [3].

As an example, let's choose two tension gauges: $T_{max} = T_{opt} + 1$ and $T_{min} = T_{opt} - 1$, and also choose two other curves included inside the two gauges: therefore T_1 varies from 20 N to 4 N and T_2 varies from 18 N to 6N. As these two curves (winding tension references) are located inside the two limits, one could expect that the corresponding calculated stresses curves are also confined between the stress calculated with T_{max} and those calculated with $T_{min.}$

To compute the stresses state within the roll being wound, a modified non-linear model is developed in the spirit of Hakiels's [10]. Using the linear tension reference defined bellow, the tangential an radial stresses are calculated. To make the comprehension easy, only the tangential stresses are represented.

Surprisingly, the obtained results are different from that expected, as illustrated in Figure 2. Indeed, the stresses σ(T1) calculated with T_1 as reference, is not confined between σ(T_{max}) and σ(T_{min}). The same observation has been made for tangential stresses σ(T_2) computed with T2 as reference tension. We can conclude that the slope of the reference tension influences the stresses as well as the tension itself. The magnitude of the tension is a key parameter, but not sufficient. The rate of the tension decrease plays an important role too. In fact, in Figure 2, the stress state calculated with the reference tension (T_{max}) greater than T1 or T2, leads to stresses lower than that calculated with T1 and T2 in a certain range of radius, and inversely in other radius range.

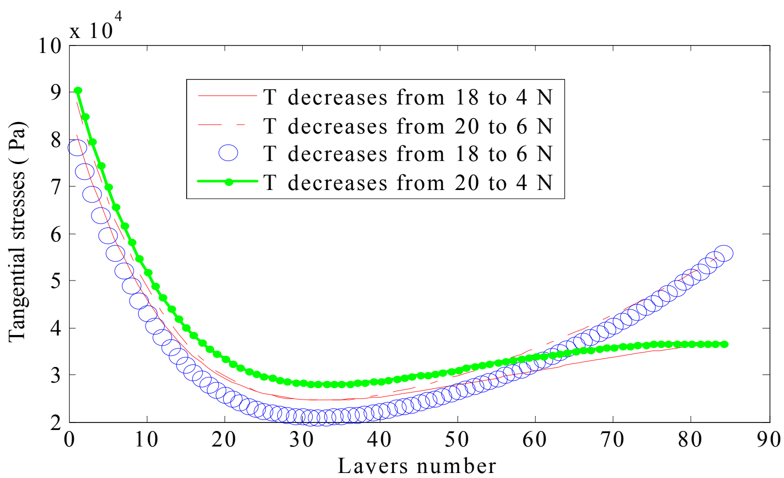

Figure 2 – Tangential stresses for several reference tensions.

EFFECT OF THE FLUCTUATIONS AROUND AN OPTIMIZED SLOPE OF THE REFERENCE TENSION

The industrial control systems never generate perfect follow-up of the tension reference T. We know that the fluctuation about the tension nominal value induces variations in the stress state. To optimize these variations between T_{max} and T_{min}, so that the quality of the roll remain well, we consider now the extreme case: T has a maximum slope and varies alternatively between T_{max} and T_{min}, for each new wound layer, T passes alternatively from T_{max} to T_{min}. Hence, the applied reference tension, named T_{alt} is worth T_{alt} = (a.R +b) +/- c (curves are given with **c** = 1 or 2 in Figure 3.

The generated stress state obtained with this reference tension is presented in Figure 3, where the tangential stresses calculated for T_{alt} are represented with continues line. This time, any tension curves located between T_{max} and T_{min} gives a curve of tangential stresses located between the upper and the lower limits in diamond sign. For greater values of the fluctuating parameter **"c"**, the same behavior is observed: for example **c** = 2, the stresses are represented by the plus sign (+), in Figure 3 for c = 1 and the sign (triangle) for c = 2.

In this case, when the slope changes alternatively from that of maximum to that of minimum value of the reference tension, the stresses still confined between the upper and lower thresholds corresponding to stresses calculated with this gauge of reference tensions.

Consequently, any reference tension which lies between $T_{min}(R)$ and $T_{max}(R)$ gives stresses, with values confined between those calculated for a tension which varies alternatively between $T_{min}(R)$ and $T_{max}(R)$. It is clear that if the dispersion $T_{min}(R)$-$T_{max}(R)$ is too large, one can leave the gauge of the stresses, and one risk to have defects in the roll. It is thus important to calculate this authorized maximum dispersion.

