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DETERMINING TENSION DISTRIBUTION AND DAMAGE EVOLUTION PATTERNS IN THREAD-STITCHED BOOK BLOCKS UNDER CYCLIC OPENING CONDITIONS

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This study investigates the process behind the stressed-strained state of the thread stitching of a spine part of book blocks at their multiple opening. Most attention is on the spatial work of the thread structure and patterns of load distribution in the spine zone of the block, predetermined by the lack of generalized models for the spatial organization of thread stitching; known approaches mainly consider adhesive or simplified connections. This study is carried out based on structural-mechanical and finite element modeling of the thread structure of spine binding.

The proposed model takes into account the spatial trajectory of the thread, the change in direction and tension of the thread in places of bending, as well as its contact interaction with paper. The geometric, force, and finite element models of thread stitching have been constructed. It was established that the tension distribution along the thread trajectory has an exponentially decreasing character. At the same time, the maximum values of the normalized contact pressure $p/p_0 = 1.0$ ***are observed in the surface stitches of the spine part.***

The calculations showed that the working interval of thread tension within the $T_{work} = 35–60$ ***conditional units limits ensures stable operation of the thread structure without noticeable evolution of degradation processes in the paper of the folds. At the same time, exceeding the limit tension level of*** $T_{paper} = 72$ ***conditional units is accompanied by the gradual development of local damage in the areas of fold openings. After 1000 load cycles, the damage parameter*** D_p ***for polyester threads reached 0.96, for cotton threads – 0.87, and for polyamide threads – 0.78.***

The results could be used to optimize the formation modes of the spatial structure of a thread-glue blinding of the spine part of book blocks

Keywords: thread, binding, book spine, tension, stress, deformation, contact, damage, durability, modeling

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1. Introduction

The mechanical reliability of thread stitching of the spine of book blocks largely determines the durability and serviceability of book products. This is especially important for publications of intensive use, such as textbooks, scientific and reference books, fine art books, pianos of musical works, etc. The operating conditions of such products are associated with repeated cyclic loads that arise when opening books and turning pages.

In modern binding technologies, the spine of a book block is formed as a multi-component system in which thread stitches interact with an adhesive layer and reinforcing elements in the form of paper tapes, gauze, or non-woven materials. The joint operation of these components ensures increased joint strength, stabilization of the spine geometry, as well as the redistribution of operational loads.

Despite the widespread use of thread-binding technology for binding the spine of book blocks, its mechanical behavior has not been studied in detail.

Most available research considers either adhesive joints or the mechanics of stitching on thread-binding equipment, or the operational characteristics of various types of binding threads. The patterns in the formation of the adhesive-thread structure, which make it possible to describe the mechanics of thread stitching taking into account its spatial organization and contact interaction with the paper material, remain to be investigated.

Of particular relevance is the construction of structural-mechanical models that take into account the interaction between the thread and anisotropic paper in the areas of its passage through the holes in the folds of notebooks.

The associated local mechanisms behind stress concentration in the areas of holes, their damage and penetration of the adhesive composition through the areas of paper degradation, allow for a more complete assessment of the operational characteristics of book blocks.

The spatial configuration of thread bond determines the features of the distribution of pre-tension and contact interaction between the thread and paper material, which directly affects the mechanical strength and durability of spine binding.

One of the factors reducing the durability of spine binding of book blocks is the uneven distribution of loads in the spatial thread structure. Its consequence is the local concentration of stresses in the areas of thread passage through the fold holes, which is accompanied by damage to the paper and a change in the conditions of contact interaction of the bonding elements.

The durability of book block spines is largely determined by the operational patterns of spatial thread structure under applied loads. Lack of clarity regarding the patterns of load distribution, contact interaction of the thread with paper, and the evolution of local damage necessitates structural and mechanical research into this area.

2. Literature review and problem statement

The reliability of a book block's spine largely determines the durability of the publication and its capability to maintain operational properties throughout its entire service life. To assess the current state of research, we have analyzed a body of research into the mechanics of spine joints of book blocks, their strength, durability, fracture processes, as well as the influence of design and technological factors, on the reliability of binding.

In work [1], the influence of various factors on adhesive joints, such as the direction of loading, joint geometry, type of glue, type of material being joined and the binding method, were investigated. However, the study did not determine how these factors can be applied to analyze the strength of binding a book block's spine. This is due to the fact that the study focused on a much simpler joint geometry than in the thread-glue binding of a book block.

In paper [2], a numerical analysis of the dynamic behavior of adhesive joints is described, which is divided into the areas of fatigue, deformation rate changes, and fracture. However, the behavior of the thread-glue joint during prolonged opening of book blocks remains uncertain. The main reason is that most studies are focused on the dynamic behavior of structural joints that are different from the loading regimes of the spine part of book blocks.

In [3], a method based on the finite element method (FEM) was devised for a comprehensive analysis of process zones inside the glue layer and for predicting the strength of glue structures. At the same time, damage arising in a complex system of simultaneous action of a spatial thread structure integrated into the paper and the glue layer remains unstudied. This can be explained by the fact that the model is built for the glue layer as the main element of failure and therefore requires significant adaptation to the multi-component structure of the spine part of the book block.

A new strategy for identifying the laws of cohesion under a mixed failure mode directly from experimental data is reported in [4]. In this case, further research is needed on mixed failure in thread stitching, where bending and friction of the thread against the paper leads to local damage to the holes in the folds. This is due to the lack of a homogeneous interface in the spine of the book and the physical behavior of the adhesives, which can be considered a drawback of the proposed method.

In [5], mechanical properties describing the onset and development of damage were investigated, depending on the type of adhesive and the current failure mode and the thickness of the adhesive layer over 0.2 mm. Despite this, no features were identified that affect the operation of thread stitches and the redistribution of the load between them with a change in the thickness of the adhesive layer on the surface of the folds. The main reason is the positioning of the adhesive layer as an independent structural element, in contrast to the block spine, on the surface of which the adhesive partially fixes the external areas of the thread stitches, changing their mobility.

The authors of work [6] highlighted the features of predicting the fatigue durability of adhesive compounds for various structural schemes. However, the mechanism of damage evolution of thread-adhesive compounds during long-term operational deployment of book blocks has not been determined. This is explained by the complex nature of the interaction between paper types, stitch formation schemes, thread tension, types, and thickness of glue.

In [7], the fatigue of composite adhesive compounds is considered; and an attempt is made to classify them based on the materials used and the thickness of the adhesive layer. Despite this, the mechanism of fatigue behavior of not the adhesive but the thread-adhesive layer remains insufficiently studied. This is due to the limited industry-specific research on local damage in places where the thread passes through the folds.

Within the study reported in [8], the importance of modeling the thickness of the adhesive layer for predicting fatigue delamination is shown, as changes in the thickness of the adhesive layer can significantly change the nature of crack growth. However, available studies do not provide an unambiguous answer regarding the thickness of the adhesive layer on the spine part of the book block and its influence on the development of damage in the stitches of the threads and the paper of the folds of the notebooks. The reason for the limited research is the focus only on delamination of adhesive joints and the lack of research on composite structures reinforced with threads.

The authors of [9] proposed an entropic approach for predicting the fatigue durability of adhesive joints and modeling the influence of different thicknesses of the adhesive layer. At the same time, there is no holistic idea of the application of such an approach to the spine part of the book block, where operational damage arises not only from energy factors, but also from the structural features of the thread-adhesive bond. This state of research is explained by the difficulty of maintaining stable loading conditions for paper, thread stitches, different thicknesses of the adhesive layer, and its capability to penetrate into the fold holes.

Study [10] describes basic methods for increasing the mechanical characteristics of adhesive compounds from composites reinforced with natural fibers. At the same time, no criteria have been defined for predicting the fatigue behavior of the fibrous structure of paper in the area of holes in the folds of notebooks of a book block where a spatial thread structure with pretension is formed. This is explained by the difficulty of identifying the composite structure of the folds of notebooks, in the holes of which local thread pressure is exerted, limited on the surface of the stitches by the adhesive layer and the continuous structure of fibrous composites.

Work [11] shows the prospects of detecting the influence of silicon dioxide and titanium dioxide nanoparticles on the elasticity and aging resistance of polyvinyl acetate adhesive used for edging the spine of a book. Despite this, there is no unified approach to determining the influence of the elasticity of the adhesive integrated on the surface of the thread stitches in the folds of notebooks on the operational behavior of the spatial thread structure with pretension. This is due to insufficient consideration of the properties of the adhesive itself in the interaction with the threads and paper of the spine part of book blocks.

In study [12], using the combined resistance model constructed for modeling the folding process by 180°, the behavior of the deflection of the folds of folded sheets of cardboard and coated paper was revealed. At the same time, the mechanism of similarity of these processes to the behavior of a multilayer system of notebooks in the spine part of a book block sewn with threads remains insufficiently studied. This is explained by the complexity of the experimental study on the bending of individual notebooks sewn with threads, the tension of which creates local pressure in the folds and the work of the glue on the surface of the stitches.

