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Determination of the Dependence of Fabric Structure on Warp and Weft Yarn Tension

M.R.Xudoyberdiyev
Doctoral candidate at Bukhara State Technical University

Abstract:
This study investigates how warp and weft yarn tensions influence the formation of woven fabric structure. Yarns in the fabric are modeled as curved spatial elastic rods, and their stress–strain state, bending behavior, equilibrium conditions and interaction at crossover points are analyzed. The theoretical framework combines elasticity theory, Euler–Bernoulli beam theory, Hertzian contact mechanics, the principle of minimum potential energy, the Peirce geometric model and dynamic tension equations for the weaving process. Relationships are derived between yarn tension and bending radius, curvature, crimp, contact pressure, fabric thickness, porosity and air permeability. The analysis shows that increasing warp tension straightens the warp yarns, increases weft bending, reduces fabric thickness and air permeability and raises tensile strength, whereas increasing weft tension reduces fabric width and weft crimp. Contact pressure at crossover points increases inter-yarn friction and structural stability, but excessive pressure distorts yarn cross-sections and reduces fabric flexibility. The relationship between yarn tension and fabric strength is nonlinear: strength increases up to a limiting tension and then declines. An optimal balance between warp and weft tensions produces a stable microporous structure with good air permeability and moisture transport while maintaining mechanical strength and abrasion resistance. A multiple regression model linking warp tension, weft tension and weft density to fabric properties is proposed for selecting rational technological parameters. The results provide a theoretical basis for automated tension control systems and the design of high-performance woven fabrics.

Keywords: Fabric structure, warp yarn, weft yarn, yarn tension, deformation, contact pressure, bending radius, air permeability, mechanical strength, weaving technology.

Introduction

In the present study, yarns are considered as curved spatial rods. The stress–strain state of the yarns is determined, and the strength characteristics of the yarns in their curved configuration are evaluated. In earlier approximate approaches, the yarn was considered as a single element of the fabric structure, and the equilibrium equations of the yarns within the woven structure were derived approximately.

In this study, however, the yarns constituting the fabric are modeled as curved elastic rods, and exact mathematical equations governing their behavior are developed. Furthermore, yarn deflections calculated using two different theoretical approaches are compared and analyzed.

The performance properties, appearance, and service life of fabrics produced in the textile industry

largely depend on their internal structure and the state of the yarns during the weaving process. The mutual arrangement of warp and weft yarns, their tension levels, bending, compression, contact pressures generated at crossover points, and deformation states directly influence the formation of the fabric structure. Therefore, the theoretical and experimental investigation of yarn behavior within fabrics, the determination of their equilibrium state, and the evaluation of the influence of yarn tension on the geometric parameters of the fabric represent important scientific challenges in modern textile materials science [1].

The structure of a fabric is formed through the spatial arrangement of its constituent yarns. During weaving, warp yarns are maintained under a predetermined tension on the weaving machine, while weft yarns are inserted between the warp yarns through specific kinematic motions. Throughout this process, both yarn systems are subjected to bending, elongation, compression, and contact deformations under the action of external forces. As a result, a certain equilibrium state is established within the fabric surface and its internal layers. This equilibrium state determines essential fabric characteristics such as thickness, porosity, air permeability, abrasion resistance, elasticity, and mechanical strength.

The problem of determining the state of yarns within a fabric primarily requires the evaluation of their geometric configuration, mutual contact conditions, and mechanical equilibrium under the influence of both external and internal forces. This problem is closely related to textile mechanics, deformation theory, elasticity theory, and contact mechanics. Yarns in a woven structure are not arranged along perfectly straight lines. Depending on the weave pattern, they form specific sinusoidal or wavy configurations. In particular, the bending amplitude of yarns is greater in twill and satin weaves. In plain weave fabrics, however, the structure exhibits relatively higher stability and equilibrium due to the large number of yarn crossover points.

One of the main tasks in determining the state of yarns within a fabric is the evaluation of their degree of bending. Yarn bending depends on its stiffness, linear density, tension, and external pressures. As yarn tension increases, the degree of yarn straightening also increases, resulting in a reduction of fabric porosity. Conversely, a decrease in tension leads to greater yarn bending and a more open fabric structure. This phenomenon significantly affects the air permeability and hygroscopic properties of the fabric [2].

