Study on Bending of Woven Fabrics Using Linear Viscoelasticity Theory

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The bending behavior of woven fabrics under low curvature conditions has been analyzed by linear viscoelastic theory. The fabric is assumed to behave viscoelastically and to be subjected to frictional restraints in bending deformation. The frictional restraint is considered to be proportional to the curvature and can be described by a frictional moment. A model has been constructed by a standard three - element solid model and a paralleled frictional sliding element. The equations of the model for a cyclic curvature variation are derived. A set of parameters of the equations for each fabric has been obtained experimentally. Predictions of the bending rigidity and hysteresis for wool, cashmere, wool/polyester blended, polyester and cotton fabrics are made, displaying very good agreement with the experimental observations.
Keywords: *bending rigidity, bending hysteresis, linear viscoelasticity, woven fabric.*

Introduction

Textile fabrics are flexible sheet materials assembled of textile fibers and/or yarns. The performance characteristics of textile materials and clothing, such as formability during garment manufacturing, shape retention, crease retention and wrinkle recovery are determined by the mechanical behavior of a fabric under some specific modes of deformation of bending and shear[1]. During such deformation, all fabrics show a varying degree of viscoelasticity and interfiber friction because of the viscoelastic nature of the constituent fibers and the rearrangement within the fiber assembly. Their responses to applied loads are rate or time dependent. At any time, the state of stress within a fabric depends on the entire loading history. The viscoelastic nature of the constituent fiber is responsible for the phenomenon of stress relaxation, and the interfiber friction provides the fabric frictional stress during deformation and responsible for the irreversible deformation. Studying these inelastic effects in fabrics enables us to understand and eventually predict important performance characteristics.

Bending test is a fundamental way to characterize the rheology of viscoelastic materials. Bending properties of a fabric is determined by the yarn - bending behavior, the weave of the fabric and the finishing treatments applied. Yarn - bending behavior, in turn, is determined by the mechanical properties of the constituent fibers and the structure of the yarn. The relationships among them are highly complex. In the past, the mechanisms of the bending moment - curvature relationship of woven fabrics were investigated by many workers over several decades, adopting numerical and phenomenological approaches.

Review of Literature

In the fundamental approaches, the most detailed analyses of the bending of plain - weave fabrics were given by Abbott *et al*[2], de Jone and Postle[3] and Ghosh *et al*[4,5]. Modeling of bending of a woven fabric requires knowledge of the relationship between fabric bending rigidity, the structural features of the fabric, and the tensile/bending properties of the constituent yarns, measured empirically or determined through the properties of its constituent fibers and the yarn structure. Involving a large number of parameters, it is essentially to be expressed in a closed form. Thus, the applicability of this kind of models is very limited. A review on the bending behavior of woven fabrics was made by Ghosh *et al*[6].

Numerical methods are used in engineering for the stress - strain analysis of a structure. Konopasek[7,8] used cubic - spline - interpolation to represent fabric moment - curvature relationship. Konopasek's model appears to be the most general and therefore most useful for computing the equilibrium fabric structure and deformation under imposed loading. Lloyd[9] and Brown[10] predicted the bending deformation of fabrics based on Konopasek's model.

In the study of fabric rheology from the phenomenological viewpoint, two simple rheological models consisting of linearly elastic and frictional elements, proposed by

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Oloffson[11], are most popular in the textile literatures[12-15]. These models do not account for fiber viscoelastic processes which occur during fabric deformation and recovery. Chapman proposed a theoretical model in which the material is termed as "generalized linear viscoelastic" (GLVE)[16] and showed that single wool and nylon fibers at low strains (1%) under changing temperature and relative humidity[17-19]. The fabric has been shown to behave as a GLVE sheet in bending with an internal frictional moment[20,21]. The frictional couple associated with each fiber in bending is principally considered as a function of strain and absolute time[22-24]. One of the fundamental ways to characterize the rheology of viscoelastic material is to bend the sample to a designated curvature and observe its transient behavior. The recovery of fabrics from bending[16], shear[25], creasing[21] and wrinkling[1] can be calculated by using knowledge of stress relaxation.