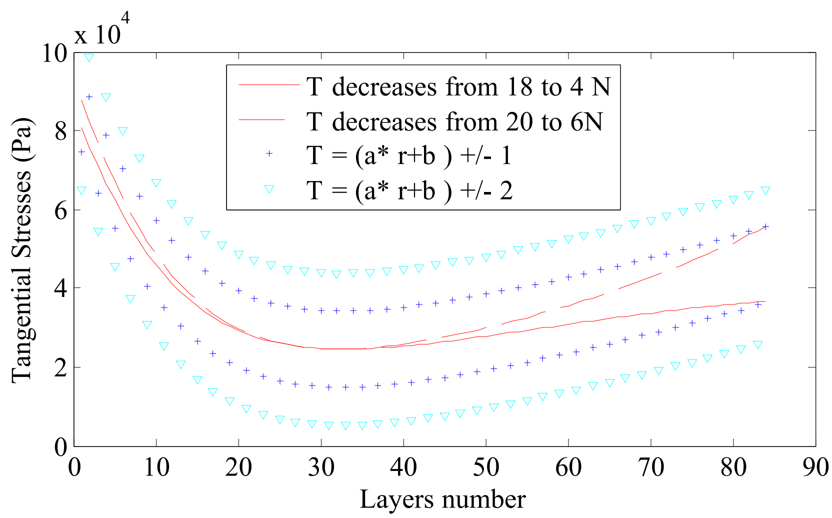

Figure 3 – Tangential stresses for several reference tensions

Now let us consider the situation concerning the case when the fluctuations become more and more (or less and less) important with the increasing of the roll radius. The parameter **"c"** becomes function of the radius, and the reference tension presents an attenuation (or an exaggeration) of its fluctuations during winding. Simulation of the stresses with a reference tension decreasing linearly but presenting fluctuations around the nominal value is presented in Figures 4 and 5.