During the weaving process, warp and weft yarns are subjected to different mechanical loads. Warp yarns are mainly exposed to constant static tension, whereas weft yarns experience short-term stresses due to dynamic motion during insertion. Therefore, it is necessary to investigate the mechanical behavior of both yarn systems separately as well as in their mutual interaction during fabric formation. In particular, an increase in warp tension leads to a denser arrangement of yarns within the fabric, while variations in weft tension influence fabric thickness and surface topography.

When formulating the problem of determining the state of yarns in a fabric, it is important to consider the fabric structure as an idealized mechanical model. In many cases, yarns are represented as cylindrical elastic elements. At their crossover points, they generate contact pressures against one another, resulting in the deformation of their cross-sections. In reality, however, yarns are not perfectly cylindrical but consist of complex assemblies of fibers, which impart anisotropic mechanical properties to the yarn structure. Therefore, the evaluation of yarn behavior should take into account not only geometric parameters but also fiber composition, yarn twist, density, and surface characteristics [3].

One of the principal factors affecting the state of yarns within a fabric is the contact pressure between adjacent yarns. Contact pressure causes mutual compression of the yarns, leading to changes in yarn diameter and redistribution of the microgeometric parameters of the fabric structure. For example, under high tension, warp yarns may strongly compress the weft yarns, causing the cross-section of the

weft yarn to assume an elliptical shape. This phenomenon affects the surface smoothness and abrasion characteristics of the fabric.

In determining the equilibrium state of yarns within a fabric, it is necessary to evaluate the relationship between external forces and internal elastic forces. If the tensile force in the yarn exceeds its bending resistance, the yarn tends to assume a relatively straight configuration. Conversely, if the bending resistance is high, the wavy shape of the yarn is preserved. Therefore, the following principal forces should be considered when analyzing the mechanical equilibrium of yarns [4]:

- Yarn tension;
- Contact pressure;
- Bending moment;
- Frictional forces;
- External dynamic effects;
- Internal elastic resistance of the yarn.

The problem of determining the state of yarns in woven fabrics is also investigated using modern mathematical modeling methods. In this approach, the equations of motion, equilibrium equations, and geometric relationships of yarns are employed. The equilibrium of forces acting on an elementary yarn segment can be expressed in the following general form:

$$\sum F=0$$

and the equilibrium of moments as:

$$\sum M=0$$

Based on these equations, the bending radius, contact pressure, and deformation state of yarns within the fabric structure can be determined. In particular, the theory of bending plays a significant role in evaluating the wave-like configurations formed on the surface of yarns in twill-woven fabrics.

In addition to geometric parameters, technological parameters are also of great importance in the investigation of yarn behavior within fabrics. During the weaving process, an increase in warp yarn tension leads to a denser fabric structure. This is characterized by reduced air permeability and increased mechanical strength. An increase in weft yarn tension, in turn, causes a reduction in fabric width and promotes a more compact arrangement of yarns. From this perspective, the optimal selection of yarn tension parameters is essential for the formation of the desired fabric structure.

In modern studies, experimental techniques are also widely used to determine the state of yarns in fabrics. In particular, digital microscopy, scanning electron microscopy (SEM) analysis, computer-based image processing, and three-dimensional (3D) modeling technologies enable the evaluation of the actual spatial configuration of yarns. These methods make it possible to identify contact zones between yarns, microporous regions, and deformation areas. They are especially effective in assessing interlayer bonding conditions in multilayer fabrics, providing a high degree of accuracy [5].

The problem of determining the state of yarns in woven fabrics has not only theoretical but also practical significance. Improper selection of yarn tension during the weaving process may result in the following undesirable effects:

- Yarn breakage;
- Non-uniformity of fabric structure;
- Surface defects;
- Excessive compactness of the fabric;
- Disturbance of fabric porosity;
- Reduction in abrasion resistance;
- Deformation after laundering.

Therefore, modern weaving technologies employ automatic warp and weft yarn tension control

systems. These systems measure the stresses acting on the yarns in real time and ensure the stable formation of the fabric structure.

