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Modeling the Bending and Recovery Behavior of Woven Fabrics

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Abstract

On the basis of viscoelastic theory of textile material, the viscoelastic solid model consisting of a spring element and viscous element either in series or parallel is one of the most useful research models to study the mechanical behaviour of fabrics. This paper presents a method to study the bending behaviour of wool/polyester fabrics using a model consisting of the three-element model in parallel with a sliding element on the assumption that the internal frictional moment is a constant during the bending processes. From the needs of practical study, a testing method has been presented to study the bending behaviour of wool/polyester fabrics using a KES-FB3 compression tester. A comparison and analysis of the experimental results and theoretical predictions indicate that the agreement between them is satisfactory.

Key words: *wool/polyester fabrics, bending, viscoelasticity, rheological model.*

Nomenclature

- $M(k)$ total bending moment on the fabric, cN.cm/cm;
- $M_v(k)$ viscoelastic bending moment of the fabric, cN.cm/cm;
- $M_f(k)$ frictional constraint in the fabric, cN.cm/cm;
- k curvature of the fabric, cm^{-1};
- E_1 and E_2 elasticity modulus of the springs, cN.cm;
- η viscosity coefficient, cN.cm.s;
- ρ rate of curvature variation of the fabric, cm^{-1}/s;
- a, b, c coefficients: $a = \frac{E_1 E_2}{E_1 + E_2}\rho$, $b = \frac{E_1^2}{(E_1 + E_2)^2}\rho\eta$, $c = \eta/(E_1+E_2)$;
- V speed that upper plate moves at, cm/s;
- T_0 initial separation between the plates at time t = 0, cm;
- T separation of the plates at time t, cm;
- α, β, γ, ω coefficients in dependence on model parameters and experiment conditions: $\alpha = -a/V$, $\beta = -be^{-T_0/cV}$, $\gamma = -1/cV$, $\omega = M_f + b + aT_0/V$.

Introduction

The shear and bending properties of fabrics at low-stress are of critical importance because many performance characteristics of textile materials and clothing, e.g. the handle, drape, formability, shape formation and wrinkle recovery of fabrics are dependent on them [1]. The performance of fabrics under most service conditions depends largely on their bending behaviour. In addition to its shear rigidity, the dependence of the drapability of an apparel fabric on its bending rigidity is also well known. The bending properties of a fabric are dependent on the mechanical properties of fibres, the structure of yarns, as well as the weave and finishing of the fabric [2, 3].

Fundamental approaches to the bending and recovery behaviour of yarns and woven fabrics was given by Abott *et al* [4], De Jone and Postle [5], Ghosh *et al* [6-7] and Mohammad Ghane [8]. Modelling of the bending properties of woven fabrics requires knowledge of the relationship between fabric bending rigidity, structural features of the fabric, and tensile/bending properties of the constituent yarns. It needs a large number of parameters to construct a model, and the solution is very difficult to express in a closed form. Thus the applicability of this kind of model is very limited. Numerical methods are also used in engineering for the stress-strain analysis of a structure. In Konopasek's model [9, 10], the relationship between the moment and curvature of fabrics is analysed using the cubic-spline-interpolation method. The structure and deformation of fabrics at equilibrium under imposed loading can be calculated. Lloyd [11] and Brown [12] predicted the bending deformation of fabrics based on Konopasek's model.

In the study of fabric rheology from the phenomenological viewpoint, Oloffson [13] proposed a simple rheological model consisting of linearly elastic and frictional elements, which is successfully used in many applications such as the bending and creasing of fabrics [14-18]. However, this model does not account for fibre viscoelastic processes which occur during fabric deformation and recovery. Chapman proposed a theoretical model

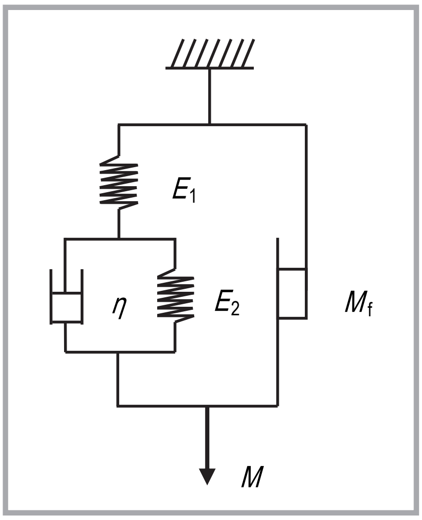

Figure 1. Rheological model for bending of fabric.

