Web Winding Simulation and Wound Roll Stresses*

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Abstract

A method for simulating a web winding process and for predicting wound roll stresses is proposed. The simulation model is two-dimensional and is composed of a web and a core. The simulation was carried out on a FEM software to investigate effects of a slip between web layers, a core rigidity, and a leading edge of a wound web on the wound roll stress distributions. The results show that both the radial and circumferential stresses of the wound roll become extremely larger when the web layer slip is considered. While they decrease when the core rigidity becomes lower. The simulated stresses for no slip cases are compared with the results obtained by Hakiel model.

Key words: Finite Element Method, Simulation, Web, Winding, Roll, Stress Distribution, Slip

1. Introduction

Recently, a huge amount of webs such as optical films, package films, and papers are produced on a large scale and used in many industrial fields. In order to rise productivity, both a production line speed and a width of web are increasing. However, there are many technical problems on web handling processes like transportation and winding. A skew and wrinkle of a web transported by rollers and several defects like a telescope, starring or concave of wound rolls are typical examples of the web handling problems. Concerning the wound roll defects, they depend strongly on the wound roll stress distributions, which are determined by material properties of a web and core and winding conditions, and many studies have been done to predict the roll stresses.

Altman⁽¹⁾ proposed integration formulas for predicting the radial and circumferential stresses of a wound roll considering that the wound roll is a thick-walled cylinder with boundary conditions of radial stresses on a core and the roll outer radius and both Young's moduli and Poisson's ratios of the roll in the radial and circumferential directions are constant and have an orthotropic nature.

Hakiel⁽³⁾ proposed a new iteration method for calculating the radial and circumferential stresses of the wound roll. In his model, the roll is assumed to be a collection of concentric hoops of web and a winding process is modeled as adding a tensioned hoop onto the roll one by one, neglecting a slip between web layers. The roll elasticity has orthotropic and non-linear properties and the roll stress distributions are a function of the roll radius only.

Good et al. ⁽⁴⁾ noticed that the radial stress of a wound roll fell far short of the Hakiel's model results and they considered that the web tension became smaller due to the decrease in the web caliper during winding. They proposed an improved Hakiel calculation model and show that the predicted results had a good agreement with the experimental results

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when the slip between web layers is negligible.

After that, Hakiel⁽⁵⁾ and Kedl⁽⁶⁾ tried to extend the one-dimensional Hakiel calculation model to a two-dimensional model, which includes the web-width direction. The wound roll is divided into several segments (strips) over the width direction. In each segment, the radial and circumferential stresses are constant in the width direction and can be calculated by the ordinary Hakiel model.

Wickert et al.^{(7),(8)} treated a two-dimensional axis-symmetrical finite element model and constructed an algorithm to calculate increments of radial, circumferential, and axial stresses of a roll when a new n-th lap of web was wrapped. They showed the predicted distributions of the above three stress components on a radial-width plane. However, the shape of the radial and circumferential stress distributions along the radial direction seem to be different from those obtained by the ordinary Hakiel model.

While, Tanimoto et al.⁽¹⁰⁾ extended the Hakiel model to taking account of both air-entrainment during winding and air-permeability of web layers. They show that the radial stress of the wound roll decreases by the air-entrainment because of the decrease in an equivalent radial stiffness of the wound roll but the air-permeability recovers the equivalent radial stiffness and the radial stress.

These studies give us useful information but the wound roll defects have not been clarified yet. It is desirable to develop a new method for predicting the roll stresses under more real situations, considering effects of the slip between web layers, a flexible core, and a leading edge of a wound web and extension to a three-dimensional model.

One of the authors⁽¹¹⁾ has simulated a generation process of a folded wrinkle of a tensioned web transferred by a tilt roller by using a FEM software. In this simulation, a driving roller is rotated step by step with a constant small angle and both displacements and stresses of the web are statically calculated at each step. A motion simulation of the folded wrinkle generation process is obtained as a sequence of the simulated results of more than thousands of steps. The results show that a wavy wrinkle runs onto the tilt roller and the wrinkle width becomes smaller with increasing its height due to a difference of web skew velocity along the web width direction, and finally it falls down on the roller and a folded wrinkle generates. This type of the folded wrinkle tends to occur as the roller tilt or the friction coefficient becomes larger or as the web tension becomes smaller.