In a limited number of papers [13, 14], the influence of technological parameters on the strength of the spine connection of book blocks sewn with threads, which form the complex nature of the stressed-strained state of the spine, was analyzed. However, the studies did not take into account the spatial thread fastening with pre-tension and local mechanisms of paper damage in the areas of thread passage through the holes in the folds. This is explained by the fact that those studies were performed for simplified models of the influence of the adhesive layer on the surface of the folds on the destructive processes of the spine part of book blocks.

Our review of the literature [1–14] showed that, despite the significant amount of research on the mechanics of adhesive joints and spine joints of book blocks, the regularities of operation of the spine part as a spatial thread-glue system remain insufficiently studied. This is due to the complex interaction of paper, threads, and the adhesive layer, as well as the difficulties of experimental and mathematical description of the processes of their joint deformation and destruction. Therefore, mechanisms behind the formation of the stressed-strained state and the evolution of damage to such a system still require further investigation. This allows us to state that it is advisable to conduct a study on the multicomponent structure of a spine joint, the distribution of thread pretension, local contact stresses in the areas of fold openings, as well as the related mechanisms behind paper damage.

3. The aim and objectives of the study

The aim of our work is to build a structural and mechanical model of thread fastening of the spine part of book blocks to establish regularities in the formation of its stressed-deformed state and mechanisms behind damage evolution during operation. This will provide an opportunity to substantiate ways to increase the strength, durability, and operational reliability of book blocks sewn with threads.

To achieve the set goal, it is necessary to solve the following tasks:

– to construct a geometric and force model of the spatial thread structure of the spine part of a book block, taking into account the configuration of the thread trajectory and the features of the spatial distribution of tension along the thread trajectory;

– to define a mathematical and finite element statement of the problem for the analysis of spatial thread fastening, taking into account the mechanical properties of sewing threads, tension losses due to friction, contact interaction, and changes in the force state when opening the book block;

– to investigate the contact interaction of the thread with the paper in the area of fold holes, to establish regularities in the formation of local stresses and the development of paper damage under the conditions of cyclic opening of the book block;

– to determine conditions for the formation of the working pre-tension of sewing threads and to assess its influence on the durability of the thread stitching of book blocks.

4. The study materials and methods

The object of our study is the processes that form the stressed-strained state of the thread stitching of the spine part of book blocks during their reader's opening. The principal hypothesis of the study assumes that the durability of the thread stitching is determined not only by the mechanical properties of the sewing thread, but it is also determined by the spatial distribution of the pre-tension, contact interaction with the paper of the folds, and the evolution of local damage in the areas of thread passage through the holes of folds.

To verify the hypothesis put forward, methods of structural-mechanical, analytical, and finite element modeling of the spatial thread system of the spine part of a book block were used. The application of these methods is due to the need for a comprehensive description of the geometrically complex thread trajectory, uneven tension distribution, local contact interaction, and damage accumulation processes in the fibrous material of the paper.

The work adopts the necessary assumptions and simplifications. The process of opening a book block is considered as a slow process with kinematically specified movements of extreme notebooks. The paper in the contact zone is described as a non-uniform, in terms of properties, fibrous material with a local damage parameter in the area of holes for stitching threads in the folds of the notebooks. The influence of the adhesive layer on the stitches of the threads on the surface of folds is taken into account only due to the possibility of penetration of the adhesive composition into the areas of local damage to paper.

The thread bond is considered as a spatially organized mechanical system formed by the surface and internal sections of the thread. For a quantitative description of the force state of the system, a model of the distribution of thread pretension was built, taking into account the tension losses due to friction and a change in the direction of the thread trajectory.

To describe the change in tension along the thread trajectory, an approach similar to the classical model of sliding of a flexible element on a surface with friction according to the Euler-Eitelwein formula was used: $T_2 = T_1 e^{\mu\theta}$.

The mechanical properties of the thread were taken into account on the basis of a nonlinear deformation characteristic of the F-ΔL type. The distribution of stresses and strains in the thread structure was determined on the basis of relations from the mechanics of a deformable solid.

For a numerical analysis of the stressed-strained state of the thread bond, a finite element model was used, in which the thread is represented by a system of spatial rod elements. The model takes into account the initial pretension of the thread acquired during the stitching of the block, the contact interaction with the paper, local friction forces, and the change in the force state when the book block is opened.

To analyze contact interaction of the thread with the paper, the holes in the folds were considered as local stress concentrators, and the development of damage was described by the scalar parameter $D_p \in [0; 1]$. The evolution of damage was analyzed under conditions of periodic opening of the book block, taking into account the accumulation of local deformations in the area of fold holes.

The calculations used the characteristics of offset paper weighing 80 g/m^2 and sewing threads of three types: cotton, polyester, and polyamide. The characteristics of the materials were taken on the basis of modern reference and experimental data. A comparative analysis of the results allowed us to assess the influence of the mechanical properties of the threads on the tension distribution, contact pressure, the development of paper damage, and the durability of the thread stitching of book blocks.

The numerical experiment was carried out by parametric modeling of the spatial thread structure for different values of pretension and mechanical characteristics of cotton, polyester, and polyamide threads. The study analyzed 36 calculation scenarios formed for three types of sewing threads at four levels of pretension and different values of the friction coefficient within $\mu = 0.30$–0.45. For each option, the parameters of tension distribution, contact pressure, paper damage. and predicted durability of the thread stitching were estimated.

During numerical modeling, changes in the stressed-strained state, contact interaction, and damage accumulation were analyzed depending on the level of pretension and mechanical properties of sewing threads. The results were used to evaluate the influence of pretension and mechanical properties of threads on the durability of thread bonding.

The results from the numerical experiment were processed by determining the characteristic parameters of the stressed-strained state, contact pressure, and paper damage. The findings were normalized relative to the initial pretension and used to construct calculated relationships between the parameters of contact interaction, paper damage, and durability of thread bonding. The values of pretension in the work are given in conditional (normalized) units that correspond to the relative load levels used in constructing the calculated relationships and plots.

5. Results of investigating the structural and mechanical regularities of thread stitching of the spine part of book blocks

5. 1. Results of investigating the geometric and force structure of the thread stitching of a book block

The spine part of a book block, formed in the process of thread stitching with the subsequent application of an adhesive layer and reinforcing materials, constitutes a complex multi-component system. Its structure combines the folds of notebooks, thread elements, an adhesive layer, and contact interactions between them.

In order to provide a generalized representation of the structure of thread stitching, a diagram of the spine part of the book block is shown in Fig. 1. The diagram depicts the mutual arrangement of the folds of notebooks, thread stitches, an adhesive layer, and the directions of tension forces after stitching.

Our scheme allows us to qualitatively assess the general organization of spine binding and establish that the formation of its mechanical strength is determined primarily by the thread elements that provide connection between the notebooks and perceive the main loads. The adhesive layer performs an auxiliary function of stabilizing the structure and redistributing loads; its influence is manifested mainly at the stage of operation.

For further quantitative analysis, the thread fastening is considered as an independent spatial mechanical system that determines principal patterns in the formation of the stressed-strained state of the spine part of a book block.

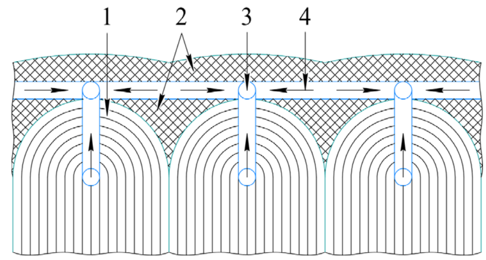

Fig. 1. The spine binding of a book block: 1 – folds of notebooks; 2 – adhesive layer; 3 – stitches of threads; 4 – thread tension force after stitching the notebooks

As a result of our analysis, it was found that the thread stitching of the spine part of a book block forms a three-dimensional organized force system. The distribution of pre-tension in this system is significantly uneven and depends on the spatial configuration of the thread and its interaction with the notebook material. To illustrate the revealed patterns, Fig. 2, 3 show a spatial model of thread stitching, which reflects the configuration of the thread trajectory and the nature of the distribution of tension forces in different parts of the structure.

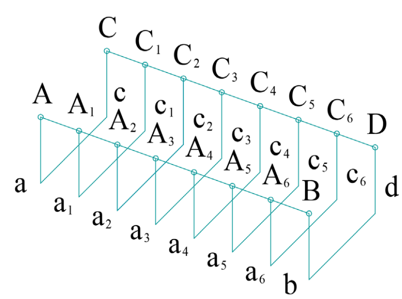

Fig. 2. Three-dimensional geometric model of the thread trajectory in one row of thread stitching: A-B and C-D are the edge surface stitches; a, a_1, ..., a_6 are the points of thread passage through notebooks; A_1–A_6, C_1–C_6 are the nodal points of stitch formation; the areas between the nodal points determine the spatial configuration of the thread trajectory

The spatial structure of a thread connection is formed by the sequential passage of the thread through a system of holes in the folds of individual notebooks. In general, the trajectory of the thread can be represented as a continuous spatial broken line

$$A \to a \to c \to C \to C_1 \to c_1 \to a_1 \to$$
$$\to A_1 \to A_2 \to a_2 \to c_2 \to C_2 \to \cdots \to D,$$

where the outer sections of the trajectory correspond to the inter-book transitions of the thread, and the inner sections correspond to its passage along the folds of the notebooks. The alternation of the inner and outer segments forms a continuous spatial thread system, which ensures the integration of individual notebooks into a single construction of a book block.

