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DEFORMATION STATES OF COMPLEX TWISTED SILK YARN

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Abstract: This article presents the results of theoretical and experimental studies of the stress-strain state of complex twisted silk threads under axial tension. Using a matrix transformation and statistical averaging method, expressions for thread stiffness are obtained, allowing the relative modulus of elasticity to be estimated through longitudinal and transverse deformations. The relative modulus of elasticity of twisted complex thread made from raw silk is estimated as a function of twist.
Key words: raw materials, raw silk, fiber, thread, twist, modulus, structure, deformation.

Introduction. The study of the mechanical properties of fibers and threads is primarily based on tensile testing. This is explained by the fact that the shape of fibers and threads (significant length with small transverse dimensions) often causes forces to be applied in a manner that causes tensile deformations. This is also facilitated to a certain extent by the longitudinal arrangement of fibers in threads, as well as threads in fabrics and other products.

This work describes the sequence of technological processes for the preparation of yarns spun from raw silk for the production of medical bandages. S 350 br/m, which is spun on the left side by adding 3 skeins of raw silk with a density of 2,33 tex, and S 500 br/m, which is spun on the left side by adding 8 skeins of raw silk with a density of 3,23 tex. Based on the results of the research, the linear density, breaking strength, coefficient of variation of linear density, elongation at break, number and direction of twists, and coefficients of variation of twists of the spun yarns are presented [1-4].

In the cited work, the classification of sewing thread assortments is based on the following characteristics: thread purpose, raw material composition, finishing method, as well as structural indicators such as the number of joints, the direction of twists, linear density (thickness), etc. [5, 6]. In the production of surgical thread woven from natural silk, it was found that the number of twists (tw/m) varied by even 10-20% compared to the given number of turns (tw/m) in the old brand of splicing machines, which used multi-process technology, because the beads moved through the belt [7, 8].

Research. Studying the deformation characteristics of textile fibers and threads, particularly complex twisted silk threads, under tension will help identify the relationship between stress (force) and deformation, taking into account the key factors influencing this relationship: thickness and linear density of fibers and threads; twist and structure of threads; loading time, etc. The importance of theoretical and experimental research into the stress-strain state of fibers and threads is determined by the discovery of patterns in the elastic-plastic behavior of materials under load, elastic characteristics, as well as the ability to create fracture models and predict the strength properties of products under operating conditions.

Figure 1 shows a general diagram of the deformation under axial tension of a fiber element with the following geometric parameters: l_j -is the diagonal length of the fiber element; x_j y_j are the transverse and axial components of the length, respectively; θ -is the orientation angle of the fiber element.

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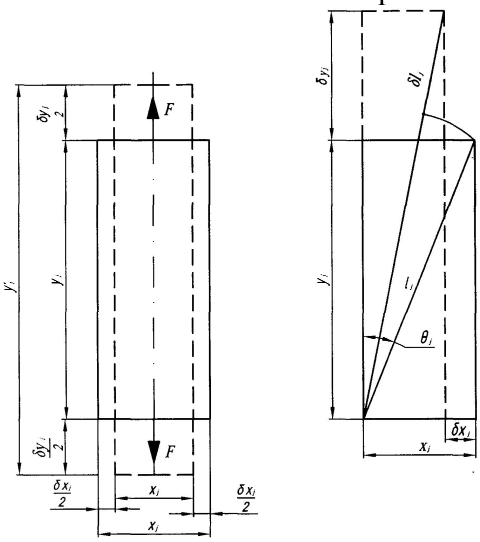
Due to the geometric similarity of the deformation of the fiber element and the thread sample, the following relationships hold:

$$\frac{\delta y_j}{y_j}=\varepsilon_y;\frac{\delta x_j}{x_j}=\varepsilon_x \qquad (1)$$

where $\delta y_j/y_j$ -is the axial deformation of the fiber element; ε_y -is the axial deformation of the thread sample; $\delta x_j/x_j$-is the transverse deformation of the fiber element; ε_x -is the transverse deformation of the thread sample.



a) b)

Fig. 1. General diagram of deformation under axial tension of a fiber element by force F (a) and calculation diagram of deformation of a fiber element (b)