In common bending tests, the fabric is bent cyclically and the moment - curvature relationship is recorded, such as those done in pure bending tester in Kawabata's Evaluation System (KES - FB). The bending performance of fabrics is characterized through parameters such as bending rigidity and hysteresis. However, how to separate the viscoelastic and frictional components in hysteresis remains unsolved. A detailed investigation of the bending of woven fabrics that determines the frictional couple through the cyclic bending curve of the fabric is needed. Hence, a theoretical model composed of standard - solid element in parallel with a sliding element is proposed. The bending properties of woven fabrics are quantitatively studied. The comparison of the theoretical predictions and the experimental results are made in the light of the theory.

Theory

Deformation, stress relaxation, and subsequent recovery of fabrics can be studied quantitatively using the rheological model of linear viscoelaticity. Linear viscoelasticity is applicable for many viscoelastic materials when they are deformed to low strains [1]. Modeling the viscoelastic behavior of materials may involve using simple multiple - element models or generalized integrated forms.

In order to simplify the calculation, the fiber is assumed to be linearly viscoelastic and its bending behavior can be described by the standard solid model. The fabric is considered to be a viscoelastic sheet with internal frictional constraint. Its bending behavior can be described by a three - element linear viscoelastic model in parallel with a frictional element, as shown in Fig.1. The model is governed by the following equation [20,21]:

$$M(k) = M_v(k) + \dot{k} / |\dot{k}| \times M_f \qquad (1)$$

in Equation (1), $M(k)$ is the bending moment of unit width (gf · cm/cm), k is the curvature of the fabric (cm^{-1}), and M_f is the frictional constraint (gf·cm/cm). The factor $\dot{k} / |\dot{k}|$ is the sign of the curvature change, which means that any curvature change of the fabric is opposed by the frictional constraint M_f. The frictional constraint interacts with the viscoelastic behavior of single fibers to impose a limit on the recovery a fabric may eventually attain.

Frictional constraint restricts free movement of the fibers in fabric during bending. In earlier works, it was assumed to be a constant[11,13]. In fact, the size of frictional component in the total coercive couple of a fabric varies with the maximum curvature imposed on the fabric[24]. In the experiment, we found that the intercept on the bending moment axis made by the hysteresis loop is smaller than the 2HB given by KES - FB - 2 Pure Bending Tester. Hence, we assume that the frictional constraint is proportional to the curvature imposed on the fabric, as depicted in Fig. 2.

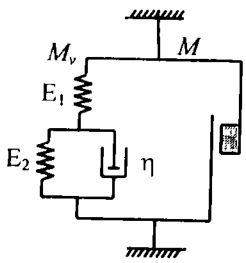

Fig.1 A three - element - plus - frictional viscoelastic model for bending of fabric

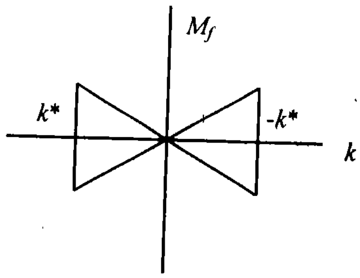

Fig.2 Idealized frictional moment - curvature relation

If a fabric is bent at a constant rate of change of curvature ρ, the viscoelastic bending moment for a three - element model is given by

$$M_v(t) = \frac{E_1 E_2}{E_1 + E_2}\rho t + \frac{E_1^2}{(E_1 + E_2)^2}\rho\eta(1 - e^{-t/T}) = at + b(1 - e^{-t/T}) \qquad (2)$$

where,

$$T = \eta/(E_1 + E_2)$$

$$a = \frac{E_1 E_2}{E_1 + E_2}\rho$$

$$b = \frac{E_1^2}{(E_1 + E_2)^2}\rho\eta$$

In Equation (2), E_1 and E_2 are the elasticity modulus of the springs and η is the viscosity coefficient.

