Viscoelastic web curl due to storage in wound rolls

SHENG PAN, AURELIE AZOUG, AND JAMES K. GOOD

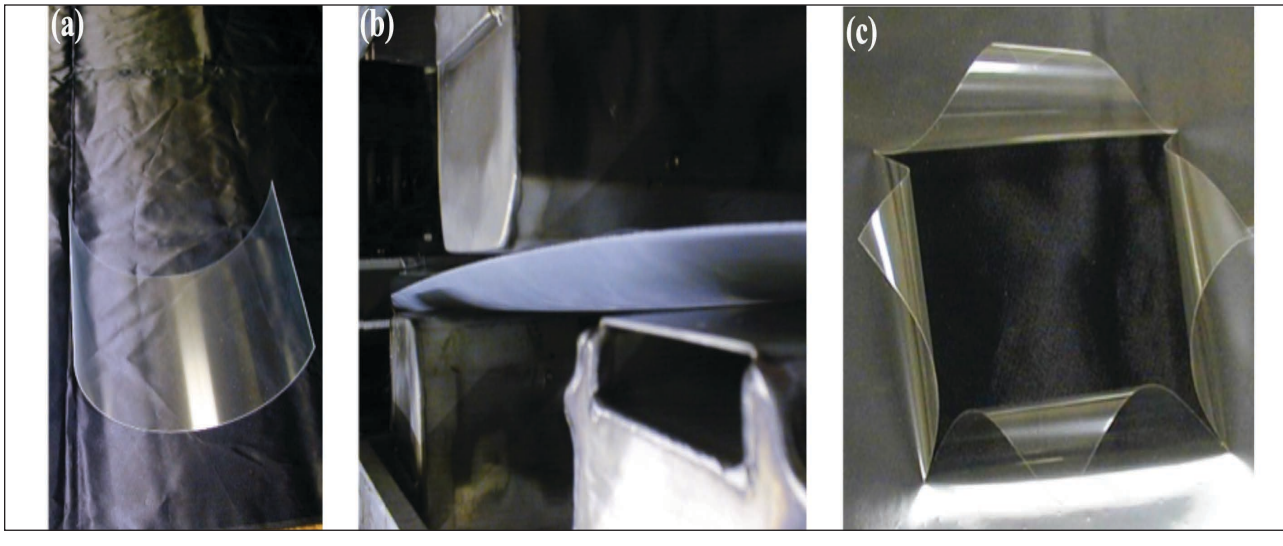
ABSTRACT: Winding is often the final operation in a roll-to-roll manufacturing process. Web materials, i.e., materials that are thin compared to their length, are wound into rolls because this form is the only practical means to store them. The resulting bending strains and associated stresses are large for thick webs and laminates. As many webs are viscoelastic on some time scale, bending stresses lead to creep and inhomogeneous changes in length. When the web material is unwound and cut into discrete samples, a residual curvature remains. This curvature, called curl, is the inability for the web to lie flat at no tension. Curl is an undesirable web defect that causes loss of productivity in a subsequent web process.

This paper describes the development and implementation of modeling and experimental tools to explore and mitigate curl in homogenous webs. Two theoretical and numerical methods that allow the prediction of curl in a web are developed: a winding software based on bending recovery theory, and the implementation of dynamic simulations of winding. One experimental method is developed that directly measures the curl online by taking advantage of the anticlastic bending resulting from the curl. These methods are demonstrated for a low-density polyethylene web.

Application: When polymeric films are stored in the form of rolls, they adopt a cylindrical shape. At unwinding, this shape remains in the form of curl and creates issues with further processing. This paper proposes and compares an analytical, a numerical, and an experimental method to predict and measure curl in any viscoelastic material.

The winding of webs at the terminus of roll-to-roll (R2R) process machines has been studied with winding models. The mission of winding models was: 1) to predict the elastic residual stresses that resulted from winding in rolls [1,2], and 2) to use these stresses to predict and mitigate damage of the web in the roll. Webs are often considered viscoelastic because these residual stresses can either decrease or increase markedly during storage time and in the storage environment [3,4]. Web damage resulting from winding and storage has been qualitatively inventoried by categorizing the various types of wound roll defects [5] and identifying the known causes and remedies.

Curl is defined as the inability of a web to lie flat when laid upon a flat surface and subject to no tension. There is more than one type of web curl (**Fig. 1**). This publication focuses on longitudinal machine direction (MD) curl (Fig. 1a). The cut sample of web resided within the wound roll at a given radius. During winding, the web was subjected to a combination of MD membrane and bending stresses,



1. Examples of a) machine direction (MD) curl; b) cross direction (CD) curl, and (c) complex curl.

which became residual stresses after the process. Since most webs are viscoelastic on some time scale, the residual stresses lead to creep phenomena. As higher stresses lead to higher creep strains in linear viscoelastic materials, the creep strain will be larger at the outside of a layer than at the inside of the same layer. This difference in length change is the source of the observed MD curl. Paradoxically, MD curl is often visible as transverse cross direction (CD) curl at unwinding. The web tension in the unwind zone will draw the MD curl flat, but anticlastic bending [6] and the Poisson's effect [7] will induce curl in the CD direction (Fig. 1b). Anticlastic bending is the concave CD curvature of the web combined with the convex MD curvature, creating a saddle shape. This CD curl can deter web quality if the magnitude is sufficient to cause contact with elements in the web process line, such as the air support drying bars (Fig. 1b). A more complex form of curl (Fig. 1c) demonstrates a case where MD and CD residual stresses in the lower surface of the web are greater than those in the upper surface; this form of curl is not attacked in this publication.

Mitigation of MD curl generally involves reversed winding where the inside of a layer at the unwind becomes the outside of that layer at the rewind. Reverse winding is often done in conjunction with elevated storage temperatures in between reversed windings [8-10]. Curl can be a viscoelastic or a plastic phenomenon, and hence, completely reversible or irreversible. Preliminary observations show that, upon release of a flat low-density polyethylene (LDPE) viscoelastic web forced to conform to a fixed radius of curvature for a period of time, the radius of curvature increases instantaneously to a finite value and further recovers with time. Given enough time, the web would completely recover and return to a flat state. This recovery time is, however, much larger than the process times. Following these observations, this study focuses on viscoelastic curl only. Plastic curl would occur at higher loads.