When formulating the problem of determining the state of yarns in a fabric, the fabric may be considered either as a continuum medium or as a discrete system of yarns. In continuum models, the fabric is treated as a uniformly deformable plate. In discrete models, each yarn is investigated as an individual structural element. Although discrete models provide higher accuracy in practical applications, they are associated with greater computational complexity. Therefore, geometric and mechanical simplifications are often employed.

An important parameter in determining the state of yarns within a fabric is the curvature of the yarn. Yarn curvature characterizes its wavy configuration and can be evaluated using the following relationship:

$$k = \frac{1}{R}$$

where:

k – yarn curvature;

R – radius of curvature (bending radius).

As the curvature increases, the internal stresses within the yarn also increase. This phenomenon is particularly evident in high-density fabrics.

The tensile deformation of the yarn is another important factor in evaluating the mechanical state of yarns in a fabric. The relative elongation of a yarn is determined by the following expression:

$$\varepsilon = \frac{\Delta l}{l_0}$$

where:

ε – relative deformation (strain);

Δl – change in yarn length;

l_0– initial yarn length.

The degree of deformation in the yarns directly affects the stability of the fabric structure. Excessive deformation may lead to yarn fatigue and a reduction in mechanical strength.

The evaluation of frictional forces is also essential in the study of yarn behavior within a fabric. Since the yarns are in constant contact with one another, internal friction is generated between them. While this friction contributes to the stability of the fabric structure, it may also cause yarn wear under certain conditions. A higher coefficient of friction reduces yarn slippage and enhances the structural integrity of the fabric.

When formulating the problem of determining the state of yarns in a fabric, it is also necessary to consider the functional purpose of the fabric. For example, air permeability and softness are of primary importance for shirting fabrics, whereas technical textiles require high strength and structural stability. Therefore, the optimal selection of warp and weft yarn tension plays a decisive role in the formation of the desired performance characteristics of the fabric.

Overall, the problem of determining the state of yarns within a fabric is one of the most important theoretical and practical issues in textile materials science and weaving technology. Solving this problem makes it possible to gain a deeper understanding of the mechanisms governing fabric structure formation, to evaluate the influence of warp and weft yarn tensions, to predict the geometric parameters of fabrics, and to develop a new generation of fabrics with enhanced performance properties. The application of modern mathematical modeling, experimental analysis, and digital technologies enables an accurate assessment of the actual state of yarns within a fabric, thereby providing a scientific basis for the production of high-quality textile products [6].

Methods

This study uses an analytical approach. Warp and weft yarns are modeled as curved spatial elastic rods, and the fabric is treated as a discrete system of interlacing yarns, with twill 2/1 fabrics as the main case considered. The equilibrium of an elementary yarn segment is described by force and moment balance and by the Euler–Bernoulli bending equation, contact pressure at crossover points is estimated with Hertzian contact theory, and the equilibrium configuration of the yarn system is taken to correspond to the minimum of total potential energy. Yarn strength and stability are checked with the von Mises criterion and Euler's buckling formula, time-dependent behavior with the Maxwell–Kelvin viscoelastic model, and the dynamic warp and weft tensions on Picanol air-jet and rapier looms with equations that combine initial tension, inertial forces and elastic elongation. Fabric geometry is described with the Peirce model, and the effect of tension on fabric properties is expressed through empirical and multiple regression models. The governing relationships are presented below.

From a theoretical perspective, simple geometric relationships are insufficient for determining the state of yarns in a fabric. During the weaving process, warp and weft yarns are simultaneously subjected to tensile, bending, compressive, and contact deformations. Therefore, the description of yarn equilibrium requires the application of elasticity theory, contact mechanics, and deformation energy formulations. For an elementary segment of a yarn in a fabric, the equilibrium of external and internal forces can be expressed by the following differential equation [4]:

$$\frac{d}{ds}\left(T\frac{d\vec{r}}{ds}\right)+\vec{q}=0$$

where:

T — tensile force acting in the yarn;

$\vec{r}$ — radius vector of the yarn axis;

s — arc-length coordinate of the yarn;

$\vec{q}$ — externally distributed force.