When the fabric is cycled between curvature k^* and $-k^*$, typical hysteresis curve for bending deformation is shown in Fig. 3. The cyclic bending curve can be separated into regions where alternately positive and negative rates of change of curvature are inserted. By application of Equation (2) the complete bending hysteresis cycle due to the viscoelasticity of the sample can be calculated. Using the Boltzman superposition principle to add the effects caused by the component strain rate for each portion of the hysteresis curve of the viscoelastic component, we can calculate the moment at points 1, 2, 3 and 4 in Fig. 3. For bending at a constant rate of ρ and limiting curvature k^*, $k = \rho t$, $t^* = k^*/\rho$, the viscoelastic bending moment at time t^*, $2t^*$, $3t^*$ and $4t^*$, is respectively obtained as

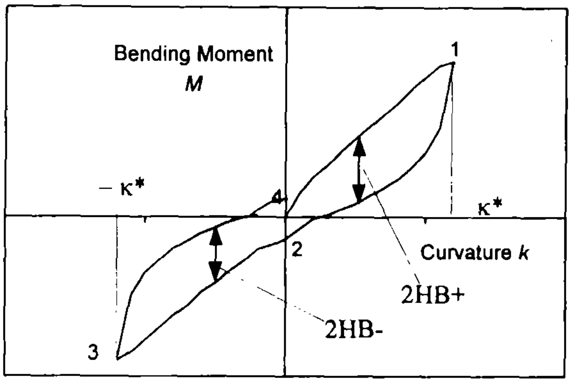

Fig. 3 An idealized hysteresis loop for fabric bending

$$
\begin{aligned}
M_{v1} &= M_v(t^*) && \text{for } t = t^* \\
M_{v2} &= M_v(2t^*) - 2M_v(t^*) && \text{for } t = 2t^* \\
M_{v3} &= M_v(3t^*) - 2M_v(2t^*) && \text{for } t = 3t^* \\
M_{v4} &= M_v(4t^*) - 2M_v(3t^*) + 2M_v(t^*) && \text{for } t = 4t^*
\end{aligned} \tag{3}
$$

Substituting Equation (2) to Equation (3), the viscoelastic moment at time t^*, $2t^*$, $3t^*$ and $4t^*$ can be expressed as, respectively

$$
\begin{aligned}
M_{v1} &= at^* + b(1-\gamma) && \text{for } t = t^* \\
M_{v2} &= -b(1-\gamma)^2 && \text{for } t = 2t^* \\
M_{v3} &= -at^* - b(1 - 2\gamma^2 + \gamma^3) = \\
&\quad -M_{v1} + \gamma M_{v2} && \text{for } t = 3t^* \\
M_{v4} &= b(1-\gamma^2)(1-\gamma)^2 && \text{for } t = 4t^*
\end{aligned} \tag{4}
$$

where

$$\gamma = e^{-t^*/T} = e^{-(E_1+E_2)t^*/\eta}$$

For cyclic bending between curvature k^* and $-k^*$, as depicted in Fig.2, the frictional constraint at points 1, 2, 3 and 4 varies as follows:

$$
\begin{aligned}
M_{f1} &= \mu k^* && \text{for } t = t^* \\
M_{f2} &= 0 && \text{for } t = 2t^* \\
M_{f3} &= -\mu k^* && \text{for } t = 3t^* \\
M_{f4} &= 0 && \text{for } t = 4t^*
\end{aligned} \tag{5}
$$

where, μ is a constant similar to frictional coefficient (gf $\cdot$ cm^2/cm).

Then, the total moments at points 1, 2, 3 and 4 in Fig. 3 can be defined in following manner:

$$
\begin{aligned}
M_1 &= M_{v1} + \mu k^* = \\
&\quad at^* + b(1-\gamma) + \mu k^* \\
M_2 &= M_{v2} = -b(1-\gamma)^2 \\
M_3 &= M_{v3} - \mu k^* = \\
&\quad -M_{v1} + \gamma M_{v2} - \mu k^* \\
M_4 &= M_{v4} = b(1-\gamma^2)(1-\gamma)^2
\end{aligned} \tag{6}
$$