From Fig. 1, b it follows that during axial tension of a fiber element the equality is satisfied

$$(l_j+\delta l_j)^2=(y_j+\delta y_j)^2+(x_j-\delta x_j)^2 \qquad (2)$$

Dividing both parts of the equality by l_j^2 and performing the transformation, we obtain и сделав преобразование, получим

$$\left(\frac{1+\delta l_j}{l_j}\right)^2=\frac{y_j^2}{l_j^2}+\frac{2y_j\delta y_j}{l_j^2}+\frac{\delta y_j^2}{l_j^2}+\frac{x_j^2}{l_j^2}-\frac{2x_j\delta x_j}{l_j^2}+\frac{\delta x_j^2}{l_j^2} \qquad (3)$$

Let us represent the relative deformation of the fiber ε_j as reduced through the relation

$$\varepsilon_j=\frac{\delta l_j}{l_j} \qquad (4)$$

and taking into account the expressions for the axial (longitudinal) deformation ε_y and the transverse deformation ε_x of the fiber element, one can obtain the general relationship between the fiber deformation and the thread sample:

$$(l+\varepsilon_j)^2=cos^2\theta+2\varepsilon_y^{'}\cdot cos\theta+\varepsilon_y^{'2}+sin^2\theta-2\varepsilon_x^{'}\cdot sin\theta+\varepsilon_x^{'2}$$

or

$$(l+\varepsilon_j)^2=1+2\varepsilon_y^{'}\cdot cos\theta-2\varepsilon_x^{'}\cdot sin\theta \qquad (5)$$

where $\frac{\delta y_j}{l_j}=\varepsilon_y^{'}$- reduced axial strain of a fiber element; $\frac{\delta x_j}{l_j}$ – reduced transverse strain of a fiber element.

In the last expression, we neglect the relative reduced second-order strains due to their small values. If the transverse strain is represented in terms of the longitudinal strain using Poisson’s ratio μ, we obtain:

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$$(l+\varepsilon_j)^2 = 1+2\varepsilon_y^{'}\cdot(\cos\theta-\mu\cdot\sin\theta) \quad (6)$$

In the case where the transverse deformation is negligible, then the last equation is simplified:

$$(l+\varepsilon_j)^2 = 1+2\varepsilon_y^{'}\cdot\cos\theta \quad (7)$$

Then the relative deformation of the fiber element will be

$$\varepsilon_j = \sqrt{1+2\varepsilon_y^{'}\cdot\cos\theta}-1 \quad (8)$$

Developing a textile thread model requires taking into account the deformation behavior of fibers and threads [9-11].

Let's assume that the thread has a circular cross-section and consists of a large number of fibers arranged in a helical line. Since the elementary fiber is arranged in a helical line, at some point *P* on the fiber, it is advisable to introduce, in addition to the orthogonal coordinate system (ξ, η, ζ), whose axes are tangent to the normal and binormal, a cylindrical coordinate system (*r, θ, z*). The *z*-axis is directed parallel to the thread axis (Fig. 2).

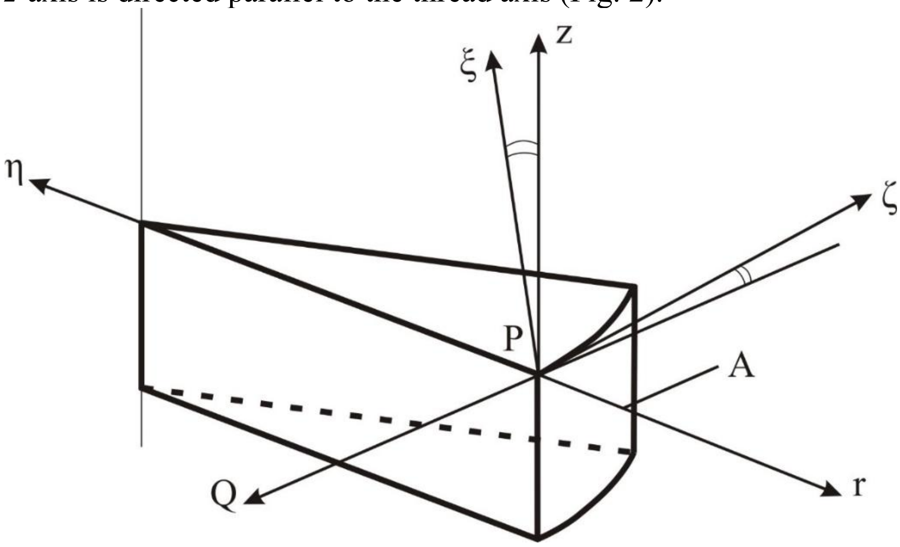

Fig. 2. Combination of orthogonal (ξ, η, ζ) and cylindrical (r, θ, z) coordinate systems for element A of the fiber on the helical line formed by twisting the thread

Taking this into account, the direction cosine matrix $S_{ij} (i,j=1,2,3)$ between the two selected coordinate systems has the form:

$$[S_{ij}] = \begin{matrix} & \xi & \eta & \zeta \\ r & 0 & -1 & 0 \\ \theta & \sin\theta & 0 & -\cos\theta \\ z & \cos\theta & 0 & \sin\theta \end{matrix} \quad (9)$$

where θ is the helical angle.