Web laminates are particularly susceptible to MD curl. The difference in tension and creep strain between the various layers of the web laminate will induce significant MD curl. Laminates are usually strain-matched at the laminator to prevent or reduce MD curl. In addition, laminated webs are often relatively thick, which induces a large difference of bending stresses between the outer and inner surfaces of a layer. Consequently, the creep strains that result from storage at a particular radius in a wound roll can lead to MD curl.

Greener et al. [11] developed and experimentally verified a theoretical expression to predict the curl. The long-term storage analysis, for times non-neglectable compared to the life of the web, showed that the aging effect in polymer materials may significantly influence core-set curl in polymeric film [12]. A two-dimensional elastic curl model based on laminate theory has been specifically developed to study the curl in laminates [13].

In this paper, we will propose and compare three methods to predict or measure the curl resulting from winding and storage of a homogeneous viscoelastic web. The first method is an analytical predictive model, the second a numerical dynamic simulation of the winding and storage, and the third a direct online measurement. These methods are also compared to the classic measurement of curl from a specimen collected on the roll after storage.

MATERIAL

This study uses as a model material a low-density polyethylene (LDPE) that is a relatively cheap, homogeneous, and linearly viscoelastic web. The methods, however, can be extended to any viscoelastic web commonly used in industry, such as nonwovens [14] or paper [15,16], with their specific viscoelastic behavior. The LDPE web is 102 mm (4 in.) wide and 508 µm (0.02 in.) thick and was purchased from Blueridge Films (Disputanta, VA, USA). All experiments and simulations have been performed on this material. Two specimens of 36.7 m and 80.8 m (120 ft and 265 ft) are wound and unwound to collect samples for the offline measurement tests. The collected sample size was between 50 and 250 mm. Five LDPE specimens of 5 m (16.4 ft) in length were prepared for the online measurement testing.

Webs are better modeled as viscoelastic orthotropic [3,4]. Due to the shape of the web, the material is characterized via tensile creep tests in the tangential direction and via compression creep tests in the radial direction. The creep function is approximated as a two-term Prony series:

$$J(t) = J_0 - \sum_{i=1}^{n} J_i \exp\left(-t/\tau_i\right) \quad (1)$$

The conversion procedure in [17] allows for the conversion of a discrete spectrum representing a creep function to the equivalent relaxation function:

$$E(t) = E_0 - \sum_{i=1}^{n} E_i \left(1 - \exp\left(-t/\lambda_i\right)\right) \quad (2)$$

where E_i are the relaxation moduli and λ_i the relaxation times. The relaxation times λ_i are the roots of Eq. 3:

$$\left(\prod_{i=1}^{m}(s\lambda_i + 1)\right)\left(\prod_{i=1}^{m}(s\tau_i + 1)\right) = \left(\sum_{i=0}^{m} J_i \prod_{j\neq i}^{m}(s\lambda_j + 1)\right)\left(\sum_{i=0}^{m} E_i \prod_{j\neq i}^{m}(s\tau_j + 1)\right) \quad (3)$$

The relaxation moduli E_i are:

$$E_i = E_0 \frac{\prod_{j=1}^{m}\left(\frac{\tau_i}{\lambda_j} - 1\right)}{\prod_{j\neq i}^{m}\left(\frac{\tau_i}{\tau_j} - 1\right)} \quad (4)$$

The elastic radial Young's modulus is $E_{r0} = K_2(P(r)+K_1)$ where K_1 and K_2 are Pfeiffer's constants [18] and $P(r)$ is the radius-dependent radial pressure. Tangential creep tests were performed using different dead weights (45 N,

Parameter	Value	Parameter	Value
$E_{\theta 0}$ (MPa)	1.53E+2	$J_{\theta 0}$ (kPa^{-1})	6.53E-6
$E_{\theta 1}$ (MPa)	4.72E-1	$E_{\theta 1}$ (kPa^{-1})	2.90E-6
$\lambda_{\theta 1}$ (s)	1325	$\tau_{\theta 1}$ (s)	1913
$E_{\theta 2}$ (MPa)	1.15E-1	$J_{\theta 2}$ (kPa^{-1})	1.16E-6
$\lambda_{\theta 2}$ (s)	89630	$\tau_{\theta 2}$ (s)	100566
K_1 (kPa)	6.9E-05	J_{r0} (kPa^{-1})	6.53E-6
K_2	246.5		
		J_{r1} (kPa^{-1})	1.29E-6
		τ_{r1} (s)	696
		J_{r2} (kPa^{-1})	1.35E-6
		τ_{r2} (s)	72810

I. Viscoelastic material parameters in the tangential and radial direction for the low-density polyethylene (LDPE) web.

66.7 N, 89 N) to exert stress levels on web samples. The creep function was then obtained by fitting the Prony series to the normalized creep data (**Table I**). Following Qualls [3,4], we assumed the creep functions coupling radial stress to tangential creep $J_r\theta(t)$ and tangential stress to radial creep $J_r\theta(t)$ were negligible. The tangential elastic Young's modulus is E_0=153 MPa and the Poisson's ratio is 0.3. The Young's modulus E_0 of LDPE was measured at a strain rate of 10%/min.

Similar material parameters can be identified for any linear viscoelastic material, including paper [15,16] and nonwovens [14], to approximate their mechanical behavior. Various methods have also been developed for nonlinear viscoelasticity [16].

ANALYTICAL CURL MODEL

Bending recovery theory

The Greener model [12] predicts the values of bending recovery (BR), which is the portion of an imposed bending deformation that is recovered with time. BR is similar to the MD curl that results from a winding process and is defined as: $BR=R/\rho$, where R is the radius at which the web layer was wound into the roll and ρ is the radius of curvature of a web free of web stress or tension cut from that same web layer immediately after unwinding. If the web is flat after unwinding, then BR = 0. If BR = 1, there is no elastic recovery.