However, there are only three independent equations in Equation group (6). Another equation must be established in order to find the solution of the other two unknown variables. One of the parameters used to characterize the bending properties of the fabric in KES – FB – 2 Bending Tester is $2HB$, as depicted in Fig. 3, which is independent of Equation (6) and is given by:

$$
\begin{aligned}
2HB_f &= M_f(k) - M_b(k) = \\
&M_{vf}(k) - M_{vb}(k) + 2M_f(k) = \\
&b\left(2 - e^{-\frac{k}{\rho T}} - 2e^{-\frac{k^*-k}{\rho T}} + e^{-\frac{2k^*-k}{\rho T}}\right) + 2\mu k^*
\end{aligned} \tag{7a}
$$

$$
\begin{aligned}
2HB_b &= M_f(-k) - M_b(-k) = \\
&M_{vf}(-k) - M_{vb}(-k) + 2M_f(-k) = \\
&b\left(2 - e^{-\frac{4k^*-k}{\rho T}} + 2e^{-\frac{3k^*-k}{\rho T}} + e^{-\frac{2k^*+k}{\rho T}} - \right. \\
&\left. 2e^{-\frac{k^*-k}{\rho T}} - 2e^{-\frac{2k^*+k}{\rho T}}\right) + 2\mu k
\end{aligned} \tag{7b}
$$

where, the subscript f means the fabric is bent forward and the subscript b means the fabric is bent backwards. $2HB_f$ and $2HB_b$ are the width of the hysteresis loop at curvature $+k$ and $-k$. The average of them can be obtained as

$$2HB = (2HB_f + 2HB_b)/2 = bQ + 2\mu k \tag{8a}$$

$$
\begin{aligned}
Q = 0.5\Big(4 &- e^{-\frac{4k^*-k}{\rho T}} + 2e^{-\frac{3k^*-k}{\rho T}} + \\
&e^{-\frac{2k^*+k}{\rho T}} - 2e^{-\frac{k^*-k}{\rho T}} + e^{-\frac{2k^*-k}{\rho T}} - \\
&2e^{-\frac{k^*+k}{\rho T}} - 2e^{-\frac{k^*-k}{\rho T}} - e^{-\frac{k}{\rho T}}\Big) + 2\mu k
\end{aligned} \tag{8b}
$$

Equation (6) can be merged as

$$
\begin{aligned}
M_1 &= M_{v1} + \mu k^* = \\
&\quad at^* + b(1-\gamma) + \mu k^* \\
M_2 &= -b(1-\gamma)^2 \\
M_1 + M_3 &= -b\gamma(1-\gamma)^2
\end{aligned} \tag{9}
$$

Solving simultaneous Equations (8) and (9), the parameters are given by

$$
\begin{aligned}
\gamma &= \frac{M_1 + M_3}{M_2} \\
b &= -\frac{M_1 + M_3}{\gamma(1-\gamma)^2} \\
\mu &= \frac{2HB - bQ}{2k} \\
a &= \frac{M_1 - b(1-\gamma) - \mu k^*}{t^*} \\
T &= -t^*/\ln\gamma
\end{aligned} \tag{10}
$$

Then, three parameters of the standard solid elemet can be obtained as follows:

$$
\begin{aligned}
E_1 &= \frac{aT + b}{T\rho} \\
E_2 &= \frac{a(aT + b)}{b\rho} \qquad (11) \\
\eta &= T(E_1 + E_2) = \frac{(aT + b)^2}{b\rho}
\end{aligned}
$$

Thus, the proposed bending model for a fabric can be established through three points in the moment - curvature curve and a hysteresis parameter.

Experimental

We selected five fabrics with different characteristics. Their details are given in Table 1. Square samples of 20cm × 20cm were cut from the fabrics with their four edges are parallel to the warp and weft direction respectively. Bending properties of the fabric are tested in KES - FB - 2 Pure Bending Tester. The bending was carried out with a curvature rate of 0.5 cm^{-1}/sec. The maximum curvature was ± 2.5 cm^{-1}. In the experiment, the bending moment was applied parallel to the warp or the weft respectively. Five samples for each fabric were tested. Each sample was measured in warp and weft direction respectively. The bending hysteresis curve was recorded, and the bending rigidity and the width of hysteresis were given. All the experiments were done at standard ambient conditions (65% ± 5% RH, 20℃ ± 1℃).