This equation makes it possible to determine the actual spatial configuration of the yarn within the fabric structure.

According to the theory of bending, the equilibrium state of the yarn is described by the Euler–Bernoulli equation [7]:

$$EI\frac{d^4y}{dx^4}-T\frac{d^2y}{dx^2}=q(x)$$

where:

E — Young's modulus (modulus of elasticity) of the yarn material;

I — second moment of area (moment of inertia) of the yarn cross-section;

y(x) — yarn deflection function;

T— yarn tension;

q(x) — external distributed load.

This equation plays an important role in evaluating the wavy configuration of the yarn and the surface relief of the fabric.

The pressure generated at the contact points between yarns in a fabric can be estimated on the basis of Hertzian contact theory [8] using the following relationship:

$$p_{max}=\sqrt{\frac{2FE^*}{\pi Rl}}$$

where:

p_{max} — maximum contact pressure;

F — contact force;
E^* — equivalent modulus of elasticity;
R — equivalent radius;
l — contact length.
An increase in contact pressure leads to deformation of the yarn cross-section and a reduction in fabric porosity.
The bending energy of a yarn within a fabric is determined by the following integral expression:

$$U_b = \frac{1}{2}\int I\left(\frac{d^2y}{dx^2}\right)^2 dx$$

This energy is an important parameter for evaluating the stable configuration of the yarn within the fabric structure.
The tensile strain energy of the yarn is expressed as:

$$Ut = \frac{1}{2}\int \frac{T^2}{EA}dx$$

where:
A — cross-sectional area of the yarn.
The equilibrium state of the yarn system in a fabric is assumed to correspond to the minimum value of the total potential energy [9]:

$$\Pi = U_b + U_t - W \rightarrow min$$

where:
W — work performed by external forces.
In evaluating the geometric configuration of yarns within a fabric, yarn waviness is considered an important parameter and is defined as:

$$C = \frac{l - l_0}{l_0} \times 100\%$$

where:
l — actual length of the yarn;
l_0 — projected length of the yarn within the fabric.
As the waviness increases, the degree of yarn bending also increases.
The mutual pressure between warp and weft yarns in a fabric may be expressed by the following relationship:

$$P = \frac{T_w \sin\theta_w + T_f \sin\theta_f}{d}$$

where:
T_w — warp yarn tension;
T_f — weft yarn tension;
θ_w, θ_f — inclination angles of the yarns;
d — contact diameter.
The probability of yarn slippage within the fabric structure can be evaluated according to the friction law:

$$F_{fr} = \mu N$$

where:
μ — coefficient of friction;
N — normal contact force.

$$T_{rel} > F_{fr}$$

the yarns begin to slip within the fabric structure.

The deformation of a yarn cross-section in a fabric is also associated with the Poisson effect:

$$\varepsilon_t = -\nu\varepsilon_l$$

where:

ε_t — transverse strain;

ε_l — longitudinal strain;

ν — Poisson's ratio.

In determining the equilibrium state of yarns in a fabric, the radius of curvature is an important parameter:

$$R = \frac{\left[1 + \left(\frac{dy}{dx}\right)^2\right]^{3/2}}{\left|\frac{d^2y}{dx^2}\right|}$$

This expression makes it possible to determine the local bending intensity of the yarn.

The porosity coefficient of a fabric can be evaluated using the following expression:

$$\phi = 1 - \frac{V_y}{V_f}$$

where:

ϕ — porosity;

V_y — volume occupied by yarns;

V_f — total volume of the fabric.

An increase in porosity improves the air permeability and hygroscopic properties of the fabric.

The strength condition of yarns within a fabric may be assessed using the von Mises equivalent stress criterion:

$$\sigma_{eq} = \sqrt{\sigma_r^2 - \sigma_r\sigma_\theta + \sigma_\theta^2}$$

If the following condition is satisfied:

$$\sigma_{eq} \leq [\sigma]$$

the yarn structure is considered mechanically stable and sufficiently strong.

The behavior of yarns under cyclic loading conditions can be evaluated using the Maxwell–Kelvin viscoelastic model:

$$\sigma + \lambda\frac{d\sigma}{dt} = E\varepsilon$$

where:

λ — relaxation time;

E — modulus of elasticity.

