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Investigation on the Ratio of Bending Rigidity of Fabric to Yarn for Low Twist Filament Yarn

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Abstract
The ratio of bending rigidity of fabric to yarn in the case of low twist filament weft yarn was studied. Samples of fabrics with different weft densities were prepared; their other parameters were identical. After steam setting treatment, the bending rigidity of the fabrics was measured. The results showed that the rigidity of the fabric per thread in the weft direction decreases as the weft density increases. However, the theoretical equations suggest an inverse trend. To explain the difference, the thickness of the fabric was considered. It was shown that the reduction in fabric bending rigidity was due to the decrease in fabric thickness. The fixed end beam theory for the deflection of weft yarns as well as the flattening effect of low twist filament weft yarns were used to explain the reduction in fabric thickness when the weft densities increase. It was concluded that in the case of low twist filament weft yarn, Leaf's theoretical equations could not be used to predict the ratio of the bending rigidity of fabric to yarn.

Key words: *low twist filaments, bending rigidity, weft density, flattening effect.*

Introduction

bending behaviour is of importance in the study of cloth properties such as handle, drape, and crease resistance. Bending rigidity, and shear rigidity introduce the damping ability of fabric, of which the latter affect the handling, deformation, crease resistance, buckling behaviour and crimp maintenance ability [1].

The bending behaviour of yarn is affected by its mechanical properties as well as the arrangement and interaction between its constituent fibers and yarn geometry [2]. Leaf et al. [3] discussed the relation between the flexural rigidity of a plain woven fabric and the fabric and yarn parameters, such as thread spacing and crimp, yarn flexural rigidity, etc.

Wei and Chen [4] outlined a theoretical analysis that leads to a concise formula for calculating the bending behaviour of set plain woven fabrics. The formula shows reasonable agreement with experimental results and good consistency with Grosberg's [5] conclusion, which is drawn from data computation.

Abbott et al. [6] presented two models for a plain woven fabric in which the yarn cross sections are incompressible so as to obtain the predicted relationship between the couple applied and the curvature of the fabric. They concluded that the predicted bending resistance does not agree with the behaviour of actual fabrics owing to the difficulty of defining the radius of the yarn in the fabric; however, many puzzling qualitative aspects of the bending behaviour of woven fabrics are, as a result of the analysis given, satisfactorily explained.

The above-mentioned works were mainly focused on staple yarns, which are usually assumed to be incompressible. The main aim of this work is to investigate the application and accuracy of classical theories to predict the bending behaviour of plain woven fabrics consisting of low twist filament weft yarn.

Theory

Leaf et al. used the energy salvation method based on the saw tooth model and presented the following Equations [3]:

$$B_1 = b_{y1} \times P_2 / P_1 (L_1 - 2c_1) \qquad (1)$$

$$B_2 = b_{y2} \times P_1 / P_2 (L_2 - 2c_2) \qquad (2)$$

Where, B is the bending rigidity of the fabric, b_y is the bending rigidity of the weft (warp), c is contact length of the yarn at the crossover points, L is the modular length of the weft (warp) and P is the thread spacing. Indices 1 and 2 refer to the warp and weft, respectively.

Considering the thread density $n = 1/P$, equations 1 and 2 can be written in the following form;

$$B_1/n_1 = b_{y1} \times P_2/(L_1 - 2c_1) \qquad (3)$$

$$B_2/n_2 = b_{y2} \times P_1/(L_2 - 2c_2) \qquad (4)$$

Replacing the bending rigidity of the fabric per thread, b, in Equations 3 and 4, we obtain:

$$b_1/b_{y1} = P_2/(L_1 - 2c_1) \qquad (5)$$

$$b_2/b_{y2} = P_1/(L_2 - 2c_2) \qquad (6)$$

To calculate the contact length, c, the contact angle, θ, is needed. This can be calculated using Equations 7 and 8;

Table 1. *Properties of five samples.*

Properties	Samples				
	A	B	C	D	E
Warp density, cm^{-1}	25.6	25.6	25.6	25.6	25.6
Weft density, cm^{-1}	14.0	16.5	17.4	23.5	27.9
Fabric weight, g/m^2	72.5	76	78.8	90	99.5
Fabric thickness, mm	0.277	0.246	0.235	0.222	0.178

Table 2. *Fabric parameters calculated using Pierce equations.*

Properties	Samples				
	A	B	C	D	E
C_{y1}, %	8.685	9.892	10.308	12.200	12.951
C_{y2}, %	1.150	1.468	1.762	2.508	3.567
L_1, cm	0.077	0.067	0.063	0.047	0.041
L_2, cm	0.039	0.039	0.040	0.040	0.040
θ_1, R	0.545	0.582	0.594	0.646	0.666
θ_2, R	0.198	0.224	0.245	0.293	0.349

Ghane M., Sheikhzadeh M., Khaburi S., Ghaeli I.; Investigation on the Ratio of Bending Rigidity of Fabric to Yarn for Low Twist Filament Yarn
FIBRES & TEXTILES in Eastern Europe 2009, Vol. 17, No. 3 (74) pp. 51-53.