In the present study, a web winding process is simulated by applying the above mentioned motion simulation. A FEM model is two-dimensional and is composed of a web and a core. The radial and circumferential stress distributions of wound rolls are obtained for several cases. The results show effects of a web layer slip, a flexible core and a starting point of web winding on the stress distributions. Some of the results are compared with those obtained by the Hakiel model.

2. Simulation model and Procedure

A web winding process was simulated by using a FEM software Marc 2005 r3. Figure 1 shows a simulation model treated here. The model is two-dimensional and is composed of a core with 20mm in radius (r_c) and a web with 6 or 20m in length (L), 1m in width (an imaginary width) and 0.5mm in thickness (h). The web is divided by quadrilateral plane strain elements with 2mm in length and 0.5mm in height. Young's modulus and Poisson's ratio for an isotropic web are $E_\theta = E_r = 50\text{Mpa}$ and $\nu = 0.01$ and the winding tension is 240N/m ($=T_w$) (see Table 1). The tension is constant throughout the winding. A radius of wound roll is 36 or 60 mm (r_s). For an orthotropic web, material properties (input data for Marc) shown in Table 2 are used ($E_\theta = E_{11} = 50\text{Mpa}$, $E_r = E_{22} = 5\text{Mpa}$). The core is rigid in most cases and is modeled as a rigid circular surface but in one case, it is assumed to be flexible and is divided by the same type of element as the web is divided.

The simulation procedure is as follows. ①The core and web are made on a pre-post display. The web is moved to the core and the leading edge of the web is fixed (glued) to the

core surface. ②The winding tension is applied to the end edge of the web. ③The core is rotated at a constant angular velocity. The web is wound around the core as the core rotates by a constant angle at each calculation step (0.01rad/step). The displacement, stress, slip, friction force, and other quantities are calculated at each step by a static analysis and a motion simulation is obtained as a series of the calculated result of each step. So many calculation steps are needed to get a relatively thick wound roll. Then only the calculation data at every 100 steps are stored and used to show the results. Five cases shown in Table 3 are simulated, considering whether the web elasticity is isotropic or orthotropic, the slip between web layers is considered or not and finally the core is rigid or flexible. The friction force acting between web layers is assumed to be a function of a friction coefficient μ , a normal force P , and a slip velocity V_r and C is a reference slip velocity (see Eq.(1) and Fig.2). It should be determined by experiments but in this simulation $\mu=1$ and $C=1\text{mm/s}$ are assumed. A total calculation steps for the Case A (80th lap) is about 50,000 and the calculation time is about 200 hours in our computer center machine (SGI- altix4700, CPU:Itanium2, 1.6GHz $\times$ 64, 409.6GFLOPS).

Fig. 1 Two dimensional FEM model for web winding simulation

Table 1 Main parameter values

h	0.5 mm
L	6/20 m
r_c	20 mm
r_s	36/60 mm
E_θ	50 MPa
E_r	5 MPa
ν	0.01
T_w	240 N/m

Table 2 Orthotropic web properties

Young's moduli [MPa]	Poisson's ratios	Shear moduli [MPa]
$E_{11}=50$	$\nu_{12}=0.01$	$G_{12}=2.48$
$E_{22}=5$	$\nu_{23}=0$	$G_{23}=0$
$E_{33}=50$	$\nu_{31}=0$	$G_{31}=0$

Table 3 Simulation cases

Case	Web elasticity	Slip between layers	Core elasticity
A	isotropic	no slip (glue)	rigid
B	orthotropic	no slip (glue)	rigid
C	isotropic	slip ($\mu=1$)	rigid
D	orthotropic	slip ($\mu=1$)	rigid
E	orthotropic	no slip(glue)	flexible

Fig.2 Friction force $C = 1\text{mm/s}$

3. Simulation results

Figure 3 shows a wound roll obtained by the FEM motion simulation. The radial and circumferential stresses of the wound roll are obtained from the simulation results of σ_{22} ($=\sigma_r$) and σ_{11} ($=\sigma_\theta$) at each nodal point. In the following figures, the average of the stresses of the inner and outer nodes of the web element is plotted. The stress data σ_{ii} ($i=1,2$) are mainly collected along a reference radial line but in some cases along a circumferential line shown in Fig.3.