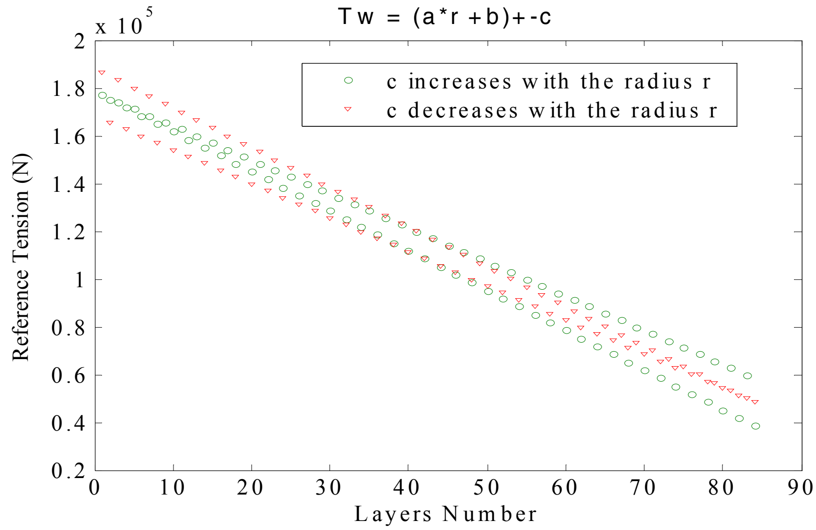

Figure 4 – Reference tension with fluctuations

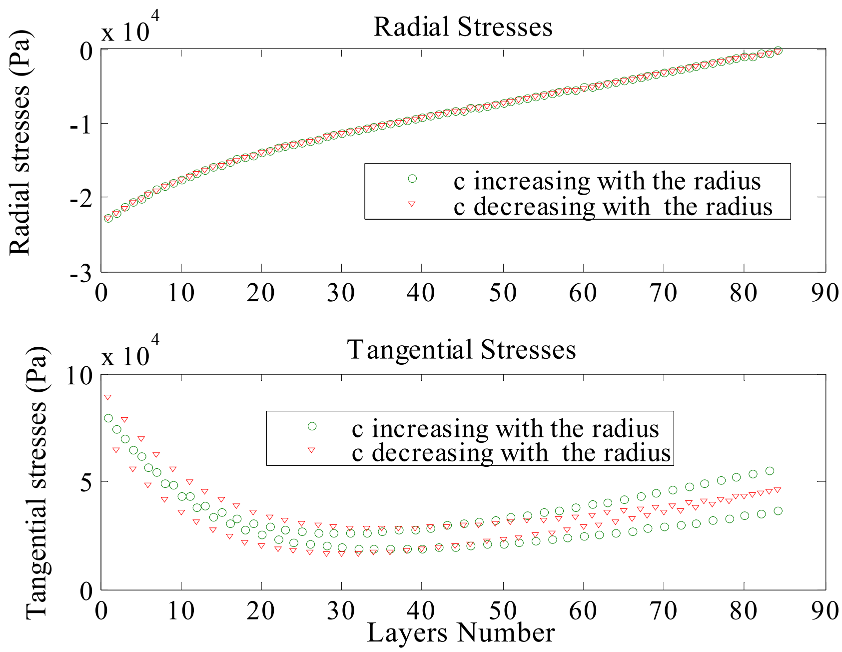

Figure 5 – Stresses generated by the fluctuating reference tension

We observe that the resulted stresses remain overall similar for the two situations. For the radial stresses the same values are obtained. The fact that the layers squeeze each other limits the disturbances. The tangential stresses remain globally comparable. But the lower limit obtained when the fluctuation decreases (triangle symbols) with the radius is smaller then that obtained when the fluctuation of the tension increase (Circle symbols). The risk of web wrinkling due to negative tangential stresses is then more important than in the inverse case. The same phenomena is confirmed when the roll radius is more important, see Figures 6 and 7.

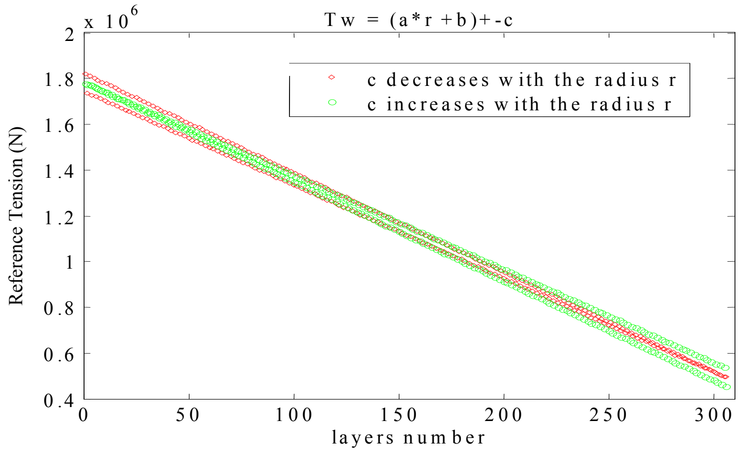

Figure 6 – Fluctuating reference tension for more important radius of the roll

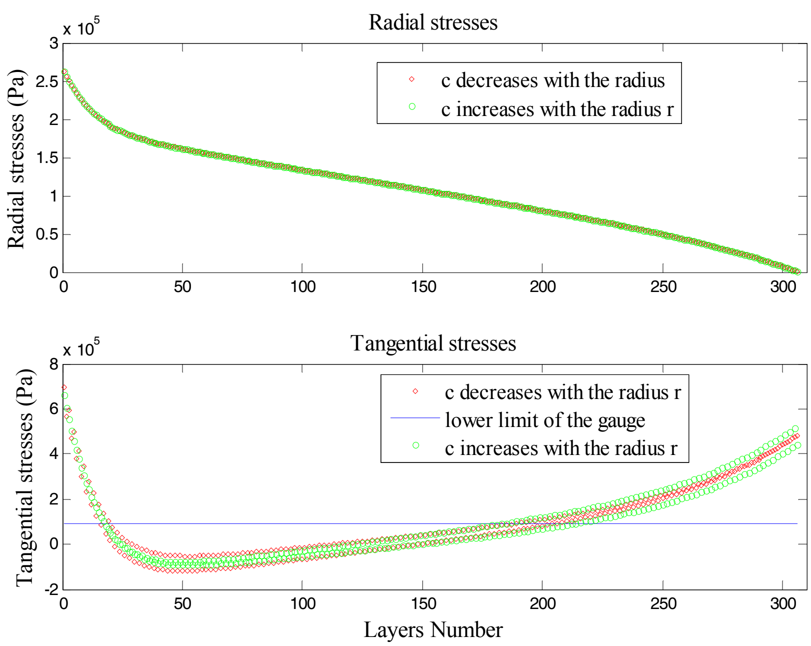

Figure 7 – Stresses generated by the fluctuating reference tension, for more important radius

TENSION OPTIMISATION

In first time, one has to optimize the nominal reference tension. This optimization is recalled quickly in this paragraph. The second step consists in calculating the maximal dispersion authorized for the reference tension.