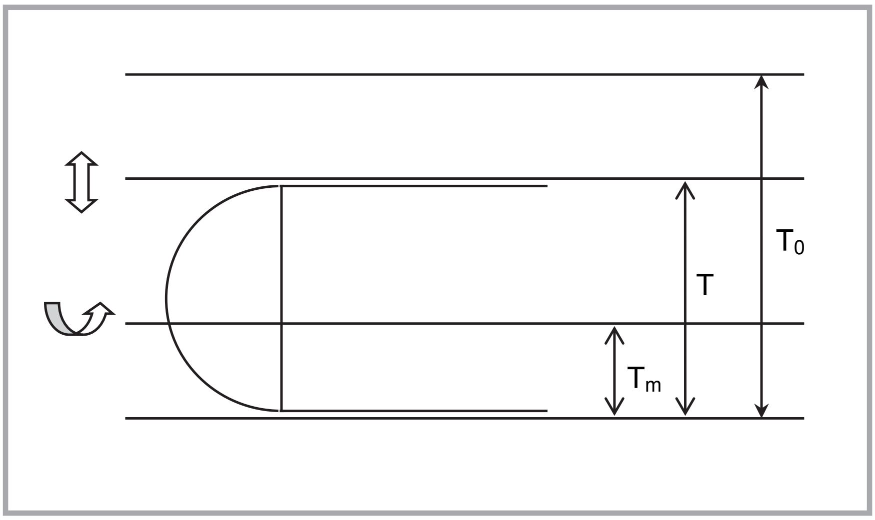

Figure 2. Fabric geometry in compression and recovery.

[19, 20] in which material is termed as "Generalised Linear Viscoelastic", and the frictional couple associated with each fibre in bending is principally considered as a function of strain and absolute time [21, 22]. Fengjun Shi *et al* investigated the bending behaviour of woven fabrics, for simplicity's sake, using linear viscoelasticity theory [23]. Here the bending and recovery behaviour of wool/polyester fabrics is further analysed based on the work above.

Theory

Generally speaking, fibre materials are intrinsically viscoelastic. For the purpose of simplifying the calculation, the fibres are assumed to be linearly viscoelastic and their mechanical properties can be described by the standard solid model. The fabric is considered to be a viscoelastic sheet with internal frictional constraint. Thus the bending behaviour of the fabric can be analysed by a standard solid element in parallel with a frictional element, as shown in ***Figure 1***.

Suppose that the bending moment M and frictional constraint couple M_f of fabrics are functions of curvature k, then the bending moment-curvature can be described as

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

where, $M(k)$ is the total bending moment imposed on the fabric of unit width (cN.m/cm), $M_v(k)$ the viscoelastic bending moment of the fabric (cN.cm/cm), $M_f(k)$ the frictional constraint in the fabric (cN.cm/cm), and k is the curvature of the fabric (cm^{-1}). $\dot{k}/\left|\dot{k}\right|$ is the sign of curvature variation, which means that any curvature variation in the fabric is opposed by the frictional constraint $M_f(k)$.

The viscoelastic bending moment of the fabric can be analysed by the standard linear solid model, which consists of a spring element and Voigt model in series. The constitutive equation of the three-element viscoelastic model is given by

$$\frac{E_1\eta}{E_1+E_2}\frac{dk}{dt} + \frac{E_1E_2}{E_1+E_2}k = \\ = \frac{\eta}{E_1+E_2}\frac{dM_v}{dt} + M_v \qquad (2)$$

In ***Equation (2)***, E_1 and E_2 are the elasticity modulus of the springs and η the viscosity coefficient. If the curvature of the fabric varies at a constant rate ρ, the viscoelastic bending moment for the standard linear solid model can be derived as

$$M_v(t) = \frac{E_1E_2}{E_1+E_2}\rho t + \frac{E_1^2}{(E_1+E_2)^2}\rho\eta(1-e^{-t/c}) \\ = at + b(1-e^{-t/c}) \qquad (3)$$

where, $a = \dfrac{E_1E_2}{E_1+E_2}\rho, b = \dfrac{E_1^2}{(E_1+E_2)^2}\rho\eta,$ $c = \eta/(E_1+E_2)$.