Many factors may influence the curl, including the radius at which the web layer was wound into the roll, the thickness of the web, the viscoelastic properties of the web, the storage time, the environmental conditions, the winding tension, etc. Based on a simple extension of the classic bending theory, a phenomenological model is developed for a linear viscoelastic material (Eq. 2) [12]:

$$BR = \left[1 - \frac{E_t(t_r)+E_c(t_r)}{2E_0}\right] \tag{5}$$

where t_r is the storage time, E_0 is the initial instantaneous modulus—modulus at the instance in time when the web was deformed from the flat state to a radius R; $E_t(t)$ is the relaxation modulus in tension; and $E_c(t)$ the relaxation modulus in compression. The instantaneous modulus E_0 should be measured in conditions where there is no viscoelastic stress relaxation, below the glass transition temperature or at high strain rate. When the compressive stresses relax substantially slower than the tensile stresses, then $E_c(t_r)=E_0$:

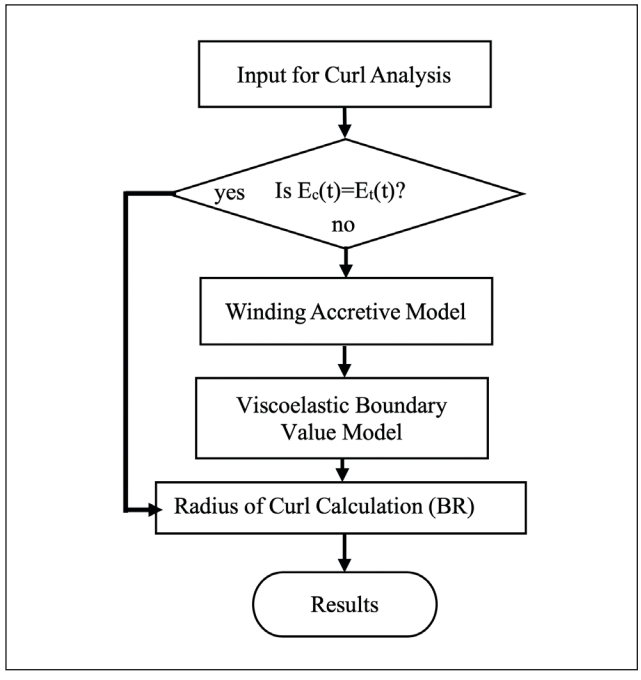
$$BR_1 = \frac{1}{2}\left[1 - \frac{E_t(t_r)}{E_0}\right] \tag{6}$$

When the stress relaxation is independent of the sign of the stress, then $E_c(t_r)=E_t(t_r)$:

$$BR_2 = 1 - \frac{E_t(t_r)}{E_0} \tag{7}$$

Model

The viscoelastic winding model developed by Qualls and Good [4] did not distinguish between compressive and tensile creep behavior in the tangential direction. This model was extended to allow unique compressive versus tensile tangential creep behavior (**Fig. 2**). The viscoelastic web is wound into a roll and stored for a given time at a given



2. Flow chart of curl analysis code.

temperature. The curl analysis predicts the level of curl after unwinding and relieving any web tension. The model assumes that the winding occurs so quickly that the winding process is entirely elastic (Fig. 2). The larger storage time, however, provides ample time for viscoelastic stress relaxation and creep.

A decision block then reviews whether the relaxation functions in tension and compression are equal. If they are equal, then the membrane stresses calculated by the winding code and the viscoelastic boundary value code are not required, and the decision block proceeds directly to the computation of bending recovery using Eq. 7. If the relaxation moduli in tension and compression differ, the membrane stresses combined with the bending stresses will determine what portion of the thickness of the web will be subject to a tensile stress and what portion will be subject to a compressive stress. The winding and viscoelastic boundary value codes are executed to obtain the membrane stresses through time. The bending recovery is determined using Eq. 5.

Model validation

To validate the implemented model, we will compare the predicted curl in a case where tensile and compressive relaxation moduli are equal to experimental results on a LDPE web wound at 22, 40, or 88 N and stored. To calculate the curl radius, Eq. 7 is transformed into:

$$\rho(R) = \frac{R}{BR_2} = \frac{R}{\left[1 - \frac{E_t(t_r)}{E_0}\right]} \quad (8)$$

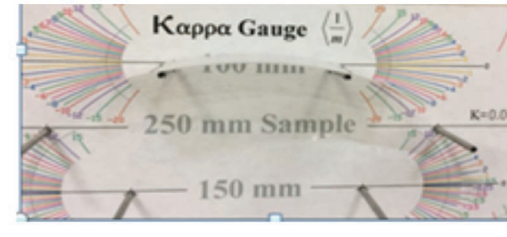
where $\rho(R,t_r)$ is the recovered radius of curvature for a web stored at a radius R for a storage time t_r in a wound roll. All the input parameters for the analytical model are provided in Table I and **Table II**.

For each tested winding tension, the winding curl tests followed the subsequent six steps.

1. Conditioning: The LDPE web was conditioned by reversed winding to remove the residual curl due to previous storage. The web was unwound and wound with the outside of the outer layer becoming the inside of the layer wound onto a downstream winder. In between reversed windings, the roll was stored at 65°C for 5 h. Samples of the innermost and outermost layers were harvested, followed by measurements of MD curl using the Kappa Gauge [19]. This curl gauge supports beams of webs such that the deformation due to gravity is minimized (**Fig. 3**). The instrument also allows measurement of curl in an up or down configuration. Averaging the results for both configurations further reduces the error due to gravity. The Kappa Gauge has output units of curvature (1/m) that are the inverse of the radius of curvature. This is a destructive measurement method; web coupons must

Web thickness	508 µm
Width	101.6 mm
Core outside diameter	88.9 mm
Core inside diameter	76.2 mm
Core Young's modulus	207 GPa
Calculated core stiffness	33.8 GPa
Core Poisson's ratio	0.3
Wound roll outside diameter	241 mm (test 1)
	229 mm (test 2)
	221 mm (test 3),
	218 mm (tests 4,5)
Winding tension	775 kPa (tests 1,2,3)
	1550 kPa (test 4)
	430 kPa (test 5)

II. Input of the winding model. The core stiffness corresponds to the relationship between pressure and radial strain of the core. This quantity has been defined for winding models in [1].