Based on the geometric model shown in Fig. 2, a force model of thread fastening was constructed, which reflects the distribution of tension in individual sections of the thread structure (Fig. 3).

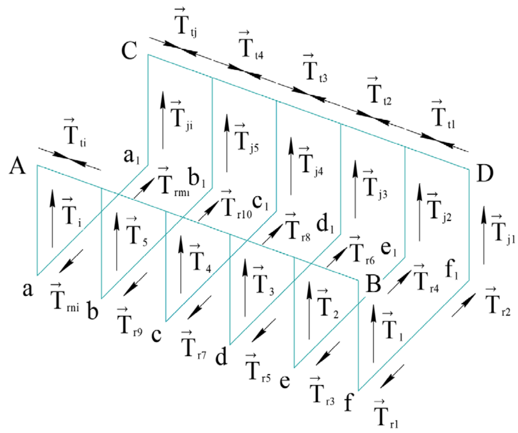

Fig. 3. Spatial force configuration of one row of thread stitching of the spine part of a book block taking into account the pre-tension: A-B and C-D — surface bearing stitches; $\vec{T_t}$, $\vec{T_r}$, $\vec{T_j}$ — tension forces in the surface, transitional, and internal sections of a thread structure

Since the diagram in Fig. 2, 3 shows one row of thread stitching stitches, it is advisable to consider it as an elementary spatial force cell of the spine binding. In a real book block, the number of such rows can be $n = 4$–6 depending on the format and volume of the publication. Therefore, the integral bearing capacity of the thread stitching can be given as the sum of the force contributions of individual rows

$$T_\Sigma = \sum_{k=1}^{n} T_k, \tag{1}$$

where T_Σ is the total force perceived by the thread system of the spine part of a book block; T_k is the force contribution of the k-th row of stitches; n is the number of parallel rows of thread fastening.

Given the same geometry of all rows, the level of pre-tension, and identical loading conditions, the total bearing capacity of the system can be approximately determined as

$$T_\Sigma = nT_0, \tag{2}$$

where T_0 is the force perceived by one row of stitches, modeled in Fig. 2, 3.

For systems with non-uniform tension distribution and different conditions of thread contact with the notebook material in individual rows, the generalized form is used

$$T_\Sigma = \sum_{k=1}^{n} \eta_k T_k, \tag{3}$$

where η_k is the efficiency coefficient of the k-th row, which takes into account the unevenness of tension, friction, local losses of effort, deviations in the geometry of the thread trajectory, and the patterns of interaction with the notebook material.

The model of one row of stitches is considered as the basic calculation unit. The entire thread fastening system of a book block is represented as a set of parallel spatial thread structures, the total work of which determines the mechanical strength and durability of the spine binding. Further analysis is focused on the geometric features of the elementary model of one row of stitches, shown in Fig. 2.

The geometry of the thread trajectory is determined by the set of characteristic nodal points A, B, C, D, which form the edge rows of surface stitches. In particular, the segment A-B corresponds to the front (from the observer's side) row of surface stitches, while the segment C-D is the second row; together, these elements form a closed three-dimensional system of thread stitching. The three-dimensional trajectory of the thread is represented by a broken spatial line that runs both along the surface of the notebook folds and through their internal volume, ensuring the integration of individual notebooks into a single structure.

In the structure of thread fastening, three main functional zones are distinguished. The first zone is the surface stitches (sections A-B and C-D), located on the outer surface of the folds and not covered with glue. It is these sections that perceive the main tensile loads and act as the basic load-bearing elements of the system. The second zone is the internal sections of the thread (segments of the a-c, a_1-c_1, a_2-c_2, a_3-c_3 type, etc.), which pass through the notebooks and form vertical and oriented along the plane of fold jumpers. They provide inter-booklet connection and perform the function of redistributing loads in the thickness of the block. The third zone is the straight sections (the A-A_1, A_1-A_2, C-C_1, C_1-C_2 type, etc.), which provide thread transitions between adjacent folds and are zones of deformation concentration and change in the direction of force flows.

The force state of the thread structure in the figure is represented as a system of tension vectors oriented according to the local geometry of the thread. The main ones are the tension forces $\vec{T_t}$, acting in the surface stitches and characterized by maximum values, determining the strength of the entire system. In the areas oriented mainly along the plane of the folds, forces $\vec{T_r}$, arise whose magnitude is smaller due to the influence of friction and a change in the direction of the thread, which is accompanied by partial tension losses. In the internal vertical segments, forces $\vec{T_j}$, act that ensure the retention of notebooks and the transfer of load between the layers, forming a damping component of the system. Additionally, local forces $\vec{T_i}$, are taken into account that characterize the stress state of individual internal sections of the thread. The model also takes into account reaction components $\vec{T_{rni}}$ and $\vec{T_{rmi}}$, which arise in the zones of contact of the thread with the material of folds. These components reflect the influence of contact interaction and local tension losses during bends and passage of the thread through the paper structure.

The directions of all force vectors are consistent with the local orientation of the thread. In the longitudinal sections, they coincide with the direction of tension, while in the internal segments they have components oriented perpendicular to the plane of the notebooks, which reflects the interlayer interaction.

Our results indicate that the thread structure functions as a spatially non-uniform force system with the localization of maximum stresses in the surface stitches and their gradual decrease in the internal sections. The established regularities are the basis of the constructed mathematical model and are used to analyze the force state of the thread bond. However, the findings require clarification taking into account the limitations associated with the interaction of the thread with the paper material.

5. 2. Results of mathematical modeling of tension distribution in a spatial thread system

For a correct description of the stressed-strained state of a spatial thread structure, it is necessary to take into account the mechanical properties of the thread, which are determined by its deformation characteristic of the *F-ΔL* type (Fig. 4).

To summarize the results of analyzing the estimation deformation diagrams of sewing threads, their basic mechanical characteristics are given in Table 1.

Typical tension diagrams of sewing threads are nonlinear and reflect the dependence of the load on elongation, which determines the value of the permissible pre-tension and the behavior of a thread under operational loads.

In the process of forming stitches, the thread interacts with the material of the notebooks and changes the direction of its trajectory, as a result of which the distribution of tension along its length becomes uneven (Fig. 5). The loss of tension occurs due to friction in the contact areas and the bending of the thread in folds.

The basic parameters of the tension relaxation process in the thread stitching of book blocks, as well as the generalized results of modeling the thread tension distribution, are given in Table 2.

To describe the change in tension along the thread, an approach similar to the equation of sliding of a flexible element on a surface with friction according to the classical Euler-Eitelwein formula [15] was used. In differential form, the change in tension can be written as

$$\frac{dP(s)}{d(s)}=-\mu(s)N(s), \quad (4)$$

where $P(s)$ is the tension of a thread at a point with coordinate s along its trajectory; $\mu(s)$ is the local coefficient of friction between the thread and the notebook material; $N(s)$ is the normal reaction occurring at the contact points; s is the curvilinear coordinate along the thread.

In the case of localized zones of thread bending with a wrap angle θ, the ratio of the tension at the entrance and exit from the contact area can be given as

$$P_{out}=P_{in}e^{-\mu\theta}, \quad (5)$$

where P_{in}, P_{out} – thread tension before and after the contact zone; θ – thread direction change angle (radians); μ – effective friction coefficient.

An exponential decrease in tension is formed along the thread trajectory, which explains the decrease in forces in the internal areas compared to the surface stitches.

Taking the above into account, the force contribution of one row of stitches (equation (5) can be specified as an integral characteristic

$$P_0=\frac{1}{L}\int_0^L P(s)\mathrm{d}s, \quad (6)$$

where L is the total length of the thread within one row of stitches.

