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Structural analysis of structural tissues and hereditary properties, taking into account the damage of threads

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ABSTRACT: The article is devoted to the study of the structure of structural tissues and hereditary properties, taking into account the damage of threads. The issues of applying the arsenal of knot theory to the analysis of the structure of woven structures are considered. Kinetic equations of damage of viscoelastic bodies are used to analyze the deformation and destruction of the thread. The parameters of viscoelastic filaments and their modulus of elasticity as a function of linear density are analyzed on the basis of experimental data from a number of authors. On the basis of the phenomenological concept of mechanics, using the theory of long-term strength, the process of damage accumulation of textile yarns has been studied. The results of calculating the damage of the warp threads in the manufacture of fabrics of various weaves are presented and the influence on technological processes is established.

I. INTRODUCTION

In recent years, an approach to analyzing the structure of composite materials has been intensively developing, based on the introduction of a macroscopic parameter characterizing the degree of damage of materials at the macro level. The issues of predicting deformation properties and theoretical and experimental studies of damage and long–term strength of composite materials, including textiles, the development of mathematical models and calculation methods taking into account the structure of materials are of current interest [1-5].

In [2], the basics of designing textile yarns and webs were developed, allowing to predict their structure and properties by directing the impact on the technological process, the topological characteristics of various textile transitions were analyzed. The nature of changes in the initial properties of yarns and yarns in the technological process has been experimentally investigated. Based on the experimental and theoretical studies carried out in [3], the main parameters of the deformation processes and the strength of cotton yarn were determined. Changes in the modulus of deformations with different linear densities are revealed. Based on the use of a model of a structurally linear viscoelastic body, a physically nonlinear elastic-viscoplastic law of deformation of cotton yarn during stretching, taking into account unloading, is proposed. Based on the results of the study of technological processes, the laws of deformation of textile yarns are derived, taking into account structural heterogeneity [3, 4].

The monograph [5] shows the exceptional importance of analyzing the causes, thread breakage and their destruction in the process of thread processing. The phenomenological process of destruction developing over time is considered as a certain process of accumulation of damage and various defects. Using the damage model, V.P.Shcherbakov developed the theoretical foundations of the processing of threads and fabrics, obtained equations of motion taking into account the viscoelastic properties of the threads. The works [6, 7] are devoted to the prediction of technological parameters of fabric manufacturing of a given structure and the development of methods for their calculation. In [7], a theory of thread deformation based on the hereditary theory of viscoelasticity is developed. Extensive experimental material on creep and relaxation of various filaments and tissues is presented. In studies [8-11], viscoelastic parameters and core coefficients for natural and a number of chemical textile yarns were experimentally determined based on the criterion of long-term strength. Based on the equation of the hereditary theory of Boltzmann-Volterra viscoelasticity, linear and nonlinear laws of deformation of textile yarns are developed and methods for determining and evaluating the strength characteristics of textile materials are proposed on their basis. The main relationships between stresses and deformations over time are given, and the functional effect under different stress conditions is shown.

The paper [12] presents the results of theoretical and experimental studies on the optimization of the physical and mechanical properties of woven composite materials and the design of fabric products taking into account the specified properties. The methods and test results for evaluating the mechanical properties of reinforced fabrics are described. As noted, in the processes of processing threads on technological equipment, it is very important to understand the causes leading to their destruction. The article[14] shows that the strength of the sewing thread on knitting machines depends on its physical and mechanical properties, as well as the nature of interaction with the executive bodies of the looping system.

II. THEORETICAL RESEARCH

As is known, woven structures are among the most common types of engineering structures and are widely used in various fields of technology [2]. This leads to a wide interest of researchers in the structural analysis of woven structures both on the basis of further development of existing approaches and on the basis of the development of new, non-traditional approaches. In this context, the paper analyzes the structures of the textile variety and the long-term strength of woven structures based on topological representations of the nature of such objects. It is known that a woven structure geometrically consists exclusively of the intersection of lines of two systems located mutually perpendicular. At the same time, the minimum area of tissue is the so-called rapport, consisting of Ro warp threads and Ry weft threads with the number of line intersections equal to the product Ro×Ry. Topologically, these intersections are transitions or passages, depending on whether an arbitrary line lies above or below at a given intersection [2, 14-17].