Frictional constraint restricts the free movement of fibres in fabric during bending and recovering. Although the size of the frictional component in the total coercive couple of fabrics varies with the maximum curvature imposed on the fabric [24], the frictional constraint couple is supposed to be a constant to simplify the analysis, as in earlier works [13, 15, 21].

From ***Equations (1)*** and ***(3)***, the total bending moment for the model in ***Figure 1***, can be rewritten as

$$M(t) = at - be^{-t/c} + M_f + b \qquad (4)$$

If a fabric strip is bent and compressed between two parallel plates, as illustrated in ***Figure 2***, the fabric would be deformed viscoelastically. When the upper plate moves downwards, the fabric strip is creased. When the upper plate moves upwards, the fabric strip is allowed to recover from creasing towards its original shape. The shape of the curved portion of the fabric strip is assumed to be a semicircle, while the other portions of the strip are assumed to be straight and always in contact with the parallel loading plates. It should be noted that there is a pure bending moment in the semi-circular portion of the fabric. However, the deformation of the fabric in the creasing test (***Figure 2***) results from a pair of compressive forces. Thus the simplification of geometry will lead to an error in the force that does not exceed 10% for linear elastic materials due to the difference in loading conditions [22].

In the compression tester, the fabric strip is creased between two parallel plates, as illustrated in ***Figure 2***. If the upper plate moves upwards and downwards at a constant speed V, the initial separation between the plates is T_0 at time $t = 0$, and the separation of the plates is T at time t. The compression stops when the creasing force reaches a preset maximum value F_m or the separation between the two plates reaches a minimum value T_m at time t_m, that is $T_m = T_0 - Vt_m$. And then the upper plate moves upwards immediately and the recovery process begins. The relationship between t, V, T_0 and T is as follows

$$t = (T_0 - T)/V \quad (5)$$

Substituting ***Equation (5)*** for ***Equation (4)***, the total bending moment of fabrics can be obtained as

$$M(t) = -\frac{a}{V}T - be^{-T_0/cV}e^{T/cV} + \\ +(M_f + b + \frac{aT_0}{V}) \quad (6)$$

In order to simplify the description, the equation can be written as

$$M(t) = \alpha T + \beta e^{\gamma T} + \omega \quad (7)$$

where, $\alpha = -a/V$, $\beta = -be^{-T_0/cV}$, $\gamma = -1/cV$, $\omega = M_f + b + aT_0/V$. α, β, γ and ω are constants in dependence on model parameters and experiment conditions.

Experiment

Four fabrics with good resilience are selected in this study: wool fabric and wool/polyester blended fabric. The structural parameters of the fabric samples are given in ***Table 1***.

The bending test is designed based on the KES-FB3 compression tester. The fabrics are cut into strips of 6 cm × 2 cm, with their longitudinal direction parallel to the warp or weft direction, respectively. The fabric strip is bent and placed between two parallel plates of the KES-FB3 compression tester. The upper end of the bent fabric strip is attached to the upper plate by a double-sided adhesive tape so that the sample remains flat against the surfaces of the plates during the test. The initial separation of the plates T_0 is equal to 4.16 mm (T_0 = 0.416 cm). The upper plate moves downwards at a speed of 0.04 mm/s (V = 0.004 cm/s) during the experiment. When the compression force reaches a preset value F_0, the upper plate reverses its travel direction instantaneously. When the separation of the plates reaches a preset maximum value T_0, the upper plate stops to end the test. The relationship between the compression/recovery force and the separation of the plates is recorded for each sample.

All fabric samples are preconditioned and experiments are carried out at an ambient condition of 65%RH and 20 °C. Five warp and five weft specimens are tested in each case.