3. The Swanson Kappa Gauge [19].

be cut such that that the curl curvature can be measured.

When both MD curls were less than 2 units on the Kappa Gauge (or a curl radius less than 0.5 m), the web was considered essentially flat and ready for further testing

2. Winding: The web was rewound at the designated winding tension.

3. Storage: The web was stored at room temperature (21°C) for 1 or 3 day(s).

4. Outer measurement: The curl of a sample harvested from the outer layer was measured on the Kappa Gauge [19].

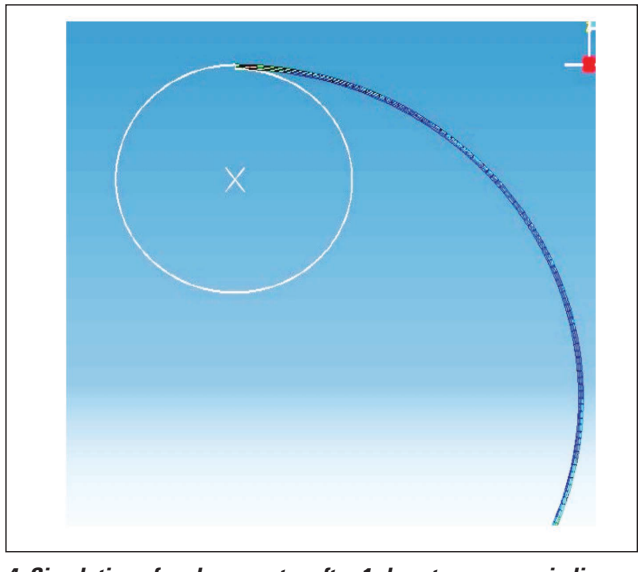
5. Unwinding: The roll was unwound to collect a coupon adjacent to the core.

6. Inner measurement: The curl of the innermost layer was measured.

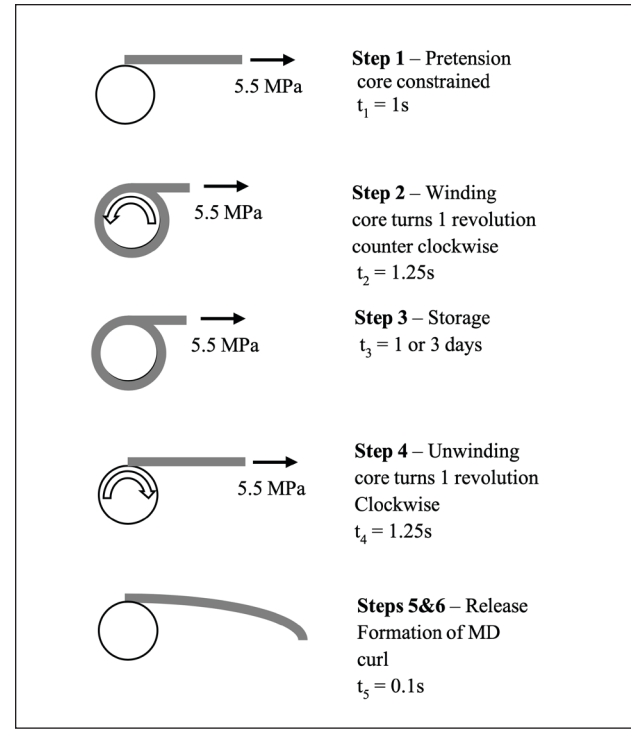
NUMERICAL DYNAMIC CURL SIMULATION

The winding and storage of a roll was simulated in Abaqus (Dassault Systèmes; Vélizy-Villacoublay, France). The simulation wound the LDPE film around a core. The core is defined as an analytical rigid surface with a 12.7 mm radius (**Fig. 4**). The LDPE web was modeled with CPS4R solid elements with materials properties described in Table I. Because only one layer is wound, the material was assumed isotropic without impacting the solution. The Abaqus Standard solution procedure was used.

The simulation is organized in six steps: pretension, winding, storage, unwinding, release, final curl (**Fig. 5**). The figure schematically represents the web and core during each step as well as the duration of each step. The duration of each step of this dynamic simulation critically controls the influence of the dynamic behavior on the simulation result.



4. Simulation of web geometry after 1-day storage, unwinding, and tension release.



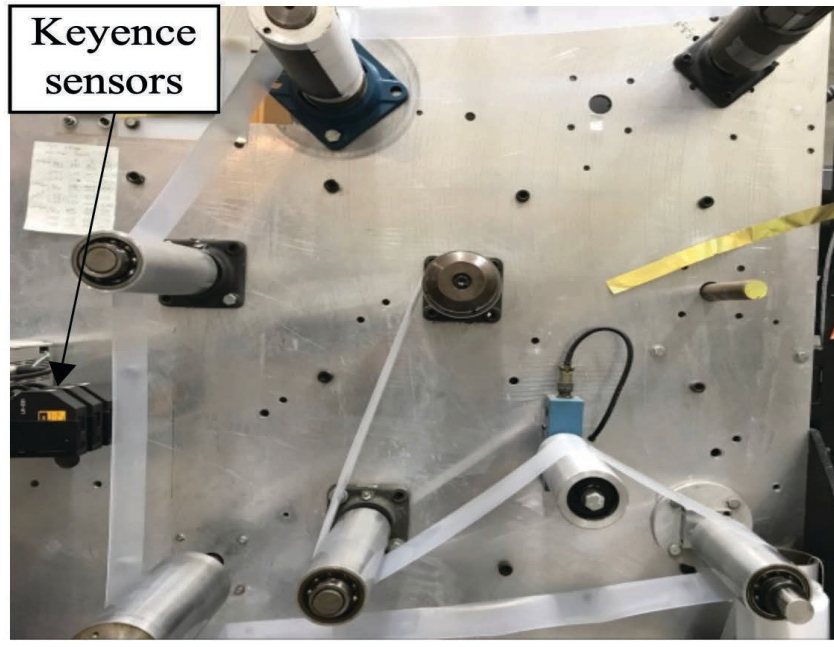
5. Schematic representation of the web and the core during each dynamic simulation step: Pretension, Winding, Storage, Unwinding, Release, and Curl formation.