Each elementary fiber, being axially oriented and therefore in an asymmetric state of stress, exhibits transverse isotropy of elastic properties. From this assumption it follows:

$$\sigma = c^{*}\cdot e \quad (10)$$

where σ, c^*, e – the stress, stiffness, and strain tensors, respectively, are expressed in expression (10).

In this expression (10), which corresponds to Hooke's law, the elastic modulus E, as demonstrated by A.N. Soloviev [12], should be considered as the relative stiffness modulus for textile materials. This is because, in elasticity theory, the ratio of load to strain is commonly referred to as stiffness. However, since determining normal stresses σ requires dividing the load by the area S, stiffness in this case becomes relative. Considering the diagonal elements of the

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stiffness matrix to be equal to the fiber elastic moduli in the longitudinal E_j and transverse E_T directions, the stiffness matrix is written in simplified form as:

$$c^* = \begin{bmatrix} E_j & E_{Tj} & E_{Tj} & 0 & 0 & 0 \\ E_{Tj} & E_T & E_{Tj} & 0 & 0 & 0 \\ E_{Tj} & E_T & E_T & 0 & 0 & 0 \\ 0 & 0 & 0 & 2E_{Tj} & 0 & 0 \\ 0 & 0 & 0 & 0 & E_{Tj} & 0 \\ 0 & 0 & 0 & 0 & 0 & 2E^*_{TT} \end{bmatrix} \quad (11)$$

where $2E^*_{TT}=E_T-E_{Tj}$; E-is the elastic modulus. The stiffness constants of the thread can be expressed through the characteristics of the elementary fiber using a matrix transformation and the statistical averaging method:

$$C_{ijkl}=\frac{1}{A}\int \rho c^*_{mnop}\, S_{mi}S_{nj}S_{ok}S_{pl}\,dA, \quad (i,j,k,l=1,2,3) \quad (12)$$

where ρ-is the number of fibers per unit area and can be considered a distribution function; A-is the cross-sectional area of the raw silk thread.

Integration (12) is performed over the entire cross-section of the thread.

For a thread consisting of fibers as highly oriented as raw silk, the stiffness constants C_{ij} can be calculated, taking into account the simplifications introduced, using the following formulas:

$$C_{11}=\left(\frac{4a}{3}\right)E_j$$

$$C_{22}=2E_j\left[\frac{sin^2\alpha}{2}+\left(1+\frac{2a}{3}\right)cos^2\alpha+2\,ctg^2\alpha lg\cos\alpha\right],$$

$$C_{33}=2E_j\left[cos^2\alpha+\left(\frac{1}{2}+\frac{4a}{3}\right)+\left(\frac{2a}{3}\right)sin^4\alpha+\left(\frac{2a}{3}\right)sin^2\alpha cos^2\alpha+\left(\frac{8a}{3}\right)ctg^2\alpha lg\cos^2\alpha\right] \quad (13)$$

$$C_{13}=\left(\frac{4E_j}{3}\right)\left(\frac{1}{2}+ctg^2\alpha\, lgcos\alpha\right),$$

$$C_{23}=-2E_j\left(1+\frac{4a}{3}\right)\left[\left(\frac{1}{2}\right)ctg^2\alpha\left(sin^2\alpha+ctg^2\alpha\, lgcos\alpha\right)\right],$$

$$C_{12}=\left(\frac{4}{3}\right)E_j ctg^2\alpha\, lgcos^2\alpha$$

where $a=\frac{E_T}{E_j}$ -is the ratio of the transverse modulus of elasticity of the fiber to its longitudinal (axial) modulus. Under uniaxial tension, the modulus of elasticity of raw silk thread is determined by the formula

$$E_y=C_{33}-\frac{(C_{13}^2C_{22}+C_{11}C_{23}^2-2C_{12}C_{13}C_{23})}{(C_{11}C_{22}-C_{12})} \quad (14)$$

Note that the elastic modulus of the yarn E_y depends on the surface helix angle α and the elastic moduli of the fiber E_T and E_j.