This model makes it possible to evaluate time-dependent deformation processes occurring in yarns.

The critical buckling condition of a yarn is determined using Euler's formula [7]:

$$P_{cr} = \frac{\pi^2 EI}{(KL)^2}$$

where:

P_{cr} — critical load;

K — effective length factor (end-condition coefficient);

L — free length of the yarn.

This formula is of considerable importance for evaluating the stability of yarns under high tension conditions.

For the dynamic motion of yarns in a fabric, the wave equation may be applied:

$$\rho A \frac{\partial^2 y}{\partial t^2} = T \frac{\partial^2 y}{\partial x^2}$$

where:

ρ — yarn density;

A — cross-sectional area;

T — yarn tension.

This equation makes it possible to evaluate yarn vibrations during the weaving process.

Thus, the problem of determining the state of yarns in a fabric represents a complex multiparameter mechanical system. Its analysis requires the combined application of geometric, mechanical, energetic, and contact theories. Such an approach provides a fundamental scientific basis for understanding the mechanisms of fabric structure formation and for developing fabrics with enhanced performance characteristics.

Results

In the investigation of fabric structure and its formation process, the interaction between warp and weft yarn tensions is considered one of the most important factors. During weaving, each yarn is subjected to a certain mechanical stress state, and this stress directly affects the geometric parameters, physical-mechanical properties, and performance characteristics of the fabric. In particular, in twill fabrics, variations in yarn tension influence yarn bending, waviness formation, the number of contact points, micropore formation, and the stability of inter-yarn bonding.

The tensions of the warp and weft yarns determine the geometric configuration of the yarns during fabric formation. If the warp yarn tension increases excessively, the warp yarns tend to align almost along a straight line, while the weft yarns are forced to undergo greater bending. Conversely, an increase in weft yarn tension intensifies the bending of the warp yarns. As a result, the fabric thickness, air permeability, surface relief, and abrasion resistance are altered [10].

From a mechanical point of view, yarns may be considered flexible cylindrical elements. In this case, the elementary equilibrium equation of a yarn can be written as:

$$EI \frac{d^2 y}{dx^2} = M(x)$$

where:

E — modulus of elasticity of the yarn material;

I — moment of inertia of the yarn cross-section;

y — yarn deflection;

M(x) — bending moment acting on the yarn.

The bending of yarns within the fabric is associated with the tension generated during weaving, and the axial force acting along the yarn can be expressed as:

$$T = \sigma A$$

where:

T — yarn tension;

σ — normal stress;

A — cross-sectional area of the yarn.

During the weaving process, contact pressure is generated as the warp and weft yarns interlace and press against each other. According to Hertzian contact theory, the contact pressure may be estimated as:

$$p = \frac{2T}{dR}$$

where:
p — contact pressure;
T — yarn tension;
d — yarn diameter;
R — radius of curvature.
An increase in contact pressure leads to a higher coefficient of friction between the yarns and enhances fabric compactness. However, excessive pressure may result in localized deformation of the yarn.
To determine the equilibrium condition between warp and weft yarn tensions, an elementary fabric cell is considered. Let (T_t) denote the warp yarn tension and (T_a) the weft yarn tension. The equilibrium condition can then be written as:

$$T_t \sin\alpha = T_a sin\beta$$

where:
α — deviation angle of the warp yarn;
β — deviation angle of the weft yarn.
This relationship indicates that an increase in yarn tension reduces the yarn deviation angle, which consequently alters the surface relief of the fabric.
In twill 2/1 fabrics, yarn bending is greater than in plain-weave fabrics because the free float length of the yarns increases. The weft yarns in twill structures possess longer floats, which are subjected to greater deformation under external frictional forces. Therefore, optimization of yarn tension is particularly important in twill fabrics [11].
The bending energy of a yarn is determined by the following expression:

$$U = \frac{1}{2}\int EI\left(\frac{d^2y}{dx^2}\right)^2 dx$$

This energy characterizes the degree of deformation of the yarn within the fabric structure. As yarn tension increases, the bending of the yarn decreases, resulting in a reduction of the stored bending energy.
The dynamic tension of yarns during the weaving process is of considerable importance. In particular, on Picanol pneumatic and rapier looms, the tension of the weft yarn varies continuously with time during its insertion and movement:

$$T_a(t) = T_{a0} + \rho_a A_a a_a(t) + \frac{E_a A_a}{l_{a0}}\Delta l_a$$

where:
T_{a0} – initial tension of the weft yarn;
ρ_a – density of the weft yarn;
A_a – cross-sectional area of the weft yarn;
$a_a(t)$ – acceleration of the weft yarn;
E_a – modulus of elasticity of the weft yarn;
l_{a0} – initial length of the weft yarn;
Δl_a – relative elongation of the weft yarn.
The time-dependent dynamic tension of the warp yarn can be expressed as:

$$T_t(t) = T_{t0} + \rho_t A_t a_t(t) + \frac{E_t A_t}{l_{t0}}\Delta l_t$$

Where:
$T_t(t)$ – dynamic warp yarn tension as a function of time, cN or N;
T_{t0} – initial warp yarn tension;
ρ_t – density of the warp yarn;

A_t – cross-sectional area of the warp yarn;
$a_t(t)$ – acceleration of the warp yarn as a function of time;
E_t – modulus of elasticity of the warp yarn;
l_{t0} – initial length of the warp yarn;
Δl_t – elongation of the warp yarn.
In this expression, T_{t0} represents the static tension applied to the warp yarn during the initial machine setting process. The term $\rho_t A_t a_t(t)$ characterizes the inertial force generated due to the motion, vibration, and acceleration of the warp yarn. The term $(E_t A_t/l_{t0})\Delta l_t$ represents the additional tension arising from the elastic elongation of the warp yarn.
Thus, the total dynamic tension of the warp yarn consists of the initial tension, inertial effects occurring during motion, and the additional forces generated by elastic deformation. Accurate determination of this parameter is essential for reducing warp yarn breakage, ensuring stable shed formation, and producing high-quality fabrics on Picanol weaving machines [12].
According to this equation, an increase in the acceleration of the weft yarn results in an increase in dynamic tension. This effect becomes especially significant in high-speed weaving machines.
The yarn crimp coefficient in a fabric can be evaluated as:

$$k = \frac{l - l_0}{l_0}$$

where:
l – actual length of the yarn in the fabric; l_0 – straightened yarn length.
The crimp coefficient is directly related to fabric density and yarn tension. As warp tension increases, the crimp coefficient of the warp yarn decreases, whereas the crimp coefficient of the weft yarn increases.
The distribution of pressure forces within the fabric may be estimated by:

$$\sigma_c = \frac{T}{rd}$$

where:
σ_c – contact stress;r – yarn bending radius; d – yarn diameter.
When the contact stress becomes excessively high, plastic deformation may occur on the yarn surface. This phenomenon accelerates fuzz formation and pilling on the fabric surface.
The geometric parameters of fabric structure are widely determined using the Peirce model [13]. According to this model, fabric thickness is expressed as:

$$h = d_t + d_a + \Delta h$$

where:
d_t – diameter of the warp yarn;d_a – diameter of the weft yarn;Δh – additional thickness resulting from yarn deformation.
As tension increases, the value of Δh decreases because the yarns become more compressed.
The relationship between fabric density and yarn tension can be written as:

$$P_t = \frac{n_t d_t}{1 + k_t}; \qquad P_a = \frac{n_a d_a}{1 + k_a}$$

where:
P_t, P_a – warp and weft fabric densities;n_t, n_a – number of warp and weft yarns;k_t, k_a – crimp coefficients of warp and weft yarns.

According to these relationships, an increase in tension reduces the crimp coefficient and increases the fabric cover factor.
The air permeability of a fabric is also related to yarn tension. According to Darcy's law, the airflow

rate is given by:

$$Q = \frac{kA\Delta P}{\mu L}$$

where:

Q – airflow rate;k – porosity coefficient; A – surface area; ΔP – pressure difference; μ – air viscosity; L – fabric thickness.

An increase in yarn tension reduces fabric porosity and consequently decreases air permeability.