As the web is released in Step 5, dynamic effects lead to large movements of the web. The web reaches a static equilibrium in a stress-free curled state during step 6. The curl radius is assessed in the last 3 s of the simulation using the deformed coordinates of three consecutive nodes along the longitudinal direction. Inverting the radius of the arc yields the curvature of the center node. The bending recovery corresponds to the curvature divided by the radius of the core.

EXPERIMENTAL ONLINE MEASUREMENT OF CURL

Theory of anticlastic bending

The Euler beam theory defines the bending moment required to bend a web to a radius r as $M = EI/r$, where E is the Young's modulus, and I the area moment of inertia. Because the web is a three-dimensional structure, it adopts a saddle shape when this moment is applied to the longitudinal edges. Specifically, the web adopts a radius of curvature $r_x = r$ in the longitudinal MD direction and a radius r_y in the transverse CD direction. This deformed shape is well-known as an anticlastic surface [6]. The edge moment



6. Online measurement of CD curl.

induces tensile strains $\varepsilon_{xx} > 0$ on the outer surface and compressive strain $\varepsilon_{xx} < 0$ on the inner surface. The Poisson effect couples strains in the longitudinal and transverse direction, i.e., $\varepsilon_{yy} = -\nu\varepsilon_{xx}$, where ν is the Poisson's ratio. Consequently, the longitudinal strain ε_{xx} results in a compressive transverse strain $\varepsilon_{yy} < 0$ on the outer surface and a tensile transverse strain $\varepsilon_{yy} > 0$ on the inner surface. If $\nu = 0$, there would be no deformation in the transverse direction and the web would adopt the shape of a cylinder of radius r ($r_y = \infty$). Although ν is generally not zero, the web does not exhibit anticlastic deformation when wound into a roll due to out-of-plane winding forces. Web tension acts to create a contact pressure beneath the outer layer, which keeps increasing with the number of layers, thus ensuring the web remains cylindrical while winding [1,2].

At unwinding, web tension elastically pulls out the longitudinal curl, which engenders a transversal out-of-plane deformation w of:

$$w = \frac{\upsilon M_x}{2D(1-\upsilon^2)} y^2 = \frac{\upsilon}{2\, r_x(1-\upsilon^2)} y^2 \qquad (9)$$

where M_x is the moment per unit length applied to the longitudinal edge of the web, and D is the bending stiffness $D = \frac{Eh^3}{12(1-\nu^2)}$ of a plate of thickness h. The radius of curvature r_y is equal to the inverse of the second derivative of the out-of-plane deformation:

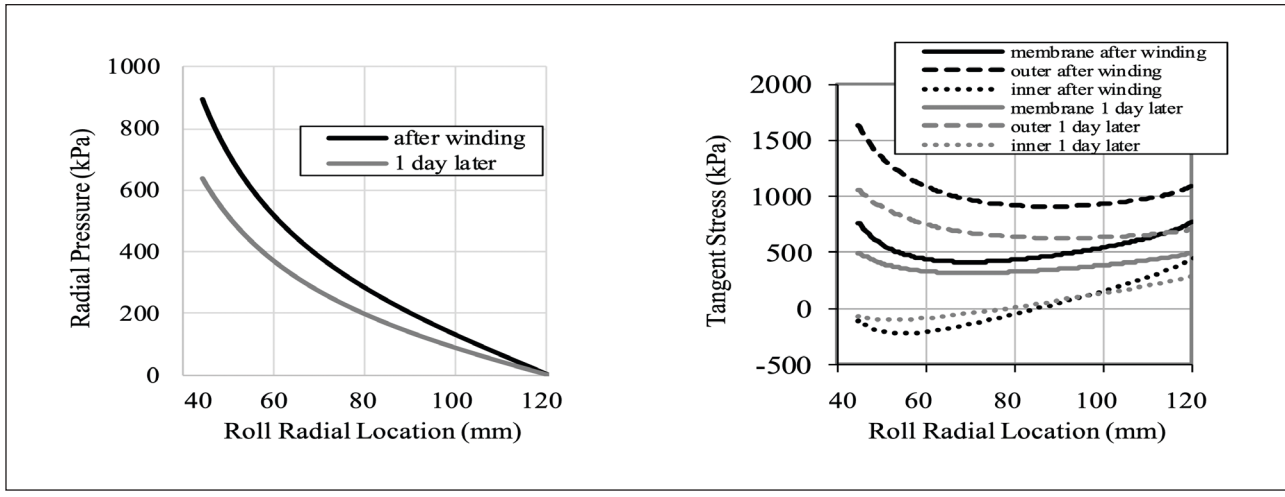
$$r_y = \left(\frac{\partial^2 w}{\partial y^2}\right)^{-1} = \frac{1-\nu^2}{\nu} r_x \qquad (10)$$

which provides a useful relationship between longitudinal and transversal curl. However, the total longitudinal and transverse curvatures are not systematically linearly dependent, meaning both MD and CD curl can exist in a stress-free state and a transverse curl can exist unrelated to anticlastic bending. In addition, web tension will not remove all the out-of-plane deformation w in the MD in the free span. This deformation will be affected by web constraints at rollers, web elasticity, web tension, and span length. Thus, Eq. 10 is only an estimate of the relationship between MD and CD curls.

Online curl measurement

The out-of-plane web displacement was measured online using Keyence LK031 laser displacement sensors (Keyence Corporation of America; Itasca, IL, USA). The sensors are mounted 30 mm (1.2 in.) away from the undeformed web plane (**Fig. 6**).