The geometry of the twisted yarn and the analysis of its mechanical properties are based on the idealized geometric model shown in Fig. 3, a.

It is assumed that the fibers are uniformly packed and arranged along helical lines with a constant pitch, i.e., the pitch of one twist turn is independent of the radius. In this case, the yarn model is a cylinder defining one twist turn and characterized by the developments shown in Fig. 3, b-d for the fiber at the center of the yarn, at radius *r*, and on the surface at radius *R*.

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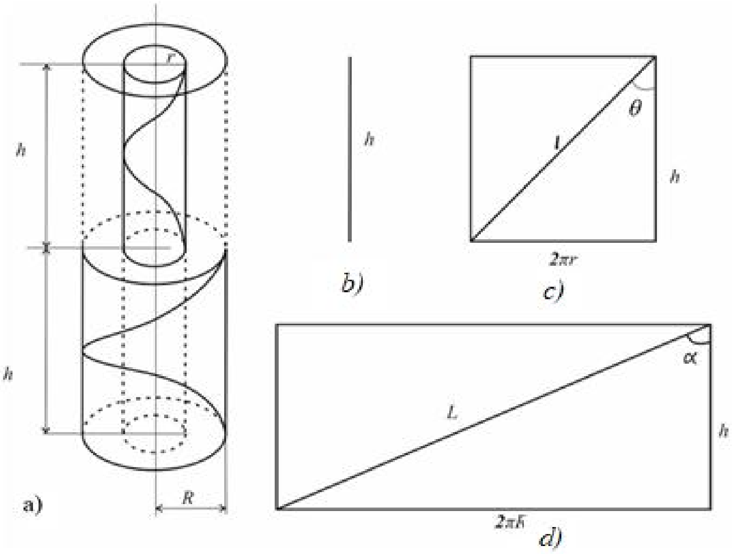

a) a uniform cylindrical thread; b) the central fiber; c) the fiber development at a radius of *r*; d) the fiber development on a surface of radius *R*, the pitch of one thread twist is *h*, the angle between the tangent to the helical line and the cylinder axis at radius *r* is *θ*, and at radius *R* is *α*.
Fig. 3. Accepted geometry of a twisted thread

Compared to the analysis of a single yarn, the mechanics of a multi-filament twisted yarn is complicated by the imposition of left and right twists of varying degrees. The combination of these twists alters the helical geometry of the elementary fibers, making it more complex.
The discussed method of statistically averaging the characteristics of elementary fibers can also be used to calculate the elastic parameters of a twisted complex silk thread. To do this, it is necessary to introduce expressions that account for the contribution of all individual elementary fibers in the raw silk thread to the properties of the twisted complex silk thread, and then sum all the contributions depending on the number of raw silk threads in the twisted complex thread. In this case, the coordinate system for the twisted complex thread (***x, y, z***) is chosen such that the ***z***-axis is directed along the central axis, and the unit vectors (unit vectors) form an orthogonal coordinate system. The coordinate system of the raw silk thread (***x, y, z***) is defined such that the ***z***-axis is parallel to the centerline of the twisted thread in question, and the unit vectors are oriented accordingly. The coordinate system of the elementary fiber (ξ, η, ζ) is defined as before.
Let us denote: φ is the angular position of a point on the fiber in a plane perpendicular to the ply axis of the raw silk thread; f is the angular position of the thread axis perpendicular to the vector. In this case, after some calculations, it can be shown that the direction cosines between the axes of the fiber and the twisted complex thread are calculated using the formulas

$$S_{11}(\xi) = \cos\varphi\cos\phi + \sin\phi\cos\beta_0\cos\phi,$$
$$S_{12}(\xi) = \sin\varphi\sin\phi + \cos\beta_0\sin\varphi\cos\phi,$$
$$S_{13}(\xi) = -\sin\varphi\sin\beta_0 \qquad (15)$$
$$S_{11}(\eta) = \cos\theta\sin\varphi\cos\phi + \cos\theta\cos\varphi\cos\beta_0\cos\phi + \sin\theta\sin\beta_0\sin\phi,$$
$$S_{12}(\eta) = -\cos\theta\sin\varphi\sin\phi + \cos\theta\cos\varphi\cos\beta_0\cos\phi + \sin\theta\sin\beta_0\cos\phi,$$
$$S_{13}(\eta) = \sin\theta\cos\beta_0 - \cos\theta\cos\varphi\sin\beta_0, \qquad (16)$$
$$S_{11}(\zeta) = \sin\theta\sin\varphi\cos\phi + \sin\theta\cos\varphi\cos\beta_0\sin\phi - \sin\beta_0\cos\theta\sin\phi,$$
$$S_{12}(\zeta) = \sin\theta\sin\varphi\sin\phi - \sin\theta\cos\beta_0\cos\varphi\sin\phi + \cos\theta\sin\beta_0\cos\varphi,$$
$$S_{13}(\zeta) = \sin\theta\sin\beta_0\cos\phi + \cos\theta\cos\beta_0, \qquad (17)$$

where *β*-is the angle of inclination of the centerline of the raw silk thread.

After substituting S_{ij} from (15) - (17) into (12) and calculating the integrals, we can write the following formula for E_c^i, which is the contribution of the typical *i*-th fold of the raw silk thread to the elastic modulus of the twisted complex thread:

$$E_c^i = E_f cos^4 \beta_o cos^2 \alpha \left[1 - \left(\frac{3}{2}\right) tg^2 \beta_o \left(\frac{1+2lgcos\alpha}{sin^2\alpha}\right)\right] \qquad (18)$$

Effective modulus of twisted complex yarn

$$E_c = \sum_{i=1}^{N} E_c^i \qquad (19)$$

is obtained by summing all contributions over all additions (N is the number of additions). The values of α and β_o in equation (18) are determined by the formulas

$$tg\alpha = 2\pi R_y t_y; \qquad tg\beta_o = 2\pi R_{y*} t_c, \qquad (20)$$

where R_y is the radius of the raw silk thread; R_{y*} is the distance between the centerline of this thread and the axis of the twisted complex thread; t_y and t_c are the twists of the raw silk thread and the twisted complex thread, respectively, per unit length. This analysis agrees well with the experimental data shown in Figure 4 and is an integral part of the model.

Figure 4 shows the characteristics of twisted complex silk thread for the case of equal twists.

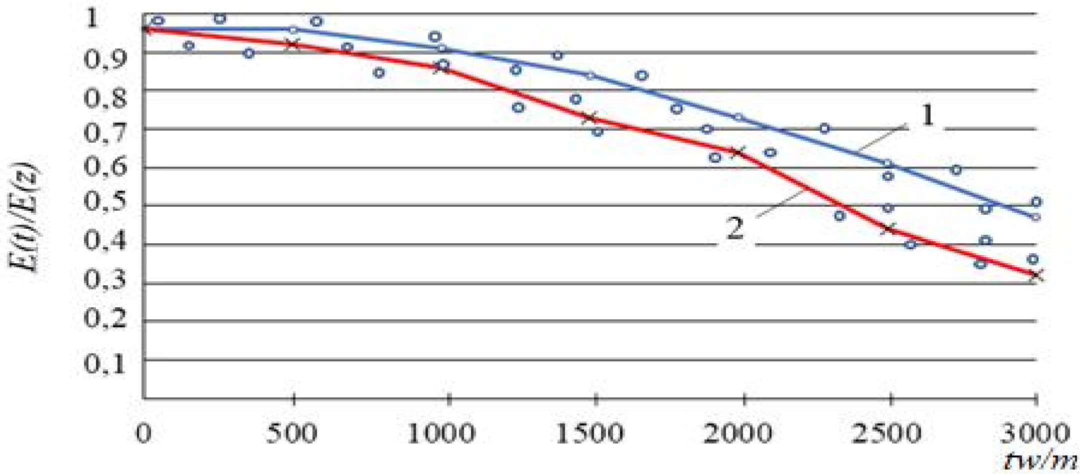

Fig. 4. Calculated and experimental relative elastic moduli of twisted complex thread: 1 - made of raw silk 9,32 tex; 2 - made of raw silk 12,92 tex (*E(t)/E(z)* - the ratio of the transverse modulus of elasticity of twisted complex thread to its axial modulus)

Conclusions. Based on theoretical and experimental studies of axial tension of threads, it was established that, at high twist, the strain state of a complex thread is affected by the deformation elements of both the raw silk and the fibers. An analytical expression for the elastic modulus of raw silk thread under uniaxial tension was obtained using the stiffness tensor elements of the elementary fibers. The relative elastic modulus of twisted complex thread made from raw silk was estimated depending on the twist.

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