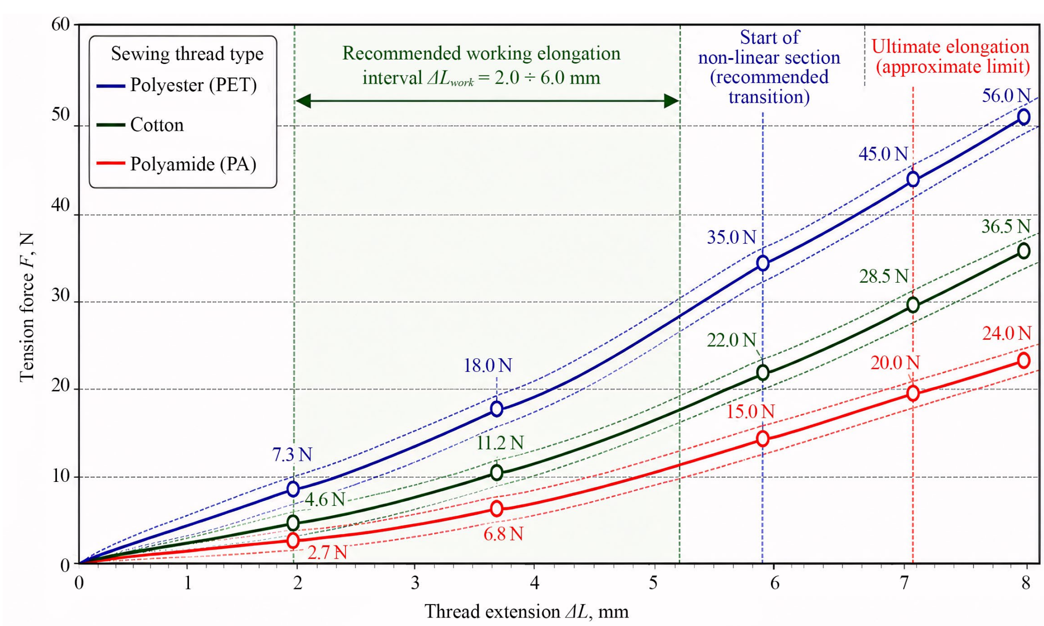

Fig. 4. Estimation deformation diagrams of sewing threads in *F-ΔL* coordinates

Table 1

Basic mechanical characteristics of threads

Sewing thread type	Working elongation interval ΔL_{work}, mm	Ultimate elongation ΔL_{gr}, mm	Force at ΔL = 6 mm, N
Polyester (PET)	2.0–6.0	7.2	35.0
Cotton (Cotton)	2.0–6.0	7.4	22.0
Polyamide (PA)	2.0–6.0	7.8	15.0

Fig. 5. Estimation tension distribution of sewing threads of different types along a fragment of the spatial trajectory taking into account friction, change of direction, and contact with the fold paper

Table 2

Basic parameters and results of modeling the distribution of thread tension in the spine part of a book block

Thread type	T_0, N	ΔT_{bend}, %	ΔT_f, %	T_k, N	T_k/T_0, %	Characteristics
Polyester (PET)	100	−12	−9	30	70	Highest tension stability
Cotton (Cotton)	100	−15	−13	25	75	Average tension stability
Polyamide (PA)	100	−16	−14	21	79	Highest elasticity

Note: ΔT_{bend} – average tension decrease at the bends; ΔT_f – average tension decrease at the folds; T_0 – initial thread tension; T_k – tension at the final section of the thread trajectory.

The total load-bearing capacity of a multi-row system (equation (6) is determined taking into account the uneven distribution of tension

$$P_\Sigma = \sum_{k=1}^{n} \eta_k \left(\frac{1}{L_k} \int_0^{L_k} P_k(s)\,ds \right). \quad (7)$$

For a quantitative description of the stressed-strained state of the spatial thread structure of the spine part of a book block, a finite element model is proposed, in which the thread is represented by a system of spatial elements that work mainly in tension.

The calculation scheme is formed according to the spatial trajectory of the thread passing through the notebooks

$$A \to a \to c \to C \to A_1 \to a_1 \to c_1 \to C_1 \to \cdots \to D, \quad (8)$$

where sections A-B and C-D correspond to surface stitches, and segments of the (ac), (a_1c_1), (a_2c_2) type correspond to internal sections of the thread passing through the notebooks.

The thread is modeled by rod elements with axial stiffness

$$k_e = \frac{E_t A_t}{L_e}, \quad (9)$$

where E_t is the elastic modulus of the thread, A_t is its cross-sectional area, L_e is the length of the element.

The axial force in the element is defined as

$$N_e = E_t A_t \varepsilon_e + N_{0e}, \quad (10)$$

where ε_e is the relative strain and N_{0e} is the initial force corresponding to the pretension of the thread.

The pretension is introduced into the model in the form of initial axial forces

$$N_{0e} = T_{0e}. \quad (11)$$

In this case, the maximum tension value is assumed for surface stitches

$$T_{0,AB} = T_{0,CD} = T_{\max}, \quad (12)$$

while for internal areas

$$T_{0,aa_1}, T_{0,bb_1}, T_{0,cc_1} < T_{\max}, \quad (13)$$

which reflects the loss of tension due to friction and changes in the direction of the thread.

The decrease in tension along the thread trajectory is described by an exponential relationship

$$T_{i+1} = T_i e^{-\mu\theta_i}, \quad (14)$$

where μ is the coefficient of friction between the thread and the notebook material, θ_i is the angle of bending of the thread in the corresponding contact area. This causes an uneven distribution of tension along the thread structure.

The deformation of the element is determined by the change in its length

$$\varepsilon_e = \frac{L_{e'} - L_e}{L_e}, \quad (15)$$

where L_e and $L_{e'}$ are the initial and deformed lengths of the element, respectively.

The global system of equilibrium equations takes the following form

$$\left[K\right]\left\{u\right\} = \left\{F\right\} + \left\{F_0\right\}, \quad (16)$$

where $[K]$ is the stiffness matrix, $\{u\}$ is the displacement vector, $\{F\}$ is the external loads corresponding to the process of opening a book block, $\{F_0\}$ is the equivalent forces from the pre-tension.

In the places of contact of the thread with the paper, the condition of one-sided contact and friction is taken into account

$$p_n \ge 0,\ \ g_n \ge 0,\ \ p_n g_n = 0,\ \left|\tau\right| \le \mu p_n, \quad (17)$$

where p_n is the normal contact pressure, g_n is the gap, τ is the tangential friction force.

The proposed finite element statement allows us to take into account the spatial geometry of the thread trajectory, the uneven distribution of the pre-tension, and the contact interaction of the thread with the material of the notebooks. This provides a description of the stressed-strained state of the spine part of a book block.

The opening of a book block is considered as a slow process, accompanied by the rotation of the notebooks relative to the spine line and the occurrence of relative displacements between their folds.

Within the framework of the finite element model, the opening process is given by kinematic boundary conditions in the form of displacements of the extreme notebooks

$$u_y = \pm\Delta, \quad (18)$$

which corresponds to the symmetrical opening of the block. The equivalent opening angle is defined as

$$\varphi \approx \frac{2\Delta}{h}, \quad (19)$$

where h is the thickness of a book block.

To eliminate the rigid motion of the system, minimal conditions for fixing the nodes on the spine line are introduced, which do not affect the stressed-strained state but ensure the correctness of the solution.

The preliminary tension of the thread is taken into account as the initial state of the system

$$N_{0e} = T_{0e}, \quad (20)$$

after which the opening load is applied. Thus, the solution to the problem is implemented in two stages: the formation of a preliminary stressed state and the modeling of the opening of a book block.

The system of equilibrium equations takes the following form

$$\left[K\right]u = F_{open} + F_0. \quad (21)$$

The proposed boundary conditions make it possible to reproduce the real unfolding process, in which the extreme notebooks undergo the largest displacements, the surface stitches perceive the main tensile forces, and the internal sections of the thread perform the function of spatial redistribution of loads.

The results of numerical modeling show that the thread tension along its spatial trajectory has a monotonically decreasing character. The maximum values of the tension are localized in the surface stitches (sections A-B and C-D), while when passing through the folds of the notebooks, its exponential decrease is observed.

The results are consistent with the adopted theoretical model

$$T_{i+1} = T_i e^{-\mu\theta_i}, \quad (22)$$

which confirms the decisive influence of friction and geometry of the thread trajectory on the tension distribution.

A tension gradient is formed along the spine part of a book block, in which the extreme sections of the thread work in the most stressed state, while the internal segments function under conditions of reduced tension.

The influence of the mechanical characteristics of sewing threads on the formation of the stressed-deformed state and the parameters of the contact interaction of the thread fastening was estimated by comparing the estimation dependences, the generalized values of which are given in Table 3.

Table 3

Influence of mechanical properties of sewing threads on thread bonding parameters

Sewing thread type	Modulus of elasticity E_t, GPa	Maximum rated contact pressure p_{max}/p_0	Maximum damage parameter D_p	Relative durability L_r, %
Polyester (PET)	4.8	1.00	0.96	100
Cotton (Cotton)	2.4	0.84	0.87	118
Polyamide (PA)	1.8	0.72	0.78	136

The study of contact interaction showed that an increase in the stiffness of the thread is accompanied by an increase in the local contact pressure and the paper damage parameter. The most uniform load distribution and the highest predicted durability are observed for polyamide threads, which are characterized by increased deformability and a lower level of stress concentration in the contact interaction zone.

Taking into account the constant cross-sectional area of the thread, the stress distribution is determined by the ratio

$$\sigma\left(x\right) = \frac{T\left(x\right)}{A_t}. \quad (23)$$

The maximum stresses occur in the surface stitches, as well as in the areas of thread entry and exit from the folds of the notebooks. These areas are potential areas of local wear, thread damage, and loss of binding integrity.