The algorithm used for the optimization was presented in [3], and for need of this paper we summarized it again.

The Offline optimization of the tension reference is supposed to guarantee *a priori* the production of a perfect roll. However, in reality, the control strategies never generate a perfect follow-up of the reference. The applied tension thus does not lead any more to the optimal stress state in the roll. It is consequently judicious to change the tension reference for the layers which still remain to be wound, throughout all the phase of winding, in order to always optimize the stresses in the final roll according to the criterion to be defined. To optimize the winding tension reference, a mathematical model of stress computation is used to define a criterion J:

$$J = \min (J_T \ , J_R) \qquad \{1\}$$

where:

$$J_T = \int_{R_{roll}}^{R_{\max}} (\sigma_T(T_w) - \sigma_{T\,mean}(r))^2 \, g(\sigma_T, r)) dr \qquad \{2\}$$

and

$$J_R = \int_{R_{roll}}^{R_{\max}} (\sigma_R(T_w) - \sigma_{R\,mean}(r))^2 \, g(\sigma_R, r)) dr \qquad \{3\}$$

T_w represents the winding tension, σ_T is the tangential stress and σ_R radial stress. The stresses are calculated using the stress state mathematical model, Bourgin & al. [11], Connolly & al. [12], or Hakiel's [9] for instance. σ_{mean} is some averaged tangential or radial stress value, in a given range (gauge) and $g(\sigma_, r)$ denotes some penalty function defined by:

$g(\sigma_T, r)$ and $g(\sigma_R, r)$ = 1 if σ is in the gauge

$g(\sigma_T, r)$ and $g(\sigma_R, r)$ >> 1 else.

The reference tension which minimizes the cost function J is optimized using an algorithm based on the principle of the simplex presented by Nelder and Mead, [2]. Of course the convergence towards a minimum does not guarantee that it is the global minimum and not a local one. One way to overcome this difficulty would be to use "genetic algorithms". However, they are generally heavy to apply to industrial problems. One compromise here is to choose the optimization region in a pertinent way. A last remark: the existence of a solution depends on the gauge.

OPTIMISATION OF THE ADMISSIBLE TENSION DISPERSION

One assume a reference tension decreasing linearly: (T_{alt} = a.r +b), **c** is a parameter introducing a dispersion about the nominal value of T_{alt}. , the reference tension becomes (T_{alt} = a.r +b +/- **c**). To optimize the parameter **c**, we proceed by increment: we start the calculation by a small value of **c**, and we compute the stresses. As long as they do not reach the gauge limiting the lower value accepted for the tangential stresses, we increase **c**. The maximum value reached by **c** gives the T_{max} and T_{min} , see Figures 8 and 9, where the example taken is for T decreasing from 8 to 2 N, and a gauge limit of 6 10E4 and 1. 10E4 the optimal **c** find is 0.1165.

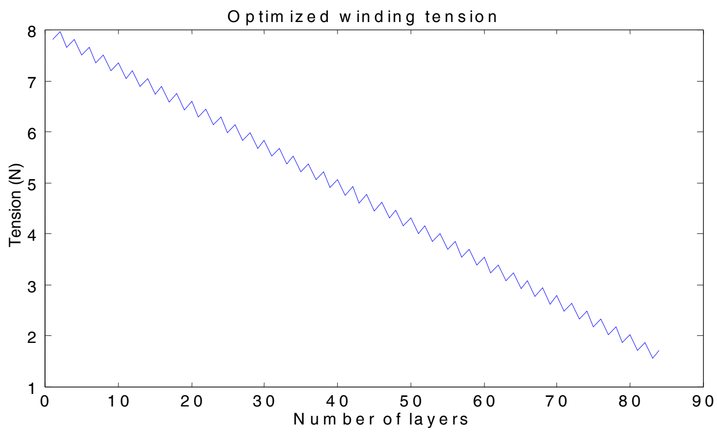

Figure 8a - Linear reference tension with dispersion (c=+-1)

