Developing a Method for Exploring the Cyclic Deformation of Textile Materials for Interior Finish of Aircraft Cabins

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Abstract. The paper discloses the method for estimating the deformation of fibroreticulate materials under the conditions of spatial multiaxial cyclic tension. The relevance of the method application for estimating the reliability performance of materials used for upholstering and finishing the interior of aircraft cabins has been justified. The equations of the elastic state of flexible fibroreticulate materials are obtained under the spatial tension in stresses and deformations. The geometric parameters of elastic deformations in the material during in the material in the design, processing treatment (molding process) and operation (shape stability) of the products. The advantage of the developed method of spatial cyclic tension of flexible fibroreticulate materials is the ability to model test conditions that simulate operating conditions. This capability of the test method allows to examine the dynamics of changes in the markers of the molding properties and shape stability of materials and to predict their behavior during operation.

1. Introduction

The assortment of textile materials and products for the aircraft industry and aeronautics is constantly expanding and updating. Textile fabrics for aircrafts are widely used for upholstering the interior of an aircraft, fuel tanks of modern fighters, wings and tail of single-engine airplanes, for manufacturing brake parachute canopies, covers for storing aircraft equipment and frame covering. In recent times, marketing competition makes the air companies give pride of place to the selection of materials for interior finish of aircraft cabins.

The interior of the aircraft cabin is a system of specifically developed and artistically designed elements of the aircraft interior, which provide aesthetic perception and favorable living environment during the flight, improve safety of passengers in case of emergency. The structural elements of the interior include:
- seat covers (seat, back, armrests, head rests);
- seat cushions (seat, back, armrests, head rests);
- carpet mat;
- curtains and so on.

To upholster and finish the interior of an aircraft cabin, a wide range of fibroreticulate materials with various structure and high strength are used:
- cloth;
- knitted fabric;
- natural leather;
- synthetic leather;
- fur;
- foam for seat cushions;
- carpet mat;

It should be noted that the passenger spends 90% of the flight time alone, surrounded by the elements of the interior, the state of which creates a certain mood, depending on the state of the interior. Clean new carpets and covers, comfortable back cushions and seats make a flight very comfortable. Shabby carpets, out-of-shape covers, bowed cushions lead to fatigue and irritation, and the passenger has a negative impression of the service quality of an air company.

During manufacturing and operation, the materials of the interior products of aircraft cabins (covers for seat, pillows, head rests, curtains) are mainly subjected to cyclic force. Mechanical force on the materials during manufacturing and operation of these products amounts to no more than 10–30% of the material strength. The main mechanical factors that change the deformation properties of the materials and products during manufacturing and operation are tensile and compressive forces. External loads lead to complex spatial deformation of the structural elements of fibroreticulate materials, changing the size and shape of parts and products of the cabin interior.

Therewith, the limiting characteristics of the strength change insignificantly and reflect the nature of structural changes in the materials during technological and operational impact inadequately. The phenomena of wear and service life of modern textile materials are mainly associated with the accumulation of non-recoverable deformations in the materials due to the macrostructure changes.

The analysis of the published works has shown that the applied methods for estimating the deformation indicators of: stiffness, crease retention, elasticity, shrinkage and others are suitable for controlling the initial quality of the materials.

Standard or mainstream devices for the material testing for repeated tension have not yet been developed. There are individual device models used in industry, research laboratories and educational institutions. They work on the principle of preserving a constant amplitude of absolute deformation, a constant amplitude of relative deformation, a constant amplitude of cyclic load in each cycle (MP-2, РП, УП-1, МТИ, ПД-5М, МРД-1, etc.). [1]. The analysis of the construction solution of these devices shows that basically they have a mechanical principle of the sample loading and a visual measurement of the deformation, which leads to significant errors in the measurement results.

In addition, almost all of these methods are based on cutting the samples with subsequent long-term tests of the latter using various laboratory instruments, which makes them rather material-intensive and time-consuming.

It should be noted that the most advanced method is the new method for estimating the deformation properties of the leather based on computer analysis of the material relaxation process after the unloading. The major disadvantage of the device is that the indenter is moved by the mechanical impact of a person, which can cause errors during the testing [2].