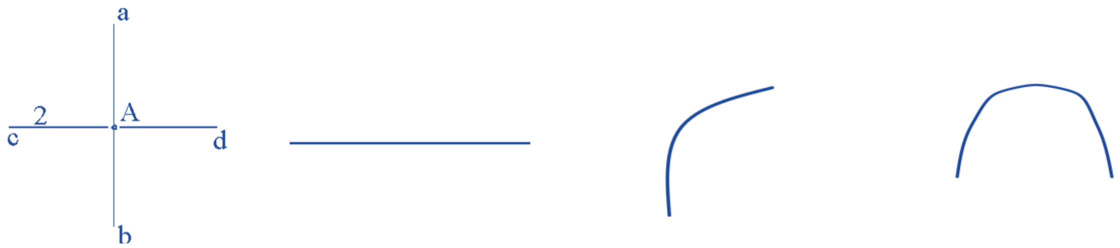
Along with the number of line crossings, the most important characteristic of a woven structure as a topological object is the order of alternation of these transitions and passages within the rapport – its assessment in relation to the so-called alternability. Since rapport is a two-dimensional object, we can naturally talk about alternating in the direction of both systems of lines: both horizontal and vertical (weft and warp threads). Ideally, when the order of alternation is strict: "one pass-one transition" in both directions within the entire rapport, the fabric is a completely alternating knot (in technology, this is a plain weave). In fact, it is a node of the highest degree of alternation. But the reality is that it is possible to deviate from this ideal to one extent or another: for example, in some individual sections of the woven structure as a node there are "two transitions-one passage", or "two transitions-two passages", etc. (in technology it can be twill, satin, matting, etc.).

Consideration of this issue shows that the Ro×Ry characterization of line intersections within a node, only as transitions and passages, is unproductive from the point of view of numerical characterization of the degree of alternation of the entire node. The fact is that all intersections of lines within a node, regardless of whether they are transitions or passages, are in relation to "neighborhood" with each other, and ultimately constitute a whole node (rapport), differing in one degree or another of alternation. Therefore, the evaluation of each of the Ro×Ry line intersections within the entire node should go beyond evaluating them only as transitions and passages.

The topological transition (passage) is an elementary intersection of two lines 1 and 2, simulating the warp and weft threads with the intersection point A (Fig.1a). Let line 1 with ends a and b pass over line 2 with ends c and d. If we take the scheme in question as a calculated overlap scheme from the rapport of an arbitrary woven structure, then lines 1 and 2 can spatially take the form of straight, semi-curved, and curved lines (Fig. 1 b, c, d), which for the position of their ends a, b, c and d corresponds to: maintaining the original level; lifting or lowering; and lifting and lowering at the same time. The number of all possible pairs can be easily determined by simple iteration, or combinatorially, as the sum of two combinations of three elements, 2 and 1 each, using a well-known dependence:

$$C_n^m = \frac{n(n-1)\cdots(n-m+1)}{1\cdot 2\cdot 3\cdots m} \tag{1}$$

It is clear that there are only 6 possible combinations. Figure 1 shows the intersection of two lines, as an imitation of a weaving floor and the possible geometric shapes of the components (a – imitation of an overlap; b – a straight line; c – a half–arc; d - an arc).



a) b) c) d)

Fig. 1. The elementary intersection of two lines, as an imitation of a weaving floor and possible geometric shapes of the components

For clarity, we will give a graphical image for some combinations of intersections (Fig. 2 – Fig. 5). Let's choose the following names of the intersection options shown in Fig. 2-5: for example, the intersection of a) the pair “straight – straight”; b) “straight – half–arc”; c) “half–arc - half-arc”; d) “half-arc - arc".

Thus, it is possible to establish the maximum number of the entire diversity of varieties of spatial intersection of lines possible within a mathematical node comparable to the rapport of weaving of single-layer fabrics. It is clear that each of these six intersections (four) can be characterized in completely different ways with respect to the formation of alternating sections [2].