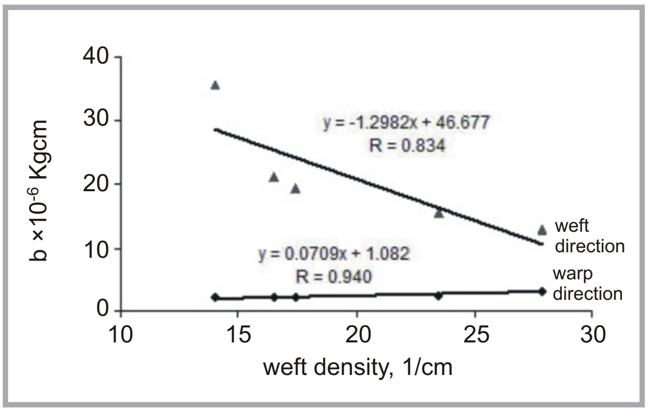

Figure 1. *Variation of the bending rigidity per thread versus weft densities.*

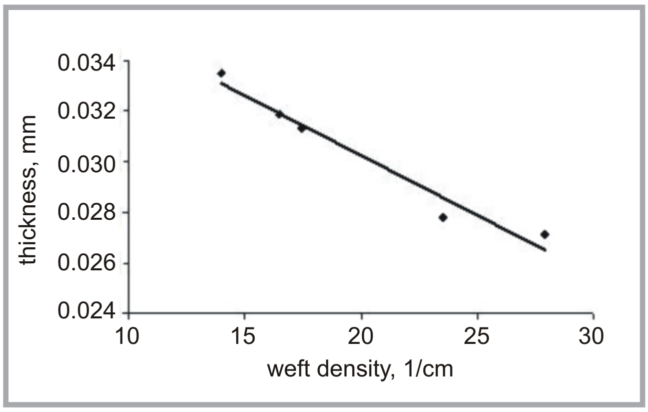

Figure 2. *Variation of the fabric thickness versus weft density.*

$$\theta_1 = 1.85\sqrt{C_{y1}} \quad (7)$$

$$\theta_2 = 1.85\sqrt{C_{y2}} \quad (8)$$

C_y is the crimp percent of the warp (weft) i.e.;

$$C_{y1} = (L_1 - P_2)/P_2 \quad (9)$$

$$C_{y2} = (L_2 - P_1)/P_1 \quad (10)$$

Experimental

Materials

Five samples of fabrics with different weft densities were prepared by a water jet weaving machine. Warp creel is composed of intermingled polyester yarns with a linear density of 150 denier. Low twist polyester filament yarn was used as weft yarn. The linear density of the weft yarn was 150 denier.

Before the bending tests, steam setting was applied to the fabrics for 15 to 30 minutes at 120 - 130 ºC under a steam pressure of 2.5 - 3 bars using steam setting equipment (Werner Mathis AG) [3]. Different properties of the samples were measured using standard methods and are shown in ***Table 1***.

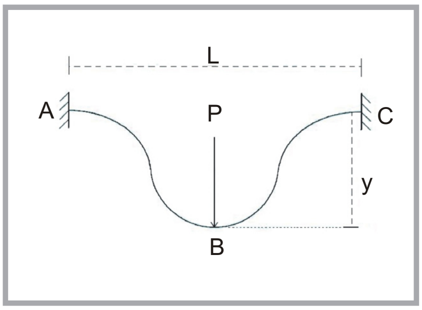

Figure 3. *Deformation of a beam of two fixed ends [8].*

Pierce's model for the geometry of plain wave fabric was used and different parameters were calculated, which are shown in ***Table 2***.

Bending Test

The cantilever test was used to calculate the bending rigidity of the fabrics. For each fabric, 10 different samples were prepared with dimensions of 25 mm × 150 mm in both the warp and weft directions. The bending length, bending rigidity and bending modulus were measured by the Shirley method [7].