The measuring range is ± 5 mm (± 0.2 in). One sensor is targeted at the CD center of the web while the other two aim symmetrically 38 mm (1.5 in.) away. The length of vertical test span is 450 mm (18 in.). The CD curl radius was inferred from the measured displacement. The relationship between MD and CD curl was characterized with the following procedure. Five LDPE specimens of 5 m (16.4 ft) in length were prepared. Their MD curl levels was measured off-line in a stress-free state using the Kappa Gauge. Every test was repeated at least 3 times on a web specimen. Each specimen was transported under tension through the test span, shown in Fig. 6. These samples were short, and the winding and unwinding were manually assisted in order



7. The pressure and tangential stress due to winding and storage of the low-density polyethylene (LDPE) web at a winding tension of 40 N.

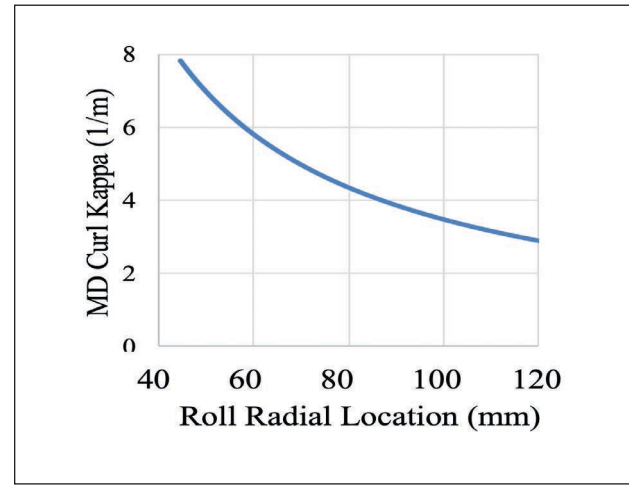
to attain the target web tension as quickly as possible (13.3 N, 26.7 N, 40.0 N). The 3 averaged signals for out-of-plane deformation measured at the 3 locations (-38 mm, 0 mm, 38 mm) were averaged for the length of the web and used to define an arc from which the CD curl radius was inferred. Finally, a relationship between initial MD curls (no tension) and CD curl (online under tension) is obtained.

RESULTS AND DISCUSSION

Analytical winding model validation

Since we assume $E_t(t_r)=E_c(t_r)$, the analytical winding model will have no impact on the curl obtained but will inform how the wound roll pressures and tangential stresses are changing through time. In **Fig. 7**, both the membrane stress and the combined membrane and bending stress on the inner and outer surface of the web can be reviewed. The majority of the stress the web witnesses is tensile through the thickness, so the use of the tensile relaxation function is reasonable. The model curl in kappa units was determined using the inverse of the curl radius in Eq. 8 (**Fig. 8**).

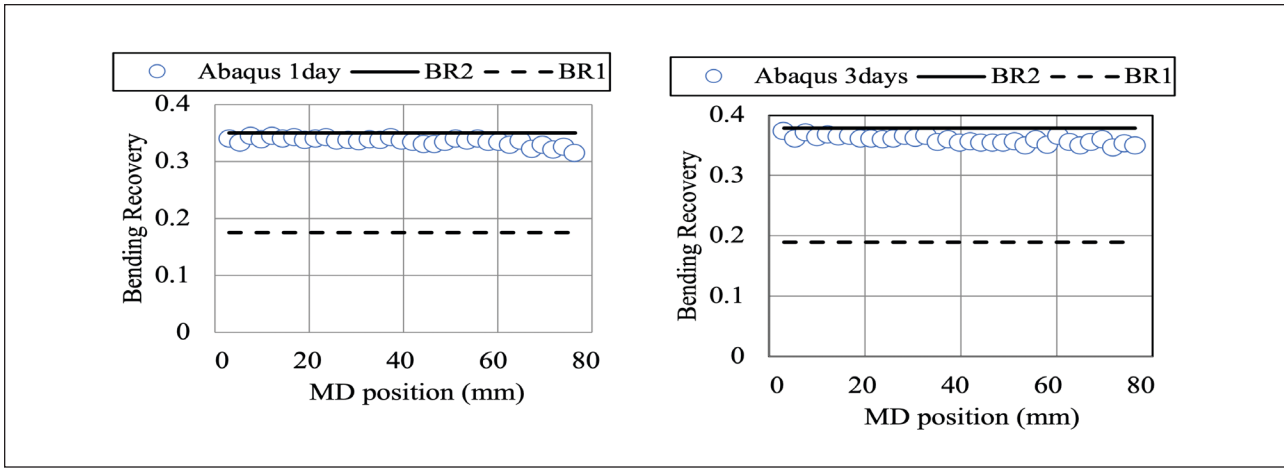
The comparison of the experimental and modeling results for the MD curl are presented in **Table III**. The results from the model can be calculated directly from Eq. 8 in this case. The curl values predicted by the model reasonably agree with the measured test values. The absolute error is



8. MD curl due to winding and storage of the web.

T, N	Outer Radius, mm	Innermost Layer, kappa 1/m			Outermost Layer, kappa 1/m		
		Lab	M	|error|	Lab	M	|error|
40	121	6.5	7.7	1.2	2.5	2.9	0.4
	114	9.0	7.7	1.3	3.5	3.1	0.4
	110	8.5	7.7	0.8	2.5	3.2	0.7
80	109	8.5	7.7	0.8	2.5	3.2	0.7
22	109	9.0	7.7	1.3	2.5	3.2	0.7

III. Comparison of the curl between lab tests (Lab) and model (M) for LDPE at 21°C.



9. Comparison of the analytical prediction (bending recovery, BR, Eq. 5 and Eq. 6) and the numerical dynamic simulation prediction, after a 1-day storage and a 3-day storage.

less than the benchmark of 2 used to establish proper conditioning. Further improvement of the agreement between Eq. 8 and experiments would first require better methods for preconditioning the web to ensure the entire web length was curl-free prior to tests. This validates the prediction of the model.