In this regard, it is possible to analyze and evaluate in detail each of the six possible types of intersections in order to complicate the shapes of the lines, giving the lines a cylindrical shape with a certain diameter for greater clarity, and bringing two sections in the direction of both component pairs. As an illustration, consider the following (Fig. 2-5):

1. The intersection of the “straight line" (Fig.2). Obviously, due to the geometric shape of the lines themselves, this type of intersection does not contribute to the appearance of alternating sections on any of the four sides around itself in relation to neighboring intersections. That is, if one of the lines of this intersection is on top of another line and is transitive, then, due to the fact that it is straight, it creates only transitions with two adjacent intersections, thus forming a section: "transition-transition-transition". Similarly, the second line of this type of intersection, located from below, with adjacent intersections on both sides creates only passages, which means the appearance of a passage-passage-passage section, respectively. It is clear that this type of intersection does not contribute to the formation of the overall degree of alternability of the node as a whole. And the more of this type of intersection occurs within a node, the lower the degree of its alternability. It is obvious that the node with the maximum degree of alternation, which imitates the fabric of a plain weave, does not contain a single intersection of this type.

2. The “straight-semi-arc” intersection (Fig. 3). This type of intersection is potentially capable of creating alternability with only one of the neighboring intersections, and non-alternating sections will be formed with the other three neighboring intersections. For example, if a semi-arc at a given intersection is located on top, forming a transition, then the pattern of alternating transitions and passages in the vicinity of this intersection will be: "transition-transition-passage", or "passage-transition-transition", and a straight line passing under the semi-arc with neighboring intersections on both sides forms a section "passage-passage-passage."

3. A pair of "half-arc-half-arc" (Fig. 4). Both elements of this pair are half-arcs, and bend around each other equally, as can be seen from the sections A-A and B-B shown in Fig. 4. Each of this pair of lines creates alternability with adjacent intersections on only one side. And the sections created around such an intersection will be, for example, of this type: "passage-transition-transition" and "passage-passage-passage".

4. The "semi-arc-arc" pair (Fig. 5). Such an intersection is quite productive in terms of creating alternating sections with neighboring intersections around itself, and makes a significant contribution to the formation of the overall degree of alternation of the entire node as a whole. It creates alternating sections with three adjacent intersections around itself, and only on one side the violations of the alternation of "one transition-one passage" and departure from alternation can be observed. Thus, the intersection of the "semi-arc-arc" creates sections of the type "passage-passage-passage" and "passage-passage-passage".

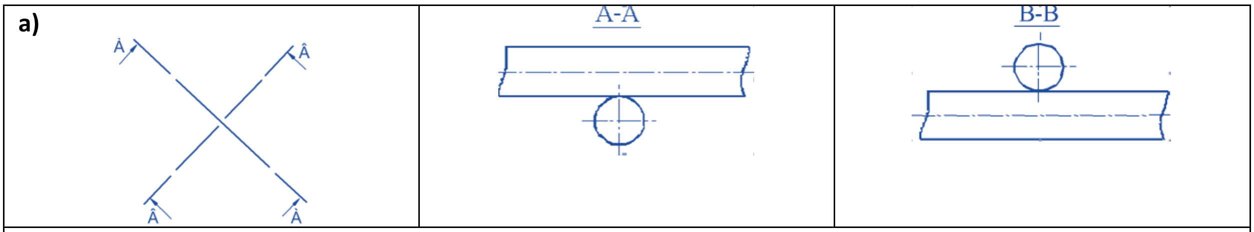


Fig. 2. The pair “straight - straight”