Table 1. *Structure parameters of samples.*

Samples	Materials	Weave	Yarn number, tex	Pick count, picks/10 cm	Weight, g/m²	Thickness, cm
1#	Wool Gabardine	twill	24×20	410×375	175.0	0.0321
2#	70W/30T Serge	twill	26×20	415×375	184.0	0.0335
3#	50W/50T Poplin	plain	24×16	540×400	192.0	0.0324
4#	50W/50T Poplin	plain	25×15	580×370	200.0	0.0344

Table 2. *Parameters calculated for compression and recovery equations.*

Samples	Parameters of compression equation				Parameters of recovery equation			
	α	β	γ	ω	α	β	γ	ω
1# warp	-468.24	834.01	0.3165	-616.31	-932.40	850.53	0.5212	-444.26
1# weft	-498.28	796.42	0.3539	-590.85	-827.11	709.48	0.5625	-383.75
2# warp	-429.46	873.40	0.2885	-680.31	-807.78	800.60	0.4972	-460.13
2# weft	-441.95	708.20	0.3564	-530.61	-756.23	757.22	0.5210	-492.23
3# warp	-304.17	285.44	0.4435	-69.71	-951.55	687.47	0.5792	-196.59
3# weft	-511.76	1004.49	0.3141	-826.29	-943.74	747.50	0.6199	-424.93
4# warp	-525.11	822.27	0.3392	-551.25	-938.21	573.12	0.6289	-47.57
4# weft	-480.88	913.59	0.3159	-730.21	-1048.73	1291.07	0.4599	-968.39

Results and discussion

Creasing and recovery tests are conducted using a KES-FB3 compression tester. The relationship between the creasing force and separation of the plates for the fabrics are recorded. Theoretical calculations are made according to ***Equation (7)***, deduced above. Parameters *α, β, γ* and *ω* for the fabrics are listed in ***Table 2***.

Comparisons of the theoretical calculations and experimental results are illustrated in ***Figures 3-6***. The abscissa in the Figures is the separation between the plates. When the fabric strip is compressed, the separation between the plates decreases, while the compression force increases gradually. When the creasing force reaches a preset value F_0 = 60 cN, the upper plate reverses its travel direction instantaneously, and the crease recovery process begins. During the initial process of compression, the separation distance between the plates is relatively large, while the corresponding creasing force is quite small, which may lead to larger error due to the accuracy of the tester. Thus the comparison between the theoretical calculation and experimental results begins from a separation distance of 1.8 mm. Even so, there is still a discrepancy between the calculation and experimental results for some fabrics, which is because there is little increase in the compression force with a decrease in the separation between the plates during the initial compression process. On the contrary, the compression force increases dramatically with a fractional decrease in the separation of the plates. It should be said that the accuracy of measurement gradually reaches the normal as the compression process continues. Thus good agreement between theoretical expectation and experimental results is obtained.

It can be seen from ***Figures 3-6*** that the recovery force is less than the compression force. When a fabric is deformed under a creasing or bending force, as is well known, its deformation consists of three parts: instantaneous elastic deformation, delayed viscoelastic deformation, and permanent plastic deformation. When the load is removed, the elastic deformation can recover immediately, while delayed viscoelastic deformation recovers gradually with time, and permanent plastic deformation is irreversible. In the standard linear solid element in ***Figure 1***, the spring element presents instantaneous deformation, and the Voigt element presents delayed deformation. The frictional element which is connected to the standard linear solid element in parallel prevents the fibre material from bending on the one hand, but it also stops the recovery of the fibre material from bending on the other. To some extent, the frictional element presents permanent deformation. It is the delayed elastic and irreversible deformation that make the recovery force smaller than the compression force.

These comparisons show that the model proposed, shown in ***Figure 1***, is applicable to fabrics with good resilience, such as worsted and wool/polyester blended fabrics. Therefore the compression and

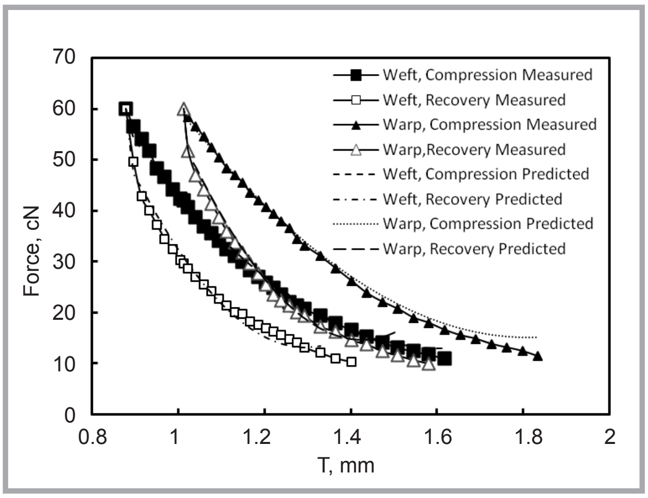

Figure 3. Comparison of theoretical and experimental results for sample 1.