3.1 $\sigma_r(r)$ and $\sigma_\theta(r)$ for no slip cases

Figures 4(a) and (b) show the simulation results of the roll stresses at the 80th lap of winding for the Case A (no-slip, isotropic case). The horizontal axis is a non-dimensional roll radius and the vertical is $\sigma_r(r)$ and $\sigma_\theta(r)$, respectively. In each figure, the dot points denote the simulation results and the solid line is the result predicted by the Hakiel model. Both results show the same tendency but the simulation results are a little bit larger than the Hakiel model results. The difference seems to arise from that in the Hakiel model, the strain compatibility equation is derived by neglecting a circumferential displacement of an element. σ_r and σ_θ are proportional to the winding tension T_w for the Hakiel model results but they are not proportional for the simulation results.

Figures 5(a) and (b) show the simulation results for the Case B (orthotropic, no-slip case). These figures show that the simulation results and the Hakiel model results show nearly the same tendency, especially, in the negative area of σ_θ .

Fig. 3 Wound roll and stresses of a node
(a simulation result at the 80th lap of winding)

Fig.4 Simulation results of roll stresses compared with Hakiel model results
(at the 80th lap, Case A : isotropic, no-slip)

Fig.5 Simulation results of the roll stresses compared with Hakiel results (at the 80th lap, Case B : orthotropic, no-slip)

3.2 $\sigma_r(r)$ and $\sigma_\theta(r)$ for slip cases

Figures 6(a) and (b) show effects of the slip between web layers. The simulated slip cases C and D are shown together with the previous no-slip cases A and B. The horizontal and vertical axes are the same as the previous figures. These results show that the roll stresses σ_r and σ_θ become larger when the slip is considered. This is because the web is tightly wrapped due to the slip. In Fig.(b), the σ_θ values fluctuate largely in the inner side of the roll. This is because the layer slip does not occur uniformly in the roll.

Figures 7(a) and (b) show the slip between web layers during winding. Figure (a) is at the 5th lap of winding, and Fig.(b) is at the 80th lap of winding. In Fig.(a), five nodes A to E on the successive web layers are close together, but in Fig.(b), they are apart from each other. This means the web layers slip each other during winding. This slip phenomenon is not considered in the Hakiel model.

Figures 8(a) and (b) show change processes of σ_r and σ_θ of four different nodes a-d (whose angular positions are apart from about 90°) of the 5th lap layer in Case C. The node d is situated on a radial line passing through a gap area between the core and web which is situated just before the leading edge of the wound web. In Fig.(a), the σ_r of the

Fig.6 Stress distributions along radial direction (Effects of the slip between web layers and orthotropic web elasticity)

a-c nodes increases gradually as the winding proceeds, but the σ_r of the d node is almost zero until 40,000 steps and then suddenly increases and decreases. The reason is that the σ_r of nodes on the inside web layers is zero above the gap area but the σ_r of the nodes increases when the nodes moves onto the leading part of the wound web due to the layer slip and it decreases when the nodes pass through the leading part. In Fig.(b), the σ_θ of the a-d nodes repeats increasing and decreasing violently and makes its amplitude larger as the winding proceeds. It is thought that web elements in the inner roll repeat expansion and contraction gradually due to the web layer slip.

Fig. 7 Slip between web layers during winding
(Case C: isotropic, slip)

Fig. 8 Stress changing process of four nodes due to web layer slip during winding
(Case C: isotropic, slip, four nodes on the 5th lap of wound web)

3.3 $\sigma_r(\theta)$ and $\sigma_\theta(\theta)$ for no slip and slip cases

Here we investigated the roll stress distributions along the circumferential direction $\sigma_r(\theta)$ and $\sigma_\theta(\theta)$. In the Hakiel model, $\sigma_r(\theta)$ and $\sigma_\theta(\theta)$ are constant because of an assumption but in this simulation there may exist some effect of the starting point P1 (the leading edge) of web winding. The angular position θ along the circumferential direction is defined as shown in Fig.9. Here the angular position of the point P1 is $\theta \approx 8.3^\circ$.