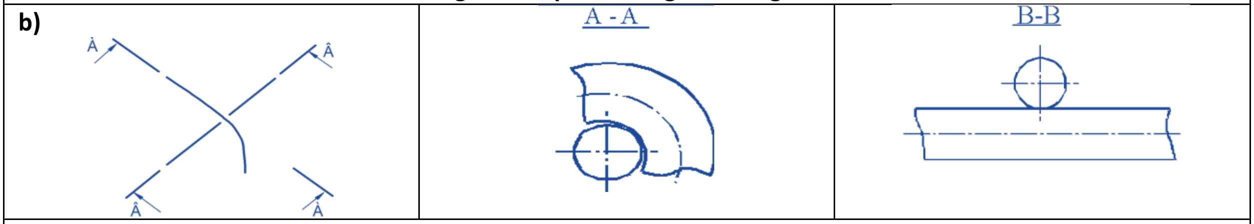


Fig. 3. The straight-half-arc pair

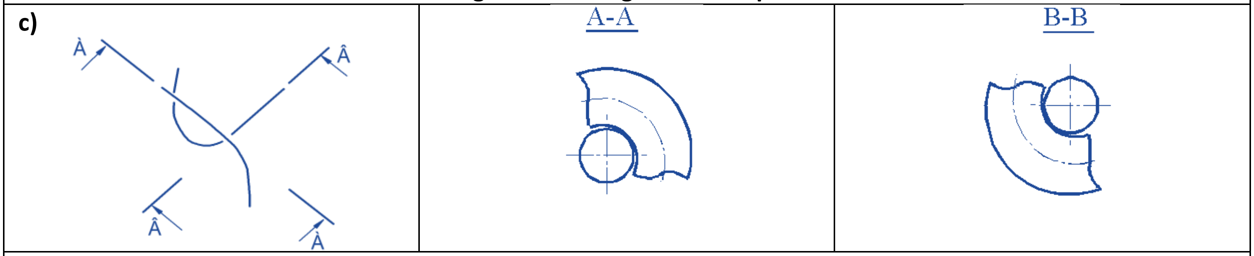


Fig. 4. The half-arc-half-arc pair

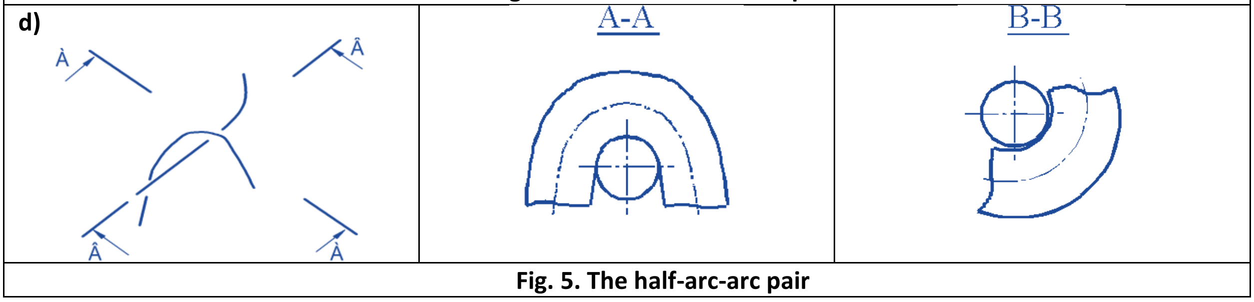


Fig. 5. The half-arc-arc pair

Let us now consider the variation of the structure – topology of the weave of fabrics. For structural fabrics, linen, satin and twill weaves are mainly used. In [2, 14], criteria for evaluating the structure of woven structures using the knot theory are presented. Woven structures are widely used in many branches of engineering and in everyday life both as load-bearing elements in complex structures and as independent structural units. Here we consider a class of single-layer fabrics of arbitrary weave made of warp thread and weft of any fibrous composition. Such a structure is represented as consisting of elementary cells, which in an integrated form determine its structural ability, known in technological usage as single weaving floors. It is noted that in the categories of knot theory, overlap is the intersection of topological lines, which is a transition or passage, depending on the location of the desired line in relation to another line at the intersection. The combination of these transitions and passages within the rapport makes up a mathematical node. The fabrics of different weaves correspond to nodes of different orders. Depending on this, the geometric shape of the topological line corresponding to the base and the weft can be a straight line, a semi-arc, or an arc [14].

It is shown that the number of pairwise combinations of these three conditional links in a technological overlap, or in a topological transition (passage), is 6. According to the marked feature, they are: "straight–straight"; "straight–half–arc"; "straight–arc"; "half-arc-half-arc"; "half-arc-arc"; "arc-arc".