The resistance to relative yarn displacement can be described using Coulomb's friction law:

$$F = \mu N$$

where:

F – friction force; μ – coefficient of friction; N – normal pressure.

Since normal pressure increases with yarn tension, resistance to yarn slippage also increases.

The stress state within the fabric may additionally be evaluated using the von Mises equivalent stress:

$$\sigma_{eq} = \sqrt{\sigma_r^2 - \sigma_r\sigma_\theta + \sigma_\theta^2}$$

where:

σ_r – radial stress; σ_θ – circumferential stress.

The equivalent stress enables the assessment of local deformation conditions of the yarns.

When warp and weft yarn tensions are in equilibrium, the fabric structure attains a stable configuration. If:

$T_t = T_a$

the yarns are arranged symmetrically, and the fabric surface relief becomes uniform. In practice, however, this equilibrium is often disturbed in twill and rep weave structures [14].

Experimental studies have shown that an increase in warp tension leads to:

- increased tensile strength of the fabric;
- reduced fabric thickness;
- decreased air permeability;
- increased surface rigidity.

An increase in weft tension, on the other hand, results in:

- reduction of fabric width;
- decrease in weft yarn crimp;
- smoother fabric surface relief.

The empirical relationship between yarn tension and fabric strength may be expressed as:

$$F_b = a + bT + cT^2$$

where:

Fb – fabric breaking force; T – yarn tension; a, b, c – experimentally determined coefficients.

In many cases, a parabolic relationship is observed. Up to a certain limit, increasing tension improves strength; however, beyond this limit, strength begins to decrease due to internal damage within the yarn.

To optimize warp tension, weft tension, and weft density of the fabric, a multiple regression model can be applied. This relationship is represented as [14]–[16]:

$$Y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3$$

where:

Y – fabric property under investigation; x_1 – warp tension; x_2 – weft tension; x_3 – weft density of the fabric.

Based on this model, optimal process parameters can be determined.

The equilibrium state of yarns in a fabric may also be analyzed using an equation analogous to the Laplace equation:

$$\frac{T_t}{R_t} + \frac{T_a}{R_a} = p$$

R_t – bending radius of the warp yarn; R_a – bending radius of the weft yarn; p – internal contact pressure. This equation describes the relationship between yarn geometry and contact pressure.

Discussion

Research results indicate that warp and weft yarn tensions are among the primary parameters governing fabric structure formation. When rational tension values are selected:

- yarn crimp is optimized;
- a microporous fabric structure is formed;
- air and moisture exchange are improved;
- abrasion resistance is enhanced;
- stable interlacement between warp and weft yarns is ensured.

Particularly in multilayer fabrics, proper coordination of warp and weft tensions can lead to the formation of a square-shaped microporous interlayer structure. This contributes to improved hygienic and service properties of the fabric.

These relationships agree with the classical description of woven fabric geometry. In the Peirce model [13], crimp, thread spacing and fabric thickness are linked geometrically, and the present analysis adds the effect of warp and weft tension on these quantities through the reduction of the crimp coefficients and of the additional thickness Δh. Kawabata et al. [17] showed that the lateral compressibility of yarns strongly influences the tensile properties of plain-weave fabrics, which is consistent with the role of contact pressure and cross-section flattening at crossover points identified in this study. The energy formulation used here, in which the equilibrium configuration corresponds to the minimum of total potential energy, follows the energy method developed for fabric mechanics by Hearle and Shanahan [9].

The present work is mainly theoretical. The coefficients a, b and c of the empirical strength model and the coefficients of the multiple regression model have to be determined experimentally for specific yarns, weave structures and looms, and the predicted trends should be verified by measuring crimp, thickness, air permeability and breaking force on fabrics woven at controlled warp and weft tensions. Future work should also account for the anisotropic, fibrous structure of real yarns, which the idealization of yarns as elastic rods does not fully capture.

Conclusion

Thus, a complex mechanical and geometric relationship exists between fabric structure, warp and weft yarn tensions, and weft density. Through theoretical and experimental investigation of these relationships, it becomes possible to design fabrics with superior performance and enhanced service characteristics.

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