Analytical winding model discussion

Neither Qualls, nor any other developers of viscoelastic wound roll codes, considered how the sign of stress could affect the creep functions. The output of winding codes demonstrates that the circumferential stresses are typically high near the core and the outside of the wound roll but, in the interior of the roll, these stresses can near zero or become negative. The degree to which they can become negative depends on the level of winding tension, the relative values of the elastic modulus in the circumferential direction E_θ, the state-dependent radial modulus E_r, the core stiffness, and the core and final wound roll radius. If $J_\theta(t)$ depends on the sign of the stress, this could be a shortcoming of current viscoelastic wound roll codes, depending on how different the tensile creep function and the compressive creep function are.

Dynamic curl simulations

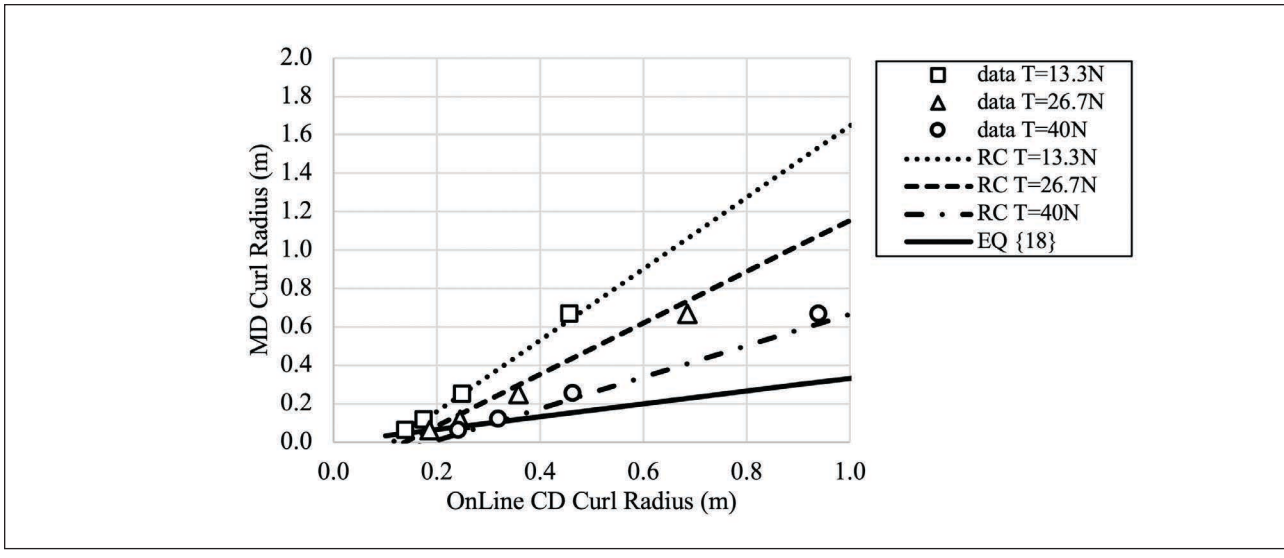
The results of the dynamic simulations are presented in **Fig. 9** for 1 day and 3 days of storage, respectively. The dynamic simulations report a significant bending recovery, which implies a significant curl in the web after storage. Since the largest time constant is 89630 s (1.04 days), this considerable curl was expected. Also shown are the bending recovery predicted by the bending recovery theory using BR_1 (Eq. 6) and BR_2 (Eq. 7). The prediction from BR_2 (Eq. 7) agrees best with the dynamic simulation results (Fig. 9). As the constitutive model used for the simulation does not differentiate between tension and compression and is fully isotropic, BR_2, where $E_c(t_r) = E_t(t_r)$, logically corresponds to the behavior of the simulated web.

The bending recovery did not evolve appreciably during two more days of storage. With the largest time constant in the relaxation function being 89630 s or 1.04 days, a large part of the time-dependent behavior is already relaxed after 1 day. Because larger time constants are not considered in this constitutive model, additional creep or changes in bending recovery would not be predicted by the simulations or the theory.

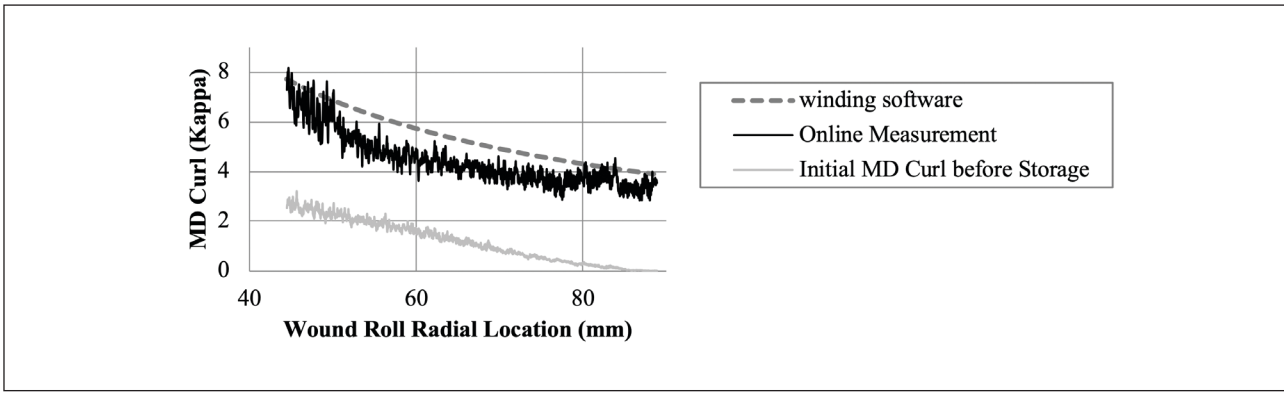
In conclusion, we showed that simulations of curl within a wound roll are possible using a commercial dynamic simulation code like Abaqus. The simulation can also predict the decrease in curl with time after unwinding depending on the time constants in the Prony series of the relaxation function. Simulation of cases where $E_c(t_r) \neq E_t(t_r)$ would be possible, as the properties of the finite elements can be partitioned through the thickness. The simulation would be computing the combined membrane and bending stresses, which can cause the neutral axis to shift, resulting in the partition of the compressive and tensile stresses varying.