The analysis of displacements reveals that the largest deformations are observed in the outer notebooks, while the inner notebooks are characterized by limited displacements. This indicates that the thread system performs the function of a spatial limiter of deformations, providing control over the opening of a book block.

The modeling showed that stress concentrations are localized in the surface stitches, thread bending zones, and places of its entry into the fold. This is due to a sharp change in thread direction, local contact with the notebook material, and uneven tension distribution. Generalization of the modeling results made it possible to determine that the thread stitching of a book block functions as a spatially anisotropic mechanical system. The surface stitches (A-B and C-D) act as the main supporting elements, while the internal sections of the thread provide load redistribution and deformation damping.

The localization of stresses in the areas of bending and contact of the thread with the paper determines potential areas of damage initiation, which is of fundamental importance for assessing the durability of the spine part of a book block.

5. 3. Results of modeling the contact interaction between thread and paper and evolution of local damage

Analysis of modeling results and thread tension diagrams reveals that the maximum value of pretension T_0 can be realized in the thread structure without destruction. It is limited not only by the thread breaking load F_{max}, but also by the strength of the paper material in the areas of contact of the thread with the folds of the notebooks.

In the process of stitching a book block, the thread passes through holes formed in the folds of the notebooks during the preliminary, before stitching, needle puncture. These holes are local stress concentrators that significantly reduce the effective strength of the paper in the contact zone.

When the thread pretension increases to levels close to its ultimate strength, contact stresses arise in the paper around the holes, which may exceed the local strength of the material.

The regularities of change in the contact state in the zone of interaction of the thread with the paper depending on the magnitude of the pretension were established on the basis of parametric numerical modeling of the spatial thread structure. The generalized calculation characteristics are given in Table 4.

The results show that with the same initial tension, different types of sewing threads form different levels of normalized contact pressure in the fold zone. The highest values are characteristic of polyester thread, which is explained by its greater rigidity and lower ability to deformatively redistribute the load. Polyamide thread, on the contrary, provides lower contact pressure due to its greater elasticity, which reduces the local concentration of stresses in the area of interaction of the thread with paper.

Exceeding local contact stresses above the structural strength limit of the paper is accompanied by the development of irreversible deformations in the area of fold openings, local disruption of the fibrous structure of the material, and a gradual increase in the geometric dimensions of the contact area (Fig. 6).

Fig. 6 shows a diagram of local damage to the folds in the spine part of a book block. The formation of stress concentration zones D_p in the places where the thread passes through the paper, local angles of deviation of the thread trajectory α_1, α_2 and penetration of adhesive composition G into the degradation zones of the paper structure are shown.

The evolution of damage causes the formation of microchannels in the area of contact of the thread with the paper, which ensure capillary penetration of the adhesive composition into the internal areas of the notebooks, their fragmentary gluing and destruction of the pages when the block is opened. The obtained patterns of local damage to the paper are consistent with the nature of the destruction of the folds, which is observed in real book blocks after prolonged use (Fig. 7).

Table 4

Effect of sewing thread pretension on the normalized contact pressure in the fold area

Sewing thread type	Initial tension T_0, N	p/p_0 at $T/T_0=0$	p/p_0 at $T/T_0=0.5$	p/p_0 at $T/T_0=0.78$	p/p_0 at $T/T_0=1.0$
Polyester	100	0.14	0.46	0.75	1.0
Cotton	100	0.11	0.36	0.64	1.0
Polyamide	100	0.08	0.28	0.54	1.0

Note: p/p_0 – normalized contact pressure; p_0 – contact pressure at T/T_0 = 1.0

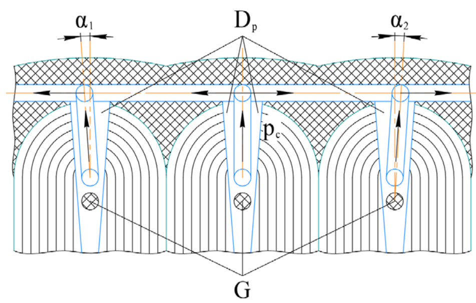

Fig. 6. Scheme of local damage to the folds in the spine part of a book block at thread stitching: α_1, α_2 – angles of local deviation of the thread trajectory; D_p – zones of local damage to the paper in the fold holes; G – penetration of the adhesive composition through locally damaged holes in the folds of the notebooks

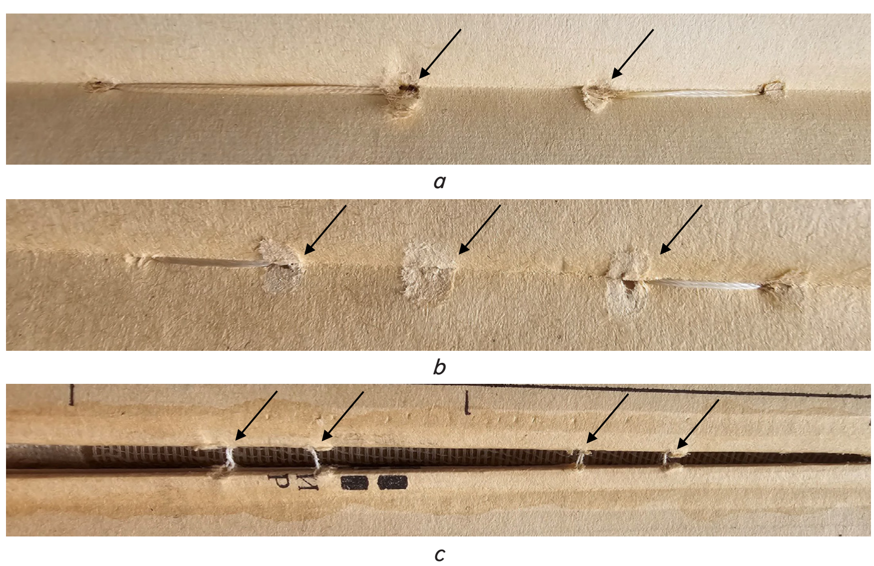

Fig. 7. Characteristic stages in the degradation of thread stitching of the spine part of a book block: *a* – local destruction of holes in the folds; *b* – penetration of the adhesive composition through damaged holes and destruction of pages when opening the block; *c* – weakening of the inter-book thread connection

As a result, local gluing of pages occurs, which reduces the flexibility of a book block and impairs its ability to fully open.

Parametric modeling of the spatial thread structure allowed us to determine the features of the development of local paper damage and changes in the durability of thread stitching. The corresponding results, depending on the type of sewing thread and the level of pre-tension, are given in Table 5.

Table 5

Effect of pretension on damage parameters and durability of thread fastening

Sewing thread type	Damage parameter D_p after 1000 cycles	Working tension interval T_{work}, conditional units	Ultimate paper breaking tension T_{paper}, conditional units
Polyester	0.96	30–52	68
Cotton	0.87	34–58	72
Polyamide	0.78	38–64	77

More elastic polyamide threads provide a decrease in the local concentration of contact stresses and allow for higher values of working tension without intensive development of paper damage. Stiff polyester threads are characterized by increased localization of loads and a lower limit level of tension.

Our parametric analysis made it possible to establish that exceeding the recommended pre-tension interval is accompanied by an intensive increase in the parameter of local paper damage and a decrease in the durability of the thread bond. An insufficient level of tension leads to a loss of stability of the spatial thread structure and a deterioration in the mechanical integrity of the spine binding.

The permissible level of thread pre-tension is determined by the following condition

$$T_0 \le \min\left(F_{\max}, T_{paper}\right), \tag{24}$$

where T_{paper} is the limit value of tension corresponding to the beginning of paper destruction in the area of the fold holes.

The holes formed in the folds of notebooks during stitching are considered as local stress concentrators in the paper layer. The thread passing through the hole transfers to its edge the contact force caused by the pre-tension T_0 (Fig. 8).

Table 6 gives generalized characteristics and basic parameters for the normalized contact pressure modeling, which reflect the evolution of local paper damage in places of contact of sewing threads with the folds of notebooks.

Table 6

Basic parameters and results of modeling the normalized contact pressure in the spine part of a book block

Thread type	T_0, N	p/p_0 at $T/T_0=0$	p/p_0 at $T/T_0=0.4$	p/p_0 at $T/T_0=0.75$	p/p_0 at $T/T_0=1.0$
Polyester (PET)	100	0.14	0.46	0.75	1.00
Cotton (Cotton)	100	0.11	0.36	0.64	1.00
Polyamide (PA)	100	0.08	0.29	0.54	1.00

Note: T_0 – initial thread tension; T/T_0 – normalized pre-tension of the thread; p/p_0 – normalized contact pressure in the contact zone of the thread with the fold paper.

In the first approximation, the contact pressure in the zone of interaction of the thread with the edge of the hole is defined as

$$p_c = \frac{T_0}{d_t h_p}, \tag{25}$$

where d_t is the effective diameter of the thread, h_p is the thickness of paper in the fold zone.