The structural analysis made it possible to assess the degree of nodulation of the threads in the fabric according to the formula [14]:

$$C_3 = \frac{\sum\limits_{i,j=1}^{R_0,R_y} C_{3ij}}{R_0 R_y}, \qquad (2)$$

where C_{3ij} – the degree of narrowing of an arbitrary overlap in the rapport corresponding to the i–th warp thread and j–th weft thread, the value of which may vary from 0 before 1 in increments of 0,25, with i=1,2, ..., R_0 and j=1, 2, ..., R_y accordingly; R_0 and R_y – rapport on the warp and on the weft, respectively.

Based on formula (2), for some types of the most common weaves, we present comparative numerical values of the traditional weave coefficient and its topological equivalent – the degree of nodulation of threads in the fabric according to the ratio (2). Plain weave, in this sense, represents a kind of standard in which the maximum potential of the mutual intertwining of the threads of the two systems is realized. And all other interlacing is a deviation to one degree or another from this maximum and the numerical values of their coefficients represent, in fact, the percentage of realization from the maximum. And indeed, twill 1/2 (or twill 2/1) with a coefficient of 0.67 has 67% of the maximum intertwining of threads in plain weave, twill 1/3 (or twill 3/1) is already 50% of plain, and loose weave – satin 12/5 is only 16%.

The nature of changes in the initial properties of yarns and yarns during weaving with the selection of various samples was also experimentally analyzed. The influence of the velocity factor on the mechanical behavior of threads and yarns has been studied. Due to the instability of the nature of fibrous textile composite materials, the paper notes the need to involve the theory of long-term strength and damage of viscoelastic bodies in the study of the problem of discontinuity.

It is known that the relationship between stress and deformation of warp and weft threads on a loom involves time. Therefore, when calculating the stress-strain state of threads and designing fabrics, it is advisable to take into account the viscoelastic properties of the threads. The mathematical record of the dependence of stresses on deformations, based on the Boltzmann-Volterra hypothesis, has the form [18]:

$$\varepsilon(t) = \frac{\sigma(t)}{E} + \frac{1}{E}\int_0^t K(t-\tau)\sigma(\tau)d\tau; \qquad (3)$$

or

$$\sigma(t) = E\varepsilon(t) - E\int_0^t \Gamma(t-\tau)\varepsilon(\tau)d\tau; \qquad (4)$$

where σ - stress; ε - strain; E - modulus of elasticity of filaments; K(t-τ) и Γ(t-τ) - influence functions; t - the duration of the load; τ - the time preceding the duration of the load. The most common influence functions are the Rzhanitsyn-Koltunov core:

$$\Gamma(t) = Ae^{-\beta t}t^{\alpha-1}(0<\alpha<1, \beta>0); \qquad (5)$$

$$K(t) = \frac{e^{-\beta t}}{t}\sum_1^n \frac{A\Gamma(\alpha)^n t^{n\alpha}}{\Gamma(n\alpha)}; \qquad (6)$$

In [7-11], the method of combinations by S. D. Nikolaev is used to determine the parameters of the singular nucleus and the resolvent.

According to the strength criterion [18], we take the following function as a characteristic of the degree of damage accumulation:

$$\eta(x_\alpha, t) = \frac{1+m}{B^{m+1}}\int_0^t (t-\tau)^m \sigma^{\alpha(1+m)}(\tau)d\tau \qquad (7)$$

In particular, when $\sigma = \sigma_0 = const$ from (7) we get the following expression for the damage function:

$$\eta = \frac{t^{m+1}\sigma_0^{(1+m)\alpha}}{B^{1+m}}, \qquad (8)$$

and at a constant loading rate $\sigma = \dot{\sigma} \cdot t$,

$$\eta = \frac{1+m}{B^{1+m}} t^{m+1} \dot{\sigma}^{\alpha(1+m)} \frac{\Gamma(1+m)\Gamma(1+\beta)}{\Gamma(2+m+\beta)} \tag{9}$$

where Γ – gamma function, α and B – durability parameters [18].

Using the criteria of damage from [5, 7], the theoretical foundations of the processing of threads and fabrics have been developed, taking into account the viscoelastic properties of materials. Extensive experimental material on the study of creep and relaxation properties for various textile materials is presented.

III. DETERMINATION OF PARAMETERS FROM THE EXPERIMENT AND ANALYSIS OF THE RESULTS

Based on the conducted experimental and theoretical studies, the main parameters of the deformation processes and the strength of threads and yarns are determined. Changes in the modulus of deformations with different linear densities are revealed.