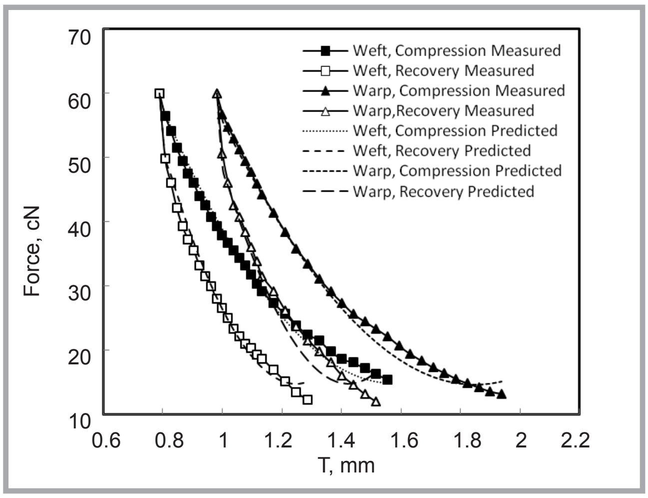

Figure 4. Comparison of theoretical and experimental results for sample 2.

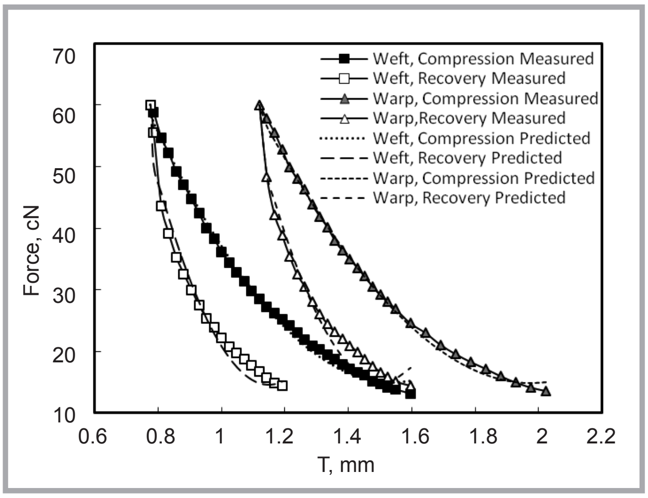

Figure 5. Comparison of theoretical and experimental results for sample 3.

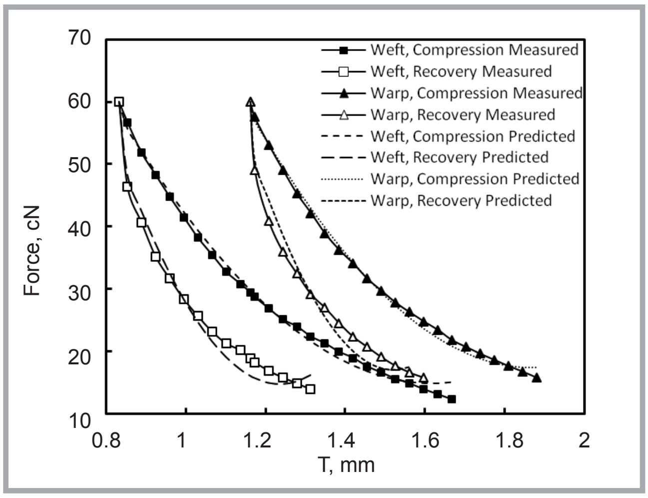

Figure 6. Comparison of theoretical and experimental results for sample 4.

crease recovery properties of such fabrics can be characterised by the four-element model. However, the model has not been tested and may not be suitable for predicting the bending and recovery properties of fabrics with poor elasticity, or under large creasing load conditions.

Conslusions

To study their bending and recovery properties, fabrics are modelled as an elastic strip with internal frictional constraints. The rheological model proposed consists of a standard linear solid element and frictional element whose frictional constraint couple is a constant. The relationship between the bending or recovery force and deformation is obtained. The bending/recovery force-deformation curves predicted and measured demonstrate good agreement for worsted and wool/polyester blended fabrics. Hence the model consisting of a standard linear solid element and frictional element can be used to predict the bending and recovery properties of fabrics under low load bending conditions.

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