With increasing thread pretension, the contact pressure in the hole zone increases nonlinearly, which leads to local stress concentration in the paper.

Taking into account the geometric stress concentration, the maximum local stress in the paper is determined by the ratio

$$\sigma_{\max} = K_t \sigma_{nom}, \tag{26}$$

where K_t is the stress concentration coefficient.

The onset of paper damage in the hole area is described by the condition

$$p_c K_t \ge \sigma_{p,crit}, \tag{27}$$

where $\Sigma_{p,crit}$ is the limiting level of local stresses in the paper.

Hence, the permissible level of thread pretension is defined as

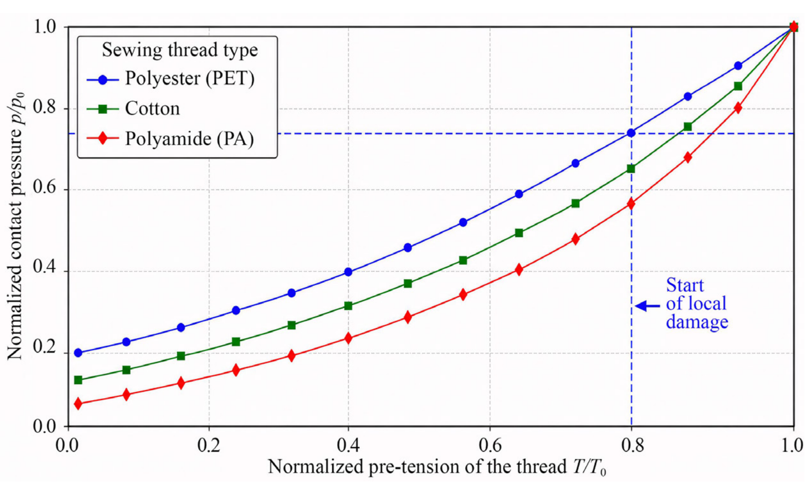

Fig. 8. Estimation dependences of contact pressure in the fold opening area on the pretension of sewing threads of different types

$$T_{paper} = \frac{\sigma_{p,crit} d_t h_p}{K_t}, \tag{28}$$

and the general criterion takes the form

$$T_0 \le \min\left(F_{\max}, T_{paper}\right). \tag{29}$$

To describe the evolution of damage, a variable $D_p \in [0, 1]$ is introduced, which characterizes the degree of paper destruction. The effective strength of the material, taking into account the damage, is defined as

$$\sigma_{p,eff} = \left(1 - D_p\right)\sigma_{p,crit}. \tag{30}$$

The increase in D_p is accompanied by the expansion of holes and the formation of microchannels in the paper structure, which promotes the penetration of the adhesive composition into the inner areas of the notebooks. This can be described by a change in permeability

$$k_p^* = k_{p0}\left(1+\beta D_p\right). \quad (31)$$

The destruction of paper in the area of the holes not only limits the permissible level of pre-tension but also determines further degradation processes in the thread system of a book block.

To describe the accumulation of paper damage in the area of the fold holes (Fig. 9), a scalar damage variable $D_p \in [0, 1]$ is introduced, where $D_p = 0$ corresponds to the undamaged state, and $D_p = 1$ – local material destruction.

The evolution of damage during cyclic opening of a book block can be described by the generalized law

$$\frac{dD_p}{dN} = A\left\langle \frac{p_c - p_{cr}}{p_{cr}} \right\rangle^m \left(\frac{\Delta u}{\Delta u_{cr}}\right)^n \left(1-D_p\right)^q, \quad (32)$$

where N is the number of opening cycles, p_c is the contact pressure of the thread on the edge of the opening, p_{cr} is the pressure at the beginning of damage, Δu is the amplitude of notebook movements.

The results of calculating the normalized damage parameter for sewing threads of different types, as well as the main characteristics of the process of accumulation of local paper damage, are given in Table 7.

The dependences shown in Fig. 9 reflect the accumulation of local damage to the paper due to repeated cyclic loading of the spine part of a book block.

Physically, this means that when $p_c \le p_{cr}$ the damage does not accumulate, while when the limit level is exceeded, its progressive growth occurs.

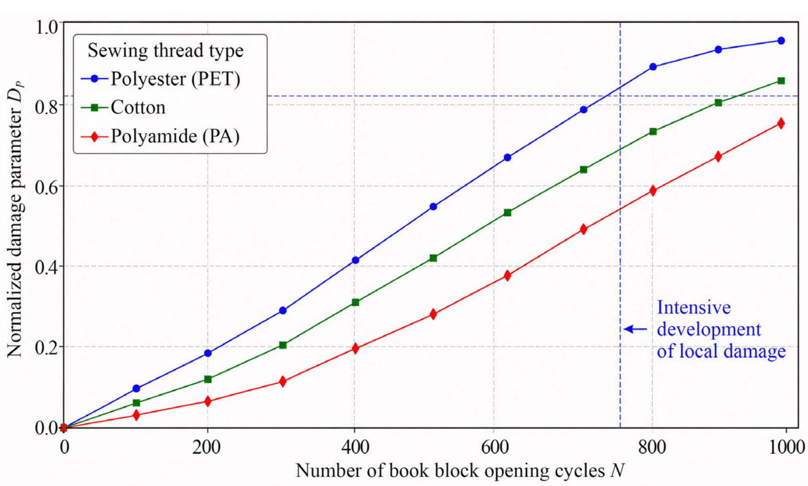

Fig. 9. Estimation dependences of the evolution of paper damage in the fold hole area on the number of book block opening cycles for sewing threads of different types

Table 7

Basic parameters and results of modeling the accumulation of local paper damage

Thread type	T_0, N	D_p at $N = 200$	D_p at $N = 400$	D_p at $N = 600$	D_p at $N = 800$	D_p at $N = 1000$
Polyester (PET)	100	0.16	0.42	0.69	0.88	0.96
Cotton (Cotton)	100	0.12	0.32	0.56	0.74	0.87
Polyamide (PA)	100	0.07	0.21	0.38	0.60	0.78

The increase in damage is accompanied by relaxation of the pre-tension of the thread and a decrease in the effective stiffness of the thread connection, which leads to an increase in the amplitude of movements of the notebooks when opening.

A positive feedback loop is formed in the system

$$D_p \uparrow \Rightarrow T \downarrow,\ k_{eff} \downarrow \Rightarrow \Delta u \uparrow \Rightarrow D_p \uparrow, \quad (33)$$

which causes the self-accelerating nature of the degradation of the spine part of a book block upon repeated opening.

5. 4. Results of determining the working tension and assessing the durability of thread bonding

The pre-tension of the thread cannot be determined only by the condition of thread strength but must take into account the local strength of the paper in the area of holes and the evolution of damage under cyclic loading. The working tension of the thread T_{work} is introduced, which ensures sufficient rigidity of the thread bonding and the absence of progressive destruction of the paper.

The working tension is determined by the condition

$$T_{work} \le \min\left(F_{\max}, T_{paper}, T_{fatigue}\right), \quad (34)$$

where $F_{\max}$ is the thread breaking force, T_{paper} is the ultimate tension under the condition of local paper destruction, $T_{fatigue}$ is the ultimate tension taking into account cyclic degradation.

To ensure the durability of the system, it is necessary to fulfill the condition

$$\frac{dD_p}{dN} \approx 0, \quad (35)$$

which is equivalent to limiting the contact pressure

$$p_c \le p_{cr}. \quad (36)$$

Taking into account the relationship between tension and contact pressure, a practical condition was obtained

$$T_{work} \le p_{cr} d_t h_p. \quad (37)$$

The optimal operating mode of thread fastening is determined by the interval

$$T_{\min} < T_{work} < T_{paper}, \quad (38)$$

where $T_{\min}$ is the minimum tension required to form a stable structure.

Based on the obtained relationships, estimation dependences of the durability of thread fastening on the value of pre-tension of sewing threads of different types were constructed (Fig. 10). Our dependences reflect the change in the operational stability of a book block under conditions of cyclic opening. They make it possible to determine the optimal working tension zone, within which the stability of the spatial thread structure is ensured without the intensive development of local paper damage in the folds of notebooks.