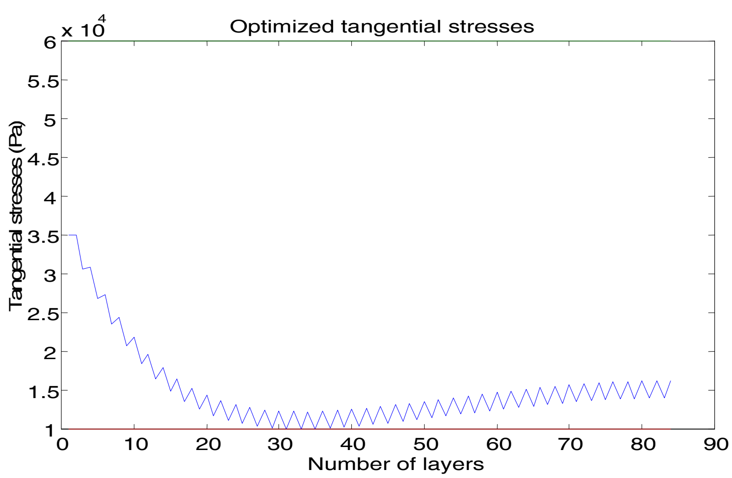

Figure 8b - Corresponding tangential stresses with dispersion in the winding tension

An automatic approach consists now, to find by optimization, the maximum value of "**c**". The simplex method, described in [2] or in [3-5], is used to minimize the "difference" between the lower threshold of a fixed gauge and the minimum value reached for the tangential stresses, with a penalty function when the gauge is exceeded. (In this example, one does not take into account the maximum value of the gauge, because the calculated stresses are rather far from its value)

Now, what it happens if the reference tension remains at first constant and after a certain value of the roll radius it decreases linearly? I.e. **"c"** is weighted by a function F(r) which depends on the radius and beforehand selected, Figure 9.

The same algorithm based on the theory of Nelder and Mead [2], is used to optimize the parameter **"c"** of the tension dispersion, in order to minimize the "difference" between the gauge and the lowest value calculated for the tangential stresses.

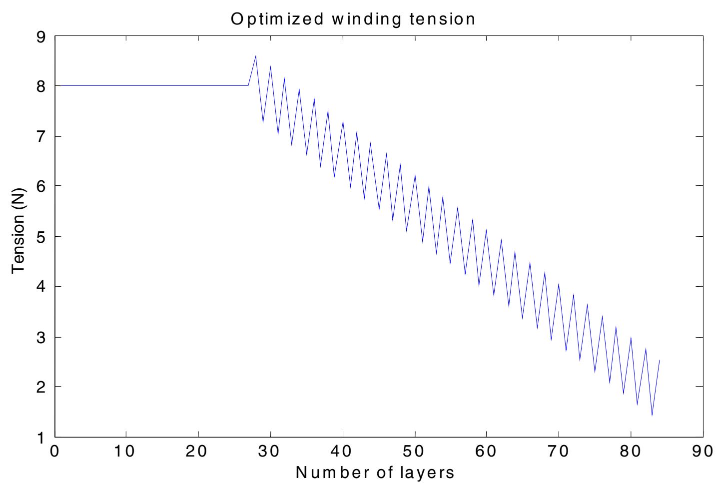

Figure 9a - Reference tension with dispersion (c=+-1)

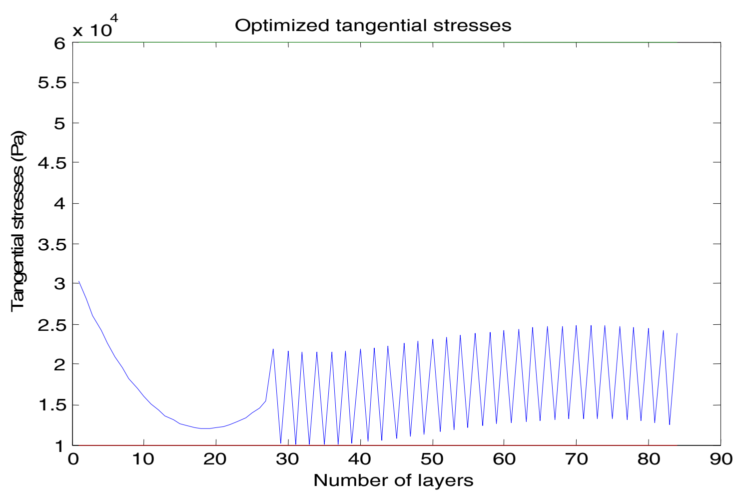

Figure 9b - Corresponding tangential stresses for c = +/- 1

For example, taking the previous values for the gauge and the reference tension, but maintaining the reference tension constant for a certain time before decreasing it. The result shows that the maximum optimized value for the dispersion is about c = 0.6007. This value is higher than that obtained before with a linear decreasing.