Table 1 Structural and bending parameters of the samples

Sample	Material	Weave	Count/ (picks/cm)	Weight/ (g/m^2)	Thickness /cm	B /($gf\cdot cm^2/cm$)		$2HB$ /($gf\cdot cm/cm$)	
						Warp	Weft	Warp	Weft
1	wool/PET	plain	22 × 19	161	0.0329	0.1081	0.0805	0.0265	0.0384
2	cotton	plain	26 × 19	198	0.0360	0.0567	0.1523	0.0506	0.0748
3	polyester	plain	24 × 22	127	0.0322	0.0276	0.0769	0.0357	0.1051
4	wool	twill	33 × 26	245	0.0627	0.1659	0.1354	0.0843	0.0642
5	cashmere	twill	39 × 24	183	0.0444	0.1243	0.0798	0.0541	0.0452

Results and Discussion

Five fabrics were tested in KES - FB - 2 Pure Bending Tester for the present study. The mean values of B and $2HB$ are given in Table 1. The bending moment in points 1, 2, 3 and 4 of the bending hysteresis curve, as illustrated in Fig. 3, are listed in Table 2. The parameters of the elements in the fabric model are calculated using Equations (10) and (11). They are also given in Table 2.

Table 2 Measured moments and calculated model parameters of the fabric

Sample		Measured Bending Momentum /($gf\cdot cm/cm$)				Calculated Model parameters			
No.	Direction	M_1	M_2	M_3	M_4	E_1	E_2	η	μ
1	Warp	0.27215	-0.01571	-0.27322	0.01465	0.12111	0.63338	12.45946	0.00045
	Weft	0.20282	-0.0137	-0.20565	0.00609	0.08051	0.39139	11.72226	0.00745
2	Warp	0.16951	-0.02265	-0.17159	0.01106	0.07679	0.14784	5.85056	0.00729
	Weft	0.38146	-0.02634	-0.39292	0.01785	0.14074	0.58010	10.24331	0.02066
3	Warp	0.20840	-0.05736	-0.22947	0.01705	0.12453	0.14562	4.33872	-0.02002
	Weft	0.07509	-0.02782	-0.0871	0.00480	0.00063	-0.00062	0.04678	0.03722
4	Warp	0.40980	-0.05625	-0.45637	0.0147	0.16206	0.02091	2.25809	0.01460
	Weft	0.36777	-0.05673	-0.41087	0.01001	0.15788	0.72983	2.92456	0.00281
5	Warp	0.33366	-0.03548	-0.34058	0.00975	0.15054	0.48243	8.40929	0.00110
	Weft	0.20512	-0.02791	-0.22395	0.01709	0.08194	0.07969	3.94512	0.00730

Two parameters characterizing the bending behavior of a fabric are its bending rigidity B ($gf\cdot cm^2/cm$) and the extent of its hysteresis $2HB$. Both are obtained from the bending - hysteresis curve. The bending rigidity is the mean of the two slopes, as shown in Fig. 3. One of them is the gradient B_f of the approximate straight line of the bending curve when the fabric is bent with its face surface outside. The other is the gradient B_b of the similar straight line when the cloth is bent with its back surface outside.

In KES - FB - 2 Pure Bending Tester, the fabrics were bent between curvature $\pm 2.5\ cm^{-1}$ at a rate of curvature variation $0.5\ cm^{-1}/sec$. B_f is the gradient of the approximate straight line of the bending curve between curvature $0.5\ m^{-1}$ and $1.5\ cm^{-1}$ when the fabric was bent with its face surface outside. B_b is the gradient of the bending curve between curvature $-0.5\ cm^{-1}$ and $-1.5\ cm^{-1}$ with its back surface outside. From Equation (4) and (5), we have

$$B_f = M_f(1.5) - M_f(0.5) = M_{vf}(1.5) - M_{vf}(0.5) + 1.5\mu - 0.5\mu = \frac{a}{\rho} - be^{-\frac{1.5}{\rho T}} + be^{-\frac{0.5}{\rho T}} + \mu \qquad (12a)$$

$$B_b = M_b(-0.5) - M_b(-1.5) = M_{vb}(-0.5) - M_{vb}(-1.5) - 0.5\mu + 1.5\mu = \frac{a}{\rho} + b(e^{-\frac{6.5}{\rho T}} - e^{-\frac{5.5}{\rho T}} - 2e^{-\frac{4}{\rho T}} + 2e^{-\frac{3}{\rho T}}) + \mu \qquad (12b)$$

$$B = \frac{1}{2}(B_f + B_b) = \frac{a}{\rho} + \frac{1}{2}b(e^{-\frac{6.5}{\rho T}} - e^{-\frac{5.5}{\rho T}} - 2e^{-\frac{4}{\rho T}} + 2e^{-\frac{3}{\rho T}} - e^{-\frac{1.5}{\rho T}} + e^{-\frac{0.5}{\rho T}}) + \mu \qquad (12c)$$

