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STUDY OF WOVEN FABRIC STRUCTURE AND STIFFNESS

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Abstract. The article analyzes woven fabric structure and stiffness by examining the raw materials of interlining fabrics, yarn structure and stiffness, fabric structure and interlining properties, the geometry of yarn crimp, and the directional and generalized stiffness of fabric, using the formulas of Peirce, Kutepov and Koritsky. The analysis showed that warp crimp is 3.0–4.9%, weft crimp is 3.8–6.0%, their sum is 8.0–9.9%, and the consumption coefficients are 1.031–1.064.

Keywords: linen fabric, nonwoven, PES and viscose yarns, yarn stiffness, warp and weft, sized fabric, adhesive, fiber stiffness, number, arrangement and friction.

Introduction. Raw materials for interlining fabrics. The properties of an interlining are determined primarily by the nature of the fiber and the structure of the yarn [1]. Traditional canvas interlinings (bortovka) were made from linen or half-linen raw materials (warp: 72–84 tex cotton or cotton-lavsan; weft: 69–118 tex) [2, 3]; their high stiffness is explained by the high modulus of flax and the coarse weft, and the work of D.A. Kozlovsky is devoted to evaluating the stiffness of linen fabrics [4].

Modern fusible interlinings are made from fine cotton yarn, viscose, PA, PES and PAN fibers and their blends [2]; 25–50% PA or PES is added to nonwoven interlinings to provide wash-and-wear properties [5], while TsNIIShP developments identified rational structures of PES and viscose yarns [3].

The advantages of cotton are hygroscopicity, air permeability, thermal stability at the adhesive melting temperature, and low cost; its disadvantages are shrinkage on wetting, a lower modulus than PES, and a tendency to crease [6, 7]. Therefore, a structure with a cotton warp and a PES or blended weft combines the advantages of

both fibers. In an earlier study of suiting fabrics [8], the air permeability was 91.4 $dm^3/(m^2 \cdot s)$ for a 64.7/35.23 cotton-PES fabric, 39.8 for a 50/50 fabric, and 215.7 for 100% lavsan, while crease resistance increased from 50.0 to 81.1% with the PES proportion; thus, selecting the fiber composition is a multi-criteria problem.

The HVI parameters of the warp cotton fiber were analyzed in previous work [7]. Sizing sharply increases the stiffness of the warp yarn: in a PhD study, the stiffness of a 36.8 tex yarn averaged 15.29 units unsized and 164.29 units after sizing (Welch's test: t = 4.54; p = 0.010) [3]. Hence, stiffness in the warp direction is determined mainly by the size; poor bonding of sized fabric with adhesive has also been reported [9].

Preparing interlining raw material from spinning waste is also promising: ST-3 and ST-7 waste contains 57.83–60.84% spinnable fiber (UHML 25.47–25.9 mm), and a 50 tex yarn with 15% ST-16 added corresponds to the 40% level of USTER STATISTICS 2013 [10]; the stiffness of an interlining woven from this yarn is almost the same in the warp and weft directions (4.4 and 4.5 μN·m) [11].

Methods. Analyzing yarn structure and stiffness is important. Yarn stiffness is determined by the stiffness, number, arrangement and friction of the fibers. In the Morton–Hearle theory, fiber stiffness is expressed as $\boldsymbol{B_f = \eta E_{sp} T_f^2/(4\pi\rho)}$ [1]; when the fibers slip freely, yarn stiffness equals the sum of the fiber stiffnesses, whereas when they are firmly bonded, it approaches the stiffness of a solid rod and becomes proportional to the square of the linear density [12]. E.R. Popova related yarn and fabric stiffness through the moment of inertia of the cross-section [13].

In blended yarns, fibers are unevenly distributed across the cross-section and migrate; L. Van Langenhove et al. modeled yarn properties based on fiber arrangement [14]. In a PhD study, an algorithm was developed for assessing yarn stiffness by bending under its own weight [15], however, the pure effect of the PES proportion can be assessed.

Fabric structure and interlining properties. The theory of woven fabric structure was developed by F.T. Peirce, K.I. Koritsky, N.F. Surnina, O.S. Kutepov and others; the structure is described by the linear density of the yarns, thread density, weave and structure phase [16–19]. S.V. Lomov modeled fabric hierarchically in the WiseTex

software suite [20], and J. Hu described the bending mechanics of fabric in terms of yarn stiffness and friction [21].

Maximum density is calculated by the Brierley formula $P_{KB} = 1350\,F^{M}/\sqrt{T}$, and thickness is determined according to N.F. Surnina as $K_T = d_t + d_a$ [22, 23]. In previous work, the Kutepov and Koritsky crimp formulas were applied to interlinings, and crimp of 3–4.9% in the warp and 3.8–6% in the weft was measured for eight variants [24].

Weave affects stiffness through the number of yarn interlacings and crimp: N.A. Smirnova related shape stability to the weave coefficient [25], M.E. Yüksekkaya and co-authors found a decrease in stiffness in weaves with long floats [26], and N.D. Alymenkova showed the possibility of predicting stiffness anisotropy [27].