Really, the dispersion has never a constant value, but changes during winding. To simulate this effect, one take a reference tension shown previously in Figure 9a, but this time we assume that the parameter **"c"** increases when the roll radius increases as in Figure 10a. The results are shown in Figure 10b. The maximum value of the dispersion parameter **"c"** is about 0.8554. This result shows that the tension rate (slope of the curve) is an important parameter, but the type of the fluctuations (stable or varying) plays an important role too.

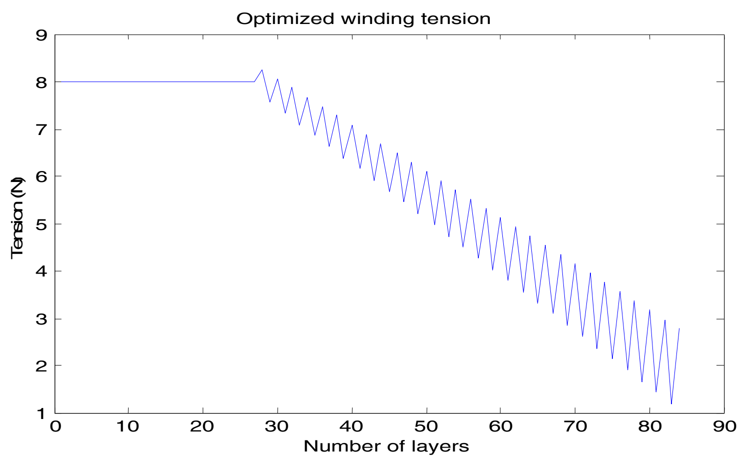

Figure 10 a - Reference tension with **c** increasing with the radius

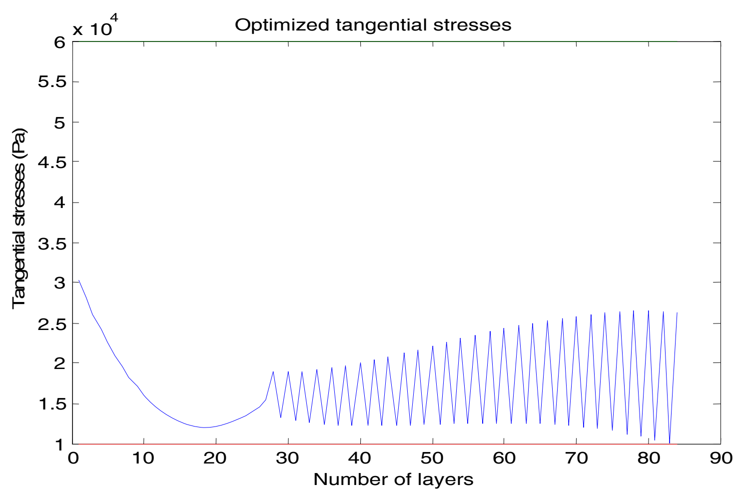

Figure 10 b - Corresponding stresses for **c** increasing with the radius.

This case is particularly useful, when one does not know the slope to be chosen for a decreasing reference tension. By this means, one can have access to the maximum value which leads to have stresses values more important than that of the gauge which limits the field of the desired constraints and which ensure a good quality of the wound roll.

CONCLUSION

During winding, the web tension acts directly on the stress state within a roll, it is very important to master and to optimize it during the winding process.

A method for practical optimization of the reference tension was presented, and several simple examples are commented. The simplex method is introduced to optimize a gauge limiting the stresses values within a roll, with respect to an optimized winding tension. The method is then used to study the fluctuations which can occur around the reference tension, and to give a knowledge of the maximum dispersion acceptable for the quality of the roll.

Two applications are aimed by this approach:

- the estimation of the dispersions of the measured tension with regard to the reference one (for which the gauge was calculated), and deducing if the wound roll respect the stress gauge, without recalculating the stresses.