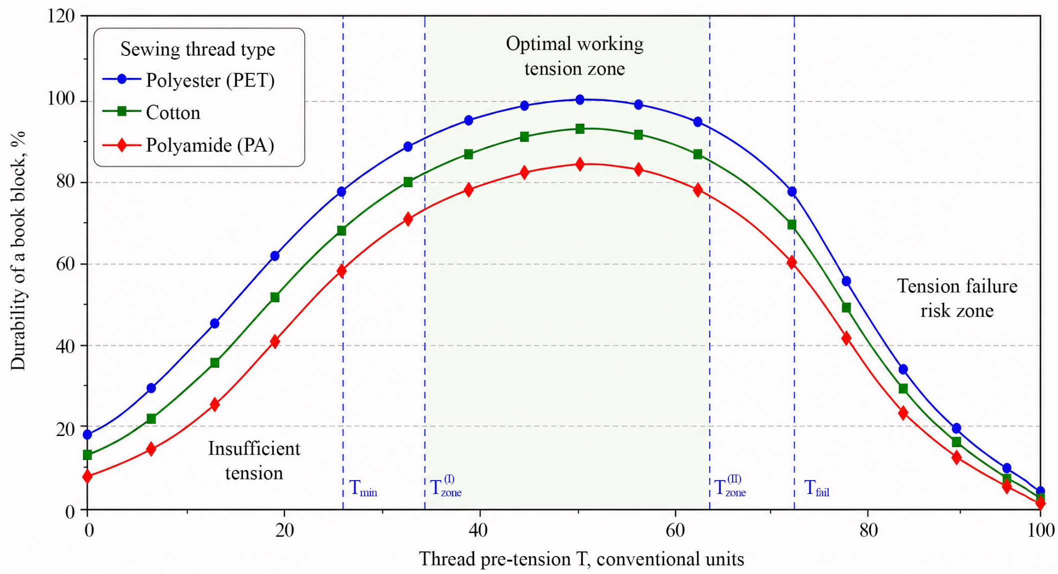

Fig. 10. Estimation dependences of the durability of a book block on the pretension of sewing threads of different types with the identification of the optimal working zone

Table 8 gives the results of calculating the optimal range of pretension of sewing threads and the basic parameters for modeling the durability of thread fastening.

The working tension of the thread is an important controllable parameter that determines the balance between the strength of the connection and the durability of a book block. Exceeding this level leads to progressive damage to the paper, relaxation of tension, and an increase in deformations, which together form the mechanism of accelerated destruction of the spine part.

It has been established that the durability of a book block has a nonlinear dependence on the value of the preliminary tension of the threads. At low tension values, the thread structure does not provide sufficient rigidity of the spine binding, which leads to an increase in the movements of the notebooks when opening and an accelerated accumulation of damage. With increasing tension, a working interval is formed, within which the stabilization of the spatial thread structure is ensured without initiating the destruction of the paper in the area of the holes. It is this interval that corresponds to the maximum durability of a book block.

Further increase in tension is undesirable, as it leads to an excess of the local strength of the paper, the expansion of the holes in the folds, relaxation of tension and the launch of the degradation mechanism.

Table 8

Basic parameters and results of thread stitching durability modeling

Thread type	T_0, N	T_{min}, N	T_{opt}, N	T_{max}, N	T_{max}/T_0, %	D_{max}, %
Polyester (PET)	100	15	35	60	72	100
Cotton (Cotton)	100	12	30	55	72	100
Polyamide (PA)	100	10	25	50	72	100

The resul ts could be used to substantiate rational technological modes of thread stitching of book blocks, in particular the choice of permissible thread pretension, which significantly affects the stability of the spatial structure of the spine binding and increases the durability of book products.

The constructed structural-mechanical model has made it possible to establish regularities in the spatial distribution of thread tension, the features of its contact interaction with the paper of the folds, as well as the mechanisms of local damage development in the spine part of a book block. The proposed approach lays a theoretical basis for predicting the stressed-strained state and durability of thread fastening under operational loads.

6. Discussion of results based on investigating the structural and mechanical regularities in the thread fastening of the spine part of book blocks

Our results indicate that the thread fastening of the spine part of a book block forms a spatially organized mechanical system. The stressed-strained state of such a system is determined by the interaction of threads, paper of the folds, and contact connections between them. Geometric and force modeling (Fig. 1–3, relations (1)–(3)) made it possible to establish that individual sections of the thread trajectory form a single spatial system. Its functioning is accompanied by the redistribution of loads between the surface, internal, and transitional segments of the thread. Analysis of the geometric structure of the thread fastening made it possible to distinguish three functionally differ ent zones. Surface stitches perform the role of the main load-bearing elements and perceive maximum loads. The internal sections provide inter-book connection and spatial redistribution of forces, and in the transitional segments there is a local concentration of stresses and tension losses. Such a spatial organization explains the non-uniform nature of the stressed-strained state of the spine part of a book block.

The results of mathematical modeling showed that the mechanical behavior of the thread fastening significantly depends on the elastic-deformation properties of the sewing threads. Analysis of the deformation diagrams (Fig. 4) and data in Table 1 reveals that polyester threads can perceive loads up to 35 N at an elongation of 6 mm, cotton threads – up to 22 N, and polyamide threads – up to 15 N. At the same time, polyamide threads are characterized by the greatest ultimate elongation (7.8 mm), which ensures their higher ability to adapt to conditions of variable load.

It was found that the tension distribution along the spatial trajectory of the thread has an exponentially decreasing character (Fig. 5, Table 2, relations (4)–(22)). Due to friction and repeated changes in the direction of the thread in places of passage through folds, a gradual decrease in its tension along the trajectory is observed. For the studied types of threads, the final tension values are 30 conditional units for polyester threads, 25 conditional units for cotton threads, and 21 conditional units for polyamide threads at the initial value $T_0 = 100$ conditional units. In this case, the average tension decrease at the bends is 12–16%, and in the zones of contact with the folds – 9–14%. The results explain the localization of maximum stresses in surface stitches and indicate a significant influence of the geometry of the trajectory and friction on the tension distribution in the thread system.

The results of finite element modeling of the contact interaction of the thread with paper allowed us to quantitatively assess the influence of the mechanical properties of the threads on the contact state of a spine joint. It was found that an increase in the thread stiffness is accompanied by an increase in the contact pressure and the intensity of local damage to the paper. Thus, for polyester threads, the maximum normalized contact pressure is $p_{\max}/p_0 = 1.00$, the damage parameter $D_p = 0.96$, while for polyamide threads these indicators decrease to 0.72 and 0.78, respectively. At the same time, the predicted relative durability of the thread bond increases from 100% for polyester threads to 136% for polyamide ones. This indicates that the durability of the spine joint is determined not only by the strength of the thread but also by its ability to reduce the concentration of contact stresses in the paper.

According to the results of the contact state modeling (Fig. 6, Table 4), the maximum normalized contact pressure $p/p_0 = 1.0$ is localized in the surface stitches and areas of thread passage through the fold holes. These areas are characterized by an increased probability of damage initiation. For the same level of pretension, polyester threads form the highest contact pressure, while polyamide threads provide its lowest values due to greater deformability.

The results allowed us to establish the mechanism of evolution of local paper damage in the spine part of a book block. Exceeding the local strength of the paper by contact stresses is accompanied by degradation of the fibrous structure in the fold hole areas, an increase in their size and the formation of microchannels for the penetration of the adhesive composition. As shown in Fig. 6, 7, this creates prerequisites for local gluing of pages, deterioration of a book block opening, and gradual weakening of the inter-book thread connection.

Parametric analysis of the effect of pre-tension (Tables 5, 6, relation (24)) allowed us to determine a limited working tension interval within which a rational relationship between the strength and durability of binding is ensured. For polyester threads, this interval is 30–52 conditional units, for cotton threads – 34–58 conditional units, and for polyamide threads – 38–64 conditional units. At the same time, the beginning of intensive paper destruction is observed when the ultimate tension $T_{paper} = 68–77$ conditional units is reached, depending on the type of thread. After 1000 loading cycles, the damage parameter reaches $D_p = 0.96$ for polyester threads, $D_p = 0.87$ for cotton threads, and $D_p = 0.78$ for polyamide threads. The resulting dependences indicate that the pretension belongs to the parameters that significantly affect both the bearing capacity of the spine binding and the intensity of the development of local paper damage in the folds.

Our results are consistent with the general principles in the mechanics of flexible elements, and they further advance approaches based on the use of Euler-Eitelwein-type dependences. In studies [3–5], most attention is paid to adhesive connections. In this work, the spatial thread structure is considered as an independent mechanical system with a non-uniform tension distribution and contact interaction with paper. In [13, 14], attention focused on the integral strength indicators of spine bindings. Instead, in this study, local mechanisms of contact stress formation, paper damage development, and tension losses in individual sections of the thread trajectory have been analyzed. This became possible due to the combination of geometric, force, and finite element modeling, which takes into account the contact interaction of the thread with paper, tension losses due to friction, as well as local mechanisms of material damage. The proposed approach could be used to predict the durability of spine joints, reasonable choice of sewing thread type, and optimization of technological modes for thread stitching of book blocks.

However, our study has certain limitations. In the work, the process of opening a book block was considered as quasi-static, while real operational loads have a complex cyclic and dynamic nature. In addition, the paper was modeled as an anisotropic fibrous material with a simplified parameter of local damage, without detailed consideration of the microstructure of fibers and interfiber bonds. The direct effect of the adhesive layer was also not modeled but was taken into account only indirectly through the possibility of glue penetration into the damaged holes of the folds of notebooks. This must be taken into account in the practical application of the results to predict the durability of specific book block designs.