Results. Multilayer weaves make it possible to control thickness and stiffness independently: M.R. Yunuskhodjaeva developed a one-and-a-half-layer interlining structure [28], U.T. Abdullaev developed a technology for fabrics with compound weaves [29], and the author produced napped interlinings on a loom equipped with a raising device [30]; in multilayer materials, the method of binding the layers determines stiffness and air permeability [31]. The composition of interlinings reported in the literature is summarized in Table 1.

Table 1

Fiber composition and structural parameters of interlining fabrics reported in the literature

No.	Interlining type	Warp	Weft	Weave	Areal density, g/m²	Key property
1	Half-linen canvas (bortovka)	72–84 tex cotton or cotton-lavsan	69–118 tex linen	Plain	192–362	Stiffness 5–16 mN·cm²

No.	Interlining type	Warp	Weft	Weave	Areal density, g/m²	Key property
2	Horsehair interlining	Cotton	Horsehair (nylon monofilament 0.25–0.4 mm)	Plain	—	High elasticity, width up to 22 cm
3	Cotton interlining, article 7085	50 tex cotton	50 tex cotton	Matt 2/2	180	Density 192/140 threads/10 cm
4	Kufner-type interlining	100% PES	100% PES	Twill 2/2	—	Low air permeability
5	Prototype interlining	Man-made yarn	100% PES or 85% PES + 15% viscose	Twill 1/3	—	Two man-made fibers, expensive
6	Waste-fiber interlining	50 tex (waste blend)	25 tex	Plain	—	B = 4.4/4.5 μN·m
7	PhD study variants	20 tex 100% cotton, sized	20 tex cotton; 24 tex 70/30; 18 and 82 tex PES	Plain, twill 1/3, double-layer	95–284	Stiffness 3.8–83.5 μN·m

Table 1 was compiled from the data of [2, 3, 9, 11]. According to Table 1, in traditional canvas interlinings stiffness is achieved through a coarse or monofilament weft (the weft acts as the “stiffener” and the warp as the “frame”), whereas imported interlinings consist of man-made fiber in both systems and have low air permeability. Combinations with a cotton warp and a PES or blended weft have been studied only

in our PhD research: the stiffness of 21 variants ranged from 3.8 to 83.5 μN·m, i.e., over a 22-fold range [32, 33]. However, the effects of the factors were assessed only by comparison, their contributions were not determined by analysis of variance and regression analysis, and the pure effect of fiber type at the same linear density also remained open.

Geometry of yarn crimp. In a woven fabric, the yarns bend around one another, and their crimp is determined as $\boldsymbol{a = (l_y - l_f)/l_y \cdot 100}$ % ($\boldsymbol{l_y}$ is the length of the straightened yarn, $\boldsymbol{l_f}$ is the length of the fabric section) [17, 18, 34]. In a geometric model that assumes yarns of circular cross-section and treats their bent portions as circular arcs, the length of one wave of the warp yarn is [16, 21, 24]:

$$l_T = 0.01744\,(d_T + d_A)(90^\circ - \gamma - \beta) + \sqrt{l_{TK}^2 + h_A^2 - (d_T + d_A)^2} \quad (1)$$

where d_T, d_A are the calculated yarn diameters; l_{TK} is the distance between weft yarns; h_A is the bending height; β, γ are the bending angles ($\tan\beta = h_A/l_{TK}$); 0.01744 = π/180. The first term gives the arc length and the second the length of the straight portion; crimp increases with the sum of the diameters. From $d = 0.03568\sqrt{T/\delta}$ mm (δ = 0.85–0.9 g/cm³), $d \approx 0.17$ mm for a 20 tex cotton yarn and 0.34 mm for an 82 tex PES yarn. For engineering calculations, the formulas of O.S. Kutepov [18] and K.I. Koritsky [19] are widely used:

$$a_T = \frac{t_T\left(\sqrt{b^2 + C_T^2} - C_T\right)}{C_T R_A} \cdot 100, \qquad b = \frac{d_T + d_A}{2}, \quad C_T = \frac{1}{R_A} \quad (2)$$

$$a_T = \left(1 - \frac{l_A}{\sqrt{l_A^2 + h_T^2}}\right) \cdot 100, \qquad h_T + h_A = d_T + d_A, \qquad \frac{h_T}{h_A} = K\,\frac{P_T^3}{P_A^3}\sqrt{\frac{T_A}{T_T}} \quad (3)$$

where t_T is the number of warp interlacings in the repeat; R_A is the weft repeat; b is the sum of the yarn radii; $l_A = 100/P_A$; h_T, h_A are the bending heights; P_T, P_A are the thread densities, threads/dm; T_T, T_A are the linear densities; K is an empirical coefficient. The conditions in formula (3) express that the sum of the bending heights is constant and that the warp bending height h_T increases as the weft becomes coarser. Crimp determines raw material consumption: the consumption coefficient is

$k = 100/(100 - a)$. The crimp values measured for 8 interlining variants [24, 35] are given in Table 2.