- the choice of the winding reference confined in a constraining gauge, with respect to the stress state within the roll.

REFERENCES

1. Krebs S., "Multiple-Tension Control Using a New Approach in Signal-Processing," Proceeding of the 4th International Conference on Web Handling, Oklahoma State University, June, 1997.
2. Nelder, J. A., Mead R. "A Simplex Method for Function Minimization," Computing Journal, No. 7, 1965, pp. 308-313.
3. Bourgin, P., Boutaous, M., and Knittel, D., "Online Control of Tension in Web Winding Systems Based on Wound Roll Internal Stress Computation," Proceeding of the 6th International Conference on Web Handling, Oklahoma State University, June, 2001.
4. Knittel, D., Bourgin, P., and Boutaous, M., "Control and Online Tension Reference Optimization in Winding Systems: Application to an identified Three Motors Simulator," Proceeding of the 8th International Conference on Web Handling, Oklahoma State University, June, 2001.
5. Boutaous, M., Bourgin, P., and Knittel, D., "Optimization of the Online Tension Control in Winding Systems," IFAC Symposium MMM'2004, France, 2004.
6. Reid, K. N., and Lin, K-C., "Control of Longitudinal Tension in Multi-Span Web Transport Systems during Start-Up", Proceeding of the 2nd Intl. Conf. Web Handling, Oklahoma, USA, 1993, pp. 77-95.
7. Wolfermann, W., "Tension Control of Webs. A Review of the Problems and Solutions in the Present and Future," Proceeding of the 3rd International Conference on Web Handling, Oklahoma State University, June, 1995.
8. Wolfermann, W., "Sensorless Tension Control of Webs," Proceeding of the 4th International Conference on Web Handling, Oklahoma State University, June, 1997.
9. Knittel D., Laroche, E., Gigan, D., and Koç, H., "Tension Control for Winding Systems with Two Degrees of Freedom H_∞ Controller," IEEE Transactions on Industry Applications (IAS), vol. 39, No. 1, pp. 113-120. 2003.

10. Hakiel Z., "Non-Linear Model for Wound Roll Stress," Tappi J. Vol. 70, 1987, pp. 113-117.
11. Bourgin, P., and Bouquerel, F., "Winding Flexible Media: A Global Approach." Adv. Info. Storage Syst. ASME, Vol. 5, 1993, pp. 493-511.
12. Connoly D., and Winarski D.J., "Stress Analysis of Wound Magnetic Tape," Proceeding of ASLE Intl. Conf. SP 16, San Diego, 1984, pp. 172-182.

Gauge Optimization of the Reference Tension in Winding Systems Using Wound Internal Stresses Calculation

M. Boutaous[1], D. Knittel[2], & P. Bourgin[3], [1]INSA, [2]Louis Pasteur University, [3]Ecole Centrale de Lyon, FRANCE

Name & Affiliation	Question
Keith Good, Oklahoma State University	Many of us are just beginning to understand what our steady state profile in winding tension ought to be. You are now showing us what the fluctuations in winding tension should not exceed. As a result of your research, do your foresee being able to forecast limits for nip load fluctuation and other sorts of variations, not just winding tension?
Name & Affiliation	**Answer**
M. Boutaous, Centre de Thermique de Lyon	The fluctuations can be due to many causes which affect the reference tension. When the tension becomes disturbed, what limit can we accept prior to the disturbance affecting the roll quality? In this research we focused on the tension fluctuations, but also other fluctuations can be studied as well – the nip pressure variation for example.
Name & Affiliation	**Question**
Marko Jorkama, Metso Paper	What was the fluctuation rate of the tension you used in your examples?
Name & Affiliation	**Answer**
M. Boutaous, Centre de Thermique de Lyon	We incorporated two types of variation rate in our study – the rate of the nominal tension decrease and the rate of the fluctuation around this nominal curve. The first one is given (it can be optimized or not as presented in our previous works); the second one is chosen with a maximum rate, and we have to optimize its magnitude as given by the parameter C.
Name & Affiliation	**Question**
Marko Jorkama, Metso Paper	Does that have any influence on the result if you have very slow fluctuation versus a very rapid fluctuation?
Name & Affiliation	**Answer**
M. Boutaous, Centre de Thermique de Lyon	Yes, it does, but we have studied the worst (extreme) case, which includes all reference tension variations. The optimized parameter C yields the tension range which ensures good roll quality.