The shortcomings of the study include the lack of experimental verification of the obtained numerical results for different types of paper and book block designs. In addition, the work did not take into account the influence of aging of polymer adhesive compositions, changes in paper moisture content, and relaxation processes in thread materials. These factors can significantly affect the durability of the spine binding during long-term operation.

Further studies should be directed towards the construction of a complex multi-component model of the spine part of a book block, taking into account the joint operation of the thread structure, adhesive layer, and reinforcing elements. It is also promising to combine numerical modeling with experimental studies on the processes of cyclic destruction and accumulation of damage to holes in the folds of notebooks. This would improve the accuracy of predicting the durability of book blocks and compile scientifically based recommendations for optimizing the technological modes of thread stitching.

7. Conclusions

1. The geometric and force models of the spatial structure of the spine part of a book block have been built, taking into account the trajectory of the sewing thread and the features of tension formation in individual sections of the binding. It has been established that the thread stitching forms a spatially non-uniform mechanical system in which the maximum loads are localized in the surface stitches, while the internal sections provide a redistribution of forces between the notebooks. For multi-row binding, the total bearing capacity is determined by the total work of individual rows of stitches.

2. The mathematical and finite element models of the thread stitching have been constructed, taking into account the mechanical properties of the threads, tension losses due to friction, and contact interaction with the material of the folds. An exponentially decreasing nature of the tension distribution along the thread trajectory has been established. For the initial tension $T_0 = 100$ conditional units, its final values are 30 conditional units for polyester, 25 conditional units for cotton, and 21 conditional units for polyamide threads. The average tension losses at the bends are 12–16%, and in the areas of contact with the folds – 9–14%.

3. The contact interaction of the thread with the paper in the area of the fold holes was investigated and the regularities of the evolution of local damage during the cyclic opening of a book block were established. It was determined that the maximum normalized contact pressure reaches the $p/p_0 = 1.0$ value in the surface stitches and areas of thread passage through the fold holes. For polyester, cotton, and polyamide threads, the maximum damage parameter after 1000 load cycles is $D_p = 0.96$; 0.87; and 0.78, respectively. It was shown that exceeding the permissible level of pretension leads to local destruction of the paper, expansion of the holes in the folds, and the formation of microchannels for the penetration of the adhesive composition.

4. The nonlinear effect of pretension on the durability of the thread bond was established. The working tension intervals that ensure the stability of the thread structure without intensive development of paper damage were determined: 30–52 conditional units for polyester, 34–58 conditional units for cotton, and 38–64 conditional units for polyamide threads. The limit values of tension corresponding to the beginning of paper destruction in the area of fold openings are 68, 72, and 77 conditional units, respectively. It has been established that polyamide threads provide the lowest level of contact damage and the highest predicted durability (136% compared to polyester threads). Our results could be used to substantiate technological modes of thread stitching and predict the durability of book blocks.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

AI model and number: GPT-5.5 model.
Used throughout the text.
Involved in the following:
1. Checking grammar, spelling, punctuation without changing the text.
2. Section 2: search for scientific sources over the past 5 years, related to the research topic, using keywords and criteria entered by the authors.
3. Section 4: all the main scientific provisions regarding the methodology and research materials were independently formulated by the authors. Artificial intelligence tools were used only for auxiliary text analysis in order to identify possible research directions that may not have been taken into account at the initial stage of the work.
4. Sections 5.2–5.4: visualization of original authors' data in the form of plots (Fig. 4, 5, 8–10).

The formulations and individual possible research directions suggested by AI tools were not used automatically. All such materials were reviewed by the authors, compared with the modeling results, available theoretical provisions, and actual research data.

The final text, interpretation of the results, and scientific conclusions were prepared by the authors independently.

Artificial intelligence tools were not used to draw the conclusions of the study. The main conclusions were drawn by the authors on the basis of their modeling results and their analysis.

AI was used only as an auxiliary tool to check the logical completeness of the presentation of the material and possible research directions that may have been insufficiently taken into account in the initial version of the text.

Authors' contributions

Oleksandr Paliukh: Conceptualization, Methodology, Formal analysis, Investigation, Validation, Project administration, Writing – original draft; **Petro Kyrychok**: Methodology, Formal analysis, Validation, Investigation, Writing – review & editing; **Volodymyr Oliynyk**: Investigation, Resources, Validation, Writing – review & editing; **Daryna Baranova**: Resources, Supervision, Writing – r eview & editing.

References

1. Akkasali, N. K., Biswas, S., Sen, S., Anitha, S. (2024). A state-of-the-art review on adhesively bonded joints of similar and dissimilar materials. Journal of Adhesion Science and Technology, 38 (24), 4317–4371. https://doi.org/10.1080/01694243.2024.2384421
2. Ramalho, L. D. C., Sánchez-Arce, I. J., Gonçalves, D. C., Belinha, J., Campilho, R. D. S. G. (2022). Numerical analysis of the dynamic behaviour of adhesive joints: A review. International Journal of Adhesion and Adhesives, 118, 103219. https://doi.org/10.1016/j.ijadhadh.2022.103219
3. Hoshikawa, Y., Kawagoe, Y., Ryuzono, K., Okabe, T. (2024). Finite element modeling for cohesive/adhesive failure of adhesive structures with a thermosetting resin. Engineering Fracture Mechanics, 311, 110552. https://doi.org/10.1016/j.engfracmech.2024.110552
4. Marzi, S. (2023). Experimental determination of coupled cohesive laws with an unsymmetrical stiffness matrix for structural adhesive joints loaded in mixed-mode I+III. Engineering Fracture Mechanics, 283, 109215. https://doi.org/10.1016/j.engfracmech.2023.109215
5. Bernardin, P., Sedlacek, F., Kozak, J., Kucerova, L., Lasova, V. (2024). Identification of the Cohesive Parameters for Modelling of Bonded Joints between Flat Composite Adherends with Thick Layer of Adhesive. Materials, 17 (19), 4880. https://doi.org/10.3390/ma17194880

6. Ibrahim, A. H., Watson, B., Jahed, H., Rezaee, S., Cronin, D. S. (2024). An experimental-cohesive zone model approach to predict fatigue life of adhesive joints with varying modes of loading and joint configurations for automotive applications. The Journal of Adhesion, 101 (7), 930–956. https://doi.org/10.1080/00218464.2024.2408372
7. Calabrese, A. S., Vassilopoulos, A. P. (2025). On the fatigue behavior of thin and thick adhesively bonded composite joints. International Journal of Fatigue, 199, 109065. https://doi.org/10.1016/j.ijfatigue.2025.109065
8. Birnie, J., Falaschetti, M. P., Troiani, E. (2025). Comparative Analysis on Modelling Approaches for the Simulation of Fatigue Disbonding with Cohesive Zone Models. Aerospace, 12 (2), 139. https://doi.org/10.3390/aerospace12020139
9. Li, Y., Deng, H., Takamura, M., Koyanagi, J. (2023). Durability Analysis of CFRP Adhesive Joints: A Study Based on Entropy Damage Modeling Using FEM. Materials, 16 (20), 6821. https://doi.org/10.3390/ma16206821
10. de Queiroz, H. F. M., Banea, M. D. (2022). Methods to increase the mechanical performance of composite adhesive joints: An overview with focus on joints with natural fibre composite adherends. Journal of Composite Materials, 56 (26), 3993–4010. https://doi.org/10.1177/00219983221125906
11. Petković, G., Pasanec Preprotić, S., Vukoje, M., Bolanča Mirković, I. (2024). Impact of SiO2 and TiO2 Nanoparticles on the Elasticity and Aging Resistance of Polyvinyl Acetate (PVAc) Adhesive. Materials, 17 (23), 5957. https://doi.org/10.3390/ma17235957
12. Jina, W., Nagasawa, S., Yamamoto, T., Nagumo, T. (2023). Analysis of the folding behavior of a paperboard subjected to indentation of a deviated creasing rule using the finite element method. AIMS Materials Science, 10 (2), 313–341. https://doi.org/10.3934/matersci.2023017
13. Paliukh, O., Kyrychok, P., Shtefan, Y., Titov, A. (2022). Development of information support for simulation of the process of deformation of root polymer plate in book blocks sewed with threads. Eastern-European Journal of Enterprise Technologies, 5 (1 (119)), 62–73. https://doi.org/10.15587/1729-4061.2022.265869
14. Pasanec Preprotić, S., Vukoje, M., Petković, G., Rožić, M. (2023). Novel Approaches to Enhancing Sustainable Adhesive System Solutions in Contemporary Book Binding: An Overview. Heritage, 6 (1), 628–646. https://doi.org/10.3390/heritage6010033
15. Bulín, R., Hajžman, M. (2019). Comparison of Detailed Belt – Cylinder Interaction Model with Classical Belt Friction Formula. Strojnícky Časopis – Journal of Mechanical Engineering, 69 (3), 9–16. https://doi.org/10.2478/scjme-2019-0024