Results and discussion

Figure 1 shows the plots of bending rigidity versus weft density for all fabrics in both the weft and warp directions. Equation 6 can be written in the following form;

$$b_2 = b_{y2} \times P_1/(L_2 - 2c_2) \quad (11)$$

The constant warp densities and identical weft yarns for all samples, P_1 and b_{y2}, in equation 11, are constant. This means that the bending rigidity of the fabric per weft is proportional to the inverse of the free length of the weft (L_2 - $2c_2$). Calculation of the free length of the weft, based on data from ***Table 2***, shows that as the weft density increases, the free length of the weft decreases, which theoretically means that, based on equation 11, the bending rigidity of the fabric per weft, b_2, should increase as the weft density increases. However, the experimental results show that with an increasing weft density, the bending rigidity of the fabric per weft will decrease in the weft direction.

To explain the discrepancy, the thickness of the fabric was considered. ***Figure 2*** shows that with the enhancement of the weft density, the thickness of the fabric will decrease. Bending rigidity is the product of the elastic modulus and the moment of inertia of the cross section. In the case of a rectangle shape, the moment of inertia of the cross section is $bh^3/12$. As the thickness of the fabric, h, decreases, the moment of inertia decreases sharply, leading to a reduction in the bending rigidity of the fabric.

Two possible explanations may be stated for a reduction in fabric thickness when the weft density increases:

Deflected beam theory

Previous investigations into significant factors affecting the surface properties of fabrics as well as the protrusions of the weft and warp yarns forming a fabric surface implied that the maximum deflection of warp (weft) in a model of two fixed ends can be found from Equation 12 below [8]**.**

$$y = pl^3/(192\ EI) \quad (12)$$

Where l is two times the distance between two adjacent warps (wefts), p, is the constant force in the fabric, in which warp and weft yarns are inserted into its opposite weft or warp yarn. This equation shows that with the enhancement of the weft density, the value of l will decrease. Other parameters are then constant, but y, which refers to the thickness of the fabric, will decrease.

Flattening effect

In this experiment weft yarns consisted of low twist multifilament, whereas warp yarns were of intermingled textured multifilament. The cross section of these low twisted yarns, due to the existence of

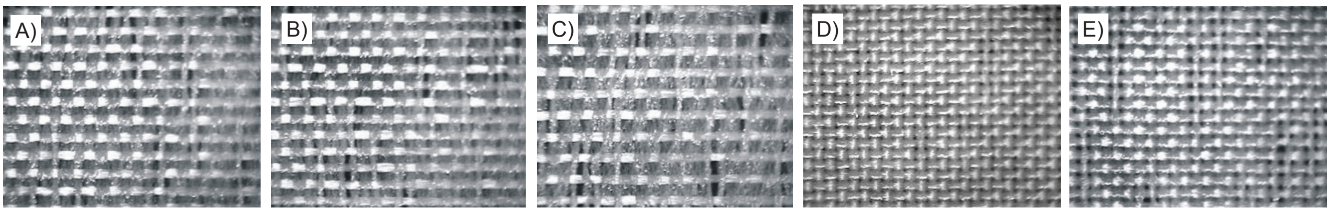

Figure 4. *Images from the surface of the fabrics.*

stresses in the fabric and forces inserted into intersection points of the warp and weft, will change from a circular to a flat shape. ***Figure 4*** shows images from the surface of the fabrics prepared.

At the intersection points, the weft yarns will loose their cylindrical shape and all filaments forming the yarn will scatter on the surface of the warp yarns. The equations based on Leaf's model consider a constant circular cross section of the yarn and the yarn diameter is calculated from this, which is obviously not true in the case of low twist filament weft yarns.

On the other hand, the tape formation of yarns in fabric, which also increases the stress on the weft and warp yarns due to the enhancement of the weft density, are factors which will cause a decrease in fabric thickness. It can be concluded that the model implemented by Leaf et. al. could not be applied for fabrics composed of low twisted multifilament yarns.

Conclusions

Experimental results show that with an increasing weft density per yarn, the bending rigidity of a fabric will decrease in the weft direction, whereas in the equation mentioned by Leaf et al. it will increase in both the weft and warp directions.

The yarns used did not have such a twist as to give the fabric a united structure, and also due to the existence of stress in the fabric and incoming forces at the weft and warp intersection points, the cross section of the yarns will no longer be curculios and will change to a tape shape. For fabrics consisting of low twist filament yarn, the taping effect causes a reduction in fabric thickness. This, in turn, leads to a reduction in the bending rigidity of the fabric. Leaf's model, which is based on a constant circular cross section of the weft yarn, does not hold in the case of low twist filament weft yarn.

Acknowledgment

The authors would like to express their sincere thanks and gratitude to the research deputy of Isfahan University of Technology for financial support.

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Received 17.02.2008 Reviewed 28.07.2008