Figures 10(a) and (b) show variations of $\sigma_r(\theta)$ and $\sigma_\theta(\theta)$ of the 5th, 20th, and 40th lap layers for the case A (no slip case). In Fig.(a), the $\sigma_r(\theta)$ increases and decreases near the P1 point which is indicated by a vertical line, but in other θ area, the σ_r is almost constant. The maximum value of the σ_r is about 1.4 times larger than the average of $\sigma_r(\theta)$ for the 5th lap layer. This change of σ_r can be observed at the 40th lap layer. It is concluded

that the starting point of the web winding affects largely the radial stress of the layer elements above or near-off the starting point P1. While in Fig(b), the $\sigma_\theta(\theta)$ of the 5th lap layer shows a concave nature before the P1 point but its effect can not be seen for other cases of the 20th and 40th lap of layers.

Figures 11(a) and (b) show variations of $\sigma_r(\theta)$ and $\sigma_\theta(\theta)$ for the Case C (slip case). In Fig.(a), the $\sigma_r(\theta)$ shows the same tendency as shown in Fig.10(a). But in Fig.11(b), $\sigma_\theta(\theta)$ changes largely, especially for the 5th lap layer. This variation of $\sigma_\theta(\theta)$ is coming from the slip between web layers and it corresponds to the $\sigma_\theta(r)$ variation in Figs. 6(b) and 8(b).

Fig. 9 Angular position of wound roll
(at the 80th lap, 50,600 step)

Fig. 10 Stress distributions along circumferential direction
(Effects of web leading edge, at the 80th lap, Case A: isotropic, no-slip)

Fig. 11 Stress distributions along circumferential direction
(Effects of web leading edge, at the 80th lap, Case C: isotropic, slip)

3.4 Effects of flexible core

Figure 12 shows a web ($L=6\text{m}$) wound on a flexible core ($r_c=20\text{mm}$, $h_c=5\text{mm}$, $E_c=1\text{MPa}$). The inside of the core is glued to a rigid circular surface. The web dimensions, web material properties and other conditions are the same as the case B. Using this model, effects of the flexible core on the wound roll stress distributions are investigated. Figure 13 shows a simulation result where the 33rd lap of the web is wrapped and a distribution of σ_r is represented in contour. The figure indicates that the leading part of the web sinks in the flexible core and a few areas with high compression and high tension exist.

Figures 14(a) and (b) show the effects of the flexible core on the roll (the web and core) stress distributions along the radial direction. Three curves denote the simulation results for three different core Young's moduli, $E_c=\infty$ (the rigid core), $E_c=5$ and 1MPa . The two figures (a) and (b) show that the roll stresses decrease as the flexible core becomes flexible, especially in the σ_r of the core outer surface and the σ_θ of the web inner and the core outer surfaces.

Fig. 12 Web winding model with flexible core (Case E)

Fig.13 Simulation result in case of flexible core
Distribution of σ_r

Fig.14 Effects of flexible core on roll stresses (at the 33rd lap, Case E)

4. Conclusions

- (1) A two-dimensional web winding simulation method was constructed by the aid of a FEM software and the wound web stress distributions $\sigma_r(r,\theta)$ and $\sigma_\theta(r,\theta)$ were

obtained for several cases.

For the cases of neglecting the web layer slip:

- (2) The simulated $\sigma_r(r)$ and $\sigma_\theta(r)$ in the most area of the angular position of the wound roll except near the wind starting angular position show nearly the same tendency as the results calculated by Hakiel model. These simulated $\sigma_r(r)$ and $\sigma_\theta(r)$ are a little bit (up to 30%) larger than the Hakiel model results. The reason seems to be that a circumferential displacement is neglected for deriving the strain compatibility equation in the Hakiel model.
- (3) The simulated $\sigma_r(\theta)$ extremely increases and then decreases near the wind starting angular position. In this simulation, $\sigma_r(\theta)$ becomes 20-30% larger and smaller for its average level, and its effect reaches 40th lap of winding when the 80th lap is wound.

For the cases of considering the web layer slip :

- (4) The slip between web layers occurs largely in the inner area of the wound roll. It makes $\sigma_r(r)$ and $\sigma_\theta(r)$ higher comparing with the cases of neglecting the web layer slip and $\sigma_\theta(\theta)$ fluctuates largely in the slip area.

Effects of the flexible core:

- (5) The flexible core makes the $\sigma_r(r)$ and $\sigma_\theta(r)$ lower, especially near the interface between the web and core. The leading part of the wound web sinks into the flexible core and it affects the core and web stress distributions.

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