The major disadvantage is that the existing methods and tools do not adequately reflect the influence of structural changes in the materials during technological and operational impact on their deformation properties. This fact does not provide an adequate assessment of the technology indices and reliability of the materials and products.

The problem resides in the absence of methods and tools to assess the impact of structural changes in the materials on their deformation properties adequately. This problem does not allow choosing various modern materials for upholstering and finishing the interior of the aircraft cabins efficiently and predicting their behavior during operation.

The purpose of the paper is to develop methods and tools for testing the materials under cyclic spatial tension.
For the purpose in view and scientific justification of the proposed method, it has been necessary to conduct the analysis of the material deformation under spatial tension.

2. Analysis of the material deformation under spatial tension

The paper considers the deformation of a flexible shell with perpendicular applied force $\mathbf{P}$. To calculate the area of the deformed object of research, it is assumed that the deformable material is an elastic homogeneous shell (Fig. 1) that has a solid cross section of a small initial thickness $L_0$ and volume $V_0$. For simplicity, the circuit to fix the shell of radius $R_1$ and friction of the material surfaces and the loading element have not been taken into account.

The change in the shell shape occurs as a result of moving a point that is at the peak to the distance of $h_{\text{aux}}$ (Fig. 1.). At the fixed position of the shell along the circuit $AB$, its movement occurs due to the thickness loss without change of the volume. To find the surface area of the shell under tension, it is necessary to find the areas of the figures (1) and (2) – $S_1$ and $S_2$ respectively. To do this, it is necessary to determine the indenter base radius $r_1$ and establish the interconnection between the movement of $H$ and the element of cylinder of the deformable figure $l$.

![Spatial deformation scheme](image)

Figure. 1. Spatial deformation scheme.

By algebraic transformations, a solution to the equation for the indenter base radius $r_1$ is found:

$$r_1 = \frac{Hr_1\sqrt{H^2 + R_1^2 - r_1^2} + r_1}{H^2 + R_1^2}.
\quad (1)$$

Next, the areas $S_1$, $S_2$ of the figures (1) and (2) are found geometrically:

$$S_1 = \pi r_1^2 + \pi r_1 \left( r - \sqrt{r_1^2 - r_1^2} \right).
\quad (2)$$

$$S_2 = \pi \left[ R_1 \sqrt{R_1^2 + h^2 \left( 1 + \frac{r_1}{R_1 - r_1} \right)^2} - r_1 \sqrt{r_1^2 + \frac{h^2 r_1^2}{(R_1 - r_1)^2}} \right],
\quad (3)$$

where $h = H + \sqrt{r_1^2 - r_1^2}$.

Analysis of equations (2) and (3) and their experimental estimate has shown that the material surface area under spatial tension depends on the sample $R_1$, indenter $r_1$ and its movement value $h$, the correlation coefficient between these values has been 0.86 ... 0.92.

The obtained formulas (2) and (3) as applied to the real objects allow us to calculate the internal surface area of the clothes objectively. Therefore, to correct the above equations (2) and (3), the experimental estimate of the change in the material thickness under spatial tension has been carried out.
The impact of the material thickness on the error in estimating the value of the material deformation under tension has been studied experimentally. As a result, the correction factor in the formula (3) has been determined, allowing to exclude the error in the deformation estimate for the materials with a thickness of more than 2.0 mm. It has been established that the equation (9) calculates the sample surface area of the material with a thickness of 0.01 mm to 2.0 mm with an error of 2.8–10.3%.

The papers [3–6] and other studies have shown that the problem to find an adequate model of the equilibrium mode of deformation of the researchable objects under spatial tension is related to the specifics of their structure and properties, including anisotropy and porosity.

Fibroreticulate polymeric materials, unlike the perfect flexible shells, can change not only the thickness but also the volume during deformation. The experience of theoretical modelling of the spatial deformation of such materials ignoring their properties leads to a significant error in the known models and limitation of their adequacy during the real process. Therefore, the modelling has involved the consideration of the material capability to change volume during deformation.

Conditionally, the shell sections can be represented as a sphere (hemisphere, cone), on the inner surface of which the pressure \( P \), Pa (Fig. 2) is distributed.

![Figure 2](image)

**Figure. 2.** Scheme to the analysis of stresses in the shell under tension.

In this case, the well-known Laplace equation is used:

\[
\frac