In studies [8-11], viscoelastic parameters and core coefficients for natural and a number of chemical textile yarns were experimentally determined based on the criterion of long-term strength.

Table 1 shows the patterns of changes in the deformation parameters of cotton yarn depending on the values of linear density when stretching it to breakage.

The change in the value of deformation and modulus of elasticity depending on the linear density of the yarn

Table 1

№ groups	1	2	3	4	5	6
T_{cp} Tex	*17*	*28,95*	*49,32*	*71,42*	*99,17*	*162,13*
ε_k	*0,0635*	*0,0732*	*0,0836*	*0,0812*	*0,0953*	*0,1342*
E_k	*3513,71*	*2307,18*	*2285,46*	*2273,63*	*1674,13*	*1382,22*
E_{cp}	*3333,94*	*2525,89*	*2690,48*	*2551,81*	*1742,55*	*2690,49*

In [8], linear – viscoelastic ratios and the criterion of long–term strength were used to assess the stress-strain state of threads on a loom. The parameters α, β and m were calculated from experiments to determine the destruction of threads and damage coefficients at various loads and times (Table 2). The method of S.D. Nikolaev is used to determine the parameters of the singular core and the resolvent, as well as the modulus of elasticity [7].

Determination of durability parameters depending on load,stress and loading time

Table 2

Type of thread	Load, H			Stress, H/mm^2			Loading time, s			Durability Parameters		
	P_1	P_2	P_3	σ_1	σ_2	σ_3	t_1	t_2	t_3	*α*	*$B \cdot 10^4$*	*m*
Carbon, 410 тех	50	40	30	7,26	3,81	0,36	3,13	60,90	325,58	2,45	1	-0,095
Quartz 612 тех	50	40	30	17,97	14,38	10,78	200.68	324,34	64,86	2,15	1	-0,094

In [9], based on experimental data, the values of viscoelastic parameters of aramid yarn of various linear densities are given (Table 3).

Viscoelastic parameters of yarns of various linear densities

Table 3

Linear yarn density, tex	Viscoelastic parameters			Modulus of elasticity E, H/mm^2
	A	*β*	*α*	
30x2	*0,0227*	*0,601*	*0,294*	*1749*
60x2	*0,0207*	*0,493*	*0,261*	*1755*
83,3x2	*0,0223*	*0,586*	*0,289*	*1750*

Based on the above, we note:

1) All the considered types of intersections are analyzed in relation to the creation of alternating sections with neighboring intersections. The total alternability of a node consists of the contributions of intersections. The more alternating sections there are within a node, the more it is alternated as a whole. And in turn, the larger the alternated node, the more its lines are narrowed in it.

2) When determining the parameters of the influence function, the three–parametric Rzhanitsyn-Koltunov kernel is used. It is noted that the viscoelastic parameters and elastic modulus of the threads determine the behavior of the warp and weft threads in different areas of the loom. The change in the modulus of elasticity over time shows the presence of relaxation processes that positively affect the technological process of weaving.

3) The results of calculating the damage of the warp threads in the manufacture of fabrics of various weaves are presented. Based on the results of the study of technological processes, the following has been established: if the damage value is η <0.25- the process takes place in calm conditions; when η =0.25-0.5 - the process takes place under rather stressful conditions; when η =0.5-0.75 - the process is possible, but there is an increase in thread breakage (about 2 times); when η =0.75-1 - the process is possible, but the thread breakage increases sharply (5 times); when η >1 - the process is almost impossible.

As noted [2, 14, 19-22], in the process of processing yarns and fabrics on technological equipment, it is very important to understand the causes of damage to the material leading to their destruction, to create models and methods for solving problems of mechanics of composite textile materials-prepregs.

IV. CONCLUSION

The structural analysis of structural tissues and hereditary properties and damage of threads are given. The application of the theory of interlacing and knots to the analysis of woven structures is considered. Based on the phenomenological concept of mechanics, involving the theory of long-term strength and damage, the problems of discontinuity of textile threads and fabrics are studied, durability criteria are given taking into account viscoelastic properties, the influence of parameters on technological processes is shown.

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