Online curl measurement

The experimental results (**Fig. 10**) demonstrate a linear relationship between longitudinal MD and transverse CD curl, as the theory predicted (Eq. 10). The data further demonstrates a dependency of the MD-CD curl linear relationship on web tension, whereas Eq. 9 depended only on the Poisson's ratio. For a web supported between two rollers in an R2R process machine, directly applying the edge moment, M_x, introduced is not possible. The web tension T, in combination with the out-of-plane deformation w due to curl, induces the internal M_x edge moments. As web tension increases the out-of-plane deformation decreases, which affects the induced edge moment M_x. A dependency of the experimental results (Fig. 10) on web tension was expected. For this web and test span, a regression curve can be developed to infer the MD curl radius r_x in a stress-free web state from the measured CD curl radius r_y in the



10. Relationship between MD curl and measured CD curl compared to the regression curve (RC).



11. Initial and 1-day storage online measurement compared to the analytical model results.

web under tension Eq. 11:

$$r_x = [-0.0390\,T + 2.3787]r_y + [0.0022\,T - 0.2420] \quad (11)$$

where r_x and r_y are in meters and T is the web tension in Newtons. This regression curve is compared with experimental data for the 3 tension levels (Fig. 10). The agreement with the experimental data is good. However, the regression curve developed herein is applicable to a unique test span and web material. Such a regression curve could also be developed using a numerical simulation.

Comparison of the different methods

In the validation of the analytical curl model, the MD curl was measured at the innermost and outermost layers using the Kappa Gauge. The standard adopted for wound roll conditioning was to alternate reversed winding and storage periods until the initial kappa measurement is less than 2. This initial MD curl was previously considered negligible and is now explored using the online measurement method, with a core radius of 44.5 mm and an outer radius of 89 mm. After several reversed windings with intermediate storage, the online measurement (**Fig. 11**) shows the majority of the wound roll exhibits an initial curl of less than 2 kappa units.

The roll was then stored for 1 day at room temperature (21°C) and the online measurement was conducted again. The MD curl measured by online measurement is shown in kappa units as a function of radial storage location in the wound roll (Fig. 11). The MD curl is logically higher after storage and decreases with radial location. The curl radius is more than double the radius in the wound roll showing extensive recovery after 1 day storage. The signal-to-noise ratio is also relatively low, validating the measurement apparatus.

Finally, the online measurements of curl after a 1 day storage agree with the offline experiments (**Table IV**), with a maximal error of 8.5%. The online measurement also compares well to the analytical winding model results for the outermost layer, 12.6% ± 9%, and innermost layer, 15.6% ± 10% (Fig. 11). The error is greater for the interme-

	Kappa Gage MD Curl Measurement, kappa	Online MD Curl Measurement, kappa
Innermost layer	8.0	7.7
Outermost layer	3.5	3.8

IV. Comparison of discrete and online experimental measurements of curl (MD = machine direction).

diate layers that are neither the innermost nor the outermost layers, 23.3% ± 10%. While it is possible that dissimilar relaxation $E_c(t_r) \neq E_t(t_r)$ may cause this error in the interior region, the compressive relaxation modulus was not characterized, and the error due to this simplification cannot be estimated. In addition, friction will affect slippage and the location of the neutral axis and hence the portions of the web that experience tension and compressive stress. This could further amplify the effects of dissimilar relaxation.

These results support the use of online direct measurement of the CD curl as an estimation of the resulting MD curl, which indicates the possibility of measuring the amount of curl in the web along the web handling process. In addition, the curl can be predicted before any process using existing winding models or numerical simulations and proper viscoelastic characterization of the webs.

CONCLUSIONS

Methods were explored to predict MD curl in wound rolls due to film viscoelasticity. The developed methods included analytical winding modeling, numerical dynamic simulations, and an experimental online direct measurement. All methods demonstrated the ability to predict and/or measure the MD curl defect with a maximum error of about 23% for the intermediate layers. The curl in an anisotropic web and the effect of dissimilarities between tensile and compressive relaxation functions remain the subject of future work.

This study shows a significant correlation between the predictive and the measuring methods. The predictive tal was the most interesting finding of this study.

This paper proposes methods to measure but also to predict curl. Mills can then use these methods to plan processes and determine storage time influence on the different steps. Mills can also setup online measurements to directly quantify the amount of curl in a process and adjust subsequent steps to mitigate it.

This research opens the door to measuring and predicting curl for more complex materials: nonlinear viscoelastic materials, laminates, heterogeneous webs, etc. The methods can be adapted by the mills to different types of papers to determine storage time.

ABOUT THE AUTHORS

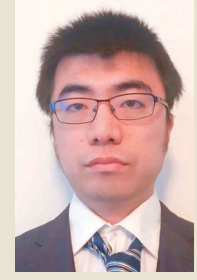
Curl in webs is a challenging phenomenon that interferes with further processing in a negative way. Even as the curl studied here is viscoelastic and hence completely reversible, the time necessary to relax the web and reverse the curl is prohibitive, considering the size and of the webs and the speed of the processes. We pursued this research because we knew it was unique and would provide tools for the industry to predict, measure, and mitigate the effect of curl.

This research complements previous efforts to predict and mitigate defects in webs. An extensive amount of research has been performed by the authors on winding and its influence on webs mechanical behavior.

A difficult aspect of this research was the online measurement of curl in the machine direction. We accomplished this by measuring the curl in the cross-machine direction that was induced by the combination of anticlastic bending of the web and web tension pulling the web curl in the machine direction flat. Thus, we inferred the machine direction curl from induced cross machine direction curl measurements. We think this is a novel idea.

We discovered that, with proper characterization of the viscoelastic properties of a web over a large time range, the curl phenomenon can be largely explained and predicted. Notably, we also confirmed that a web is never completely flat and determining a level 0 of curl is impossible.

The very good correlation between methods that are completely analytical, numerical, or experimen-



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methods can be useful to limit storage times and temperatures in order to mitigate MD curl in a planned process. The direct online measurement method is useful for quantifying MD curl in webs stored in wound rolls for indefinite periods of time or for cases where reversed windings and intermediate storage is being used to eliminate MD curl. **TJ**

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