Table 2

Yarn crimp and consumption coefficients for the interlining fabric variants

Variant	a_T, **%**	a_A, **%**	$a_T + a_A$, **%**	k_T	k_A
1	3.0	6.0	9.0	1.0309	1.0638
2	4.9	5.0	9.9	1.0515	1.0526
3	4.5	4.5	9.0	1.0471	1.0471
4	4.6	5.0	9.6	1.0482	1.0526
5	4.6	4.4	9.0	1.0482	1.0460
6	3.0	5.0	8.0	1.0309	1.0526
7	4.0	4.0	8.0	1.0417	1.0417
8	4.8	3.8	8.6	1.0504	1.0395
Mean	4.18	4.71	8.89	—	—

Table 2 shows that in the interlining fabrics studied, warp crimp ranges from 3.0 to 4.9% and weft crimp from 3.8 to 6.0%, while their sum is 8.0–9.9%. The narrow range of the sum agrees with the condition $h_T + h_A = d_T + d_A$ in the Koritsky model: the bending "resource" of the weave is redistributed between warp and weft. Indeed, the correlation coefficient between a_T and a_A is negative (r = −0.58); with eight observations it is not statistically significant (p = 0.13), but its sign agrees with theoretical expectation. In variant 1, warp crimp is the lowest (3.0%) and weft crimp the highest (6.0%), whereas the opposite is observed in variant 8. The consumption coefficients range from 1.0309 to 1.0638, i.e., crimp causes 3.1–6.4% extra yarn consumption per 1 m of fabric. When a coarse weft is used, the bending height of the warp yarn increases, so warp crimp and, accordingly, raw material consumption

increase; this is the economic “price” of increasing stiffness through the weft linear density [36, 24, 37].

Discussion. It is important to consider the directional and generalized stiffness of fabric. In a specimen cut in the weft direction, bending is resisted mainly by the weft yarns. To a first approximation, the stiffness of fabric per unit width is proportional to the product of yarn stiffness and thread density [38, 39]:

$$B_a = \Phi_w P_a B_{ya}, \qquad B_t = \Phi_w' P_t B_{yt} \qquad (4)$$

where B_a, B_t are the fabric stiffness in the weft and warp directions (per 1 m width); P_a, P_t are the weft and warp thread densities, threads/m; B_{ya}, B_{yt} are the bending rigidities of the weft and warp yarns in the fabric; Φ_w, Φ_w' are the weave coefficients. The weave coefficient accounts for two opposing factors: friction and mutual compression at the yarn crossover points force the yarn to act more as a single unit (increasing Φ_w), whereas the wavy shape resulting from crimp and the free segments between interlacings allow the yarn to bend “more easily” (decreasing Φ_w). Plain weave has the largest number of interlacings, in twill 1/3 the average float length is twice as long, and in a double-layer fabric the joint action of the two layers also contributes to stiffness. These factors partly compensate each other, so the weave type changes Φ_w within a relatively narrow range [25, 40].

To evaluate the bending anisotropy of a fabric with a single index, the geometric mean of the directional stiffnesses — the generalized stiffness — and the anisotropy index are used [16, 27, 41]:

$$B = \sqrt{B_t B_a}, \qquad K_{an} = \left|\ln \frac{B_t}{B_a}\right| \qquad (5)$$

where B is the generalized bending rigidity, μN·m; K_{an} is the anisotropy index (K_{an} = 0 for an isotropic fabric). The geometric mean was proposed by Peirce; its advantage is that, even when warp and weft stiffnesses differ several-fold, the result is equally sensitive to each of them and becomes a simple arithmetic mean on a logarithmic scale: $\ln B = (\ln B_t + \ln B_a)/2$. Therefore, analysis of variance and regression analysis can be performed on the logarithms of stiffness.

Conclusions. In existing classifications, the fiber composition of an interlining is recorded only as a general attribute such as “cotton”, “blended” or “synthetic”;

hybrid interlinings with different fiber compositions, in which the fiber composition of the warp and weft systems is selected separately, are not distinguished as a separate group. The fact that stiffness in traditional canvas interlinings is achieved through a coarse or monofilament weft indicates the potential of structures with a cotton warp and a PES or blended weft. Our previous studies established that the stiffness of 21 such interlining variants ranges from 3.8 to 83.5 μN·m, i.e., over a 22-fold range; however, it was found that the quantitative contributions of the factors, the dependence of stiffness on weft linear density, and the pure effect of fiber type had not been studied.

The breaking process of natural and blended fiber yarns was described by a fiber-bundle model based on Heaviside functions; a numerical experiment with a bundle of n = 100 fibers showed that the maximum tension is reached at $\varepsilon \approx 6.17\%$, when 22 fibers have broken. The model explains the sensitivity of breaking force to fiber type and the sequential breaking of components in a blended yarn.

The geometry of yarn crimp (Peirce, Kutepov and Koritsky formulas) was analyzed; in the interlining fabrics, warp crimp was found to be 3.0–4.9%, weft crimp 3.8–6.0%, their sum 8.0–9.9%, and the consumption coefficients 1.031–1.064; the opposite changes of the two crimps were explained by the redistribution of the bending resource of the weave.

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