Then, B_f, B_b and B of the fabrics can be calculated through Equation (12) using the parameters given in Table 2. The predictions of the bending rigidity for the fabrics are shown in Table 3. It can be seen that a good agreement exists between the experimental results and the theoretical predictions.

Similarly, $2HB_f$ and $2HB_b$ are the width of the hysteresis loop at curvature $\pm 1\ cm^{-1}$. Substituting $k = 1$ and the model parameters of the fabric in Table 2 to Equations (7) and (8), the bending hysteresis can also be computed. The comparison of the calculated and observed values for $2HB$ is shown in Table 4. It is clear that the prediction and the measured data have very good agreement as well.

Table 3 Comparison of calculated and observed values of bending rigidity B

Sample		Calculated B (gf·cm/cm)			Measured B (gf·cm/cm)	Relative error (%)
No.	Direction	B_f	B_b	B		
1	Warp	0.10908	0.10303	0.10606	0.1081	1.89
	Weft	0.08165	0.07697	0.07931	0.0805	1.48
2	Warp	0.06831	0.05966	0.06398	0.0567	12.84
	Weft	0.15372	0.14741	0.15056	0.1523	1.14
3	Warp	0.08581	0.07031	0.07806	0.0769	1.51
	Weft	0.03111	0.02570	0.02841	0.0276	2.93
4	Warp	0.16625	0.16231	0.16428	0.1659	0.98
	Weft	0.14949	0.14389	0.14669	0.1354	8.33
5	Warp	0.13479	0.12251	0.12865	0.1243	3.50
	Weft	0.08323	0.07948	0.08135	0.0798	1.94

The intercept of the bending hysteresis curve on the moment axis (W) is given by

$$W = M_4 - M_2 = b\gamma^2(1 - \gamma)^2 \qquad (13)$$

The calculated W is listed in Table 4 and compared to the experiment results.

Table 4 Comparison of calculated and observed values of hysteresis $2HB$

Sample		Calculated B (gf·cm/cm)			Calculated W	Measured W
No.	Direction	$2HB_f$	$2HB_b$	$2HB$		
1	Warp	0.02393	0.02906	0.02650	0.03135	0.03036
	Weft	0.03171	0.03790	0.03480	0.02683	0.01979
2	Warp	0.04646	0.05467	0.05056	0.04511	0.03866
	Weft	0.06884	0.08076	0.07480	0.04769	0.04420
3	Warp	0.02226	0.04914	0.03570	0.10698	0.07440
	Weft	0.09970	0.01150	0.10510	0.04382	0.02962
4	Warp	0.07901	0.08959	0.08430	0.07394	0.07095
	Weft	0.05706	0.07134	0.06420	0.08074	0.06675
5	Warp	0.04617	0.06203	0.05410	0.06961	0.08815
	Weft	0.04072	0.04968	0.04520	0.04310	0.04500

Conclusion

Inthis study, the inelastic phenomena in the bending of woven fabrics are quantitatively analyzed using linear viscoelasticity theory. The fabrics are considered as viscoelastic material with internal constraints. A rheological model consisting of a standard solid element in parallel with a frictional element has been developed. The bending behavior of the fabric under cyclic curvature is analyzed. The solution of the parameters in the model is given. Theoretical predictions are made and compared with the experimental results, showing a good agreement. From this paper, three conclusions can be drawn:

(1) The bending properties of the fabric under low curvature can be characterized using a standard solid element in parallel with a frictional element.

(2) Element parameters of the model can be determined through three points in the bending curve and the bending hysteresis.

(3) The frictional constraint associated with each fiber in bending changes with the curvature imposed on the fabric. The difference in $2HB_+$ and $2HB_-$ and the intercept of the curve at moment axis must therefore be attributed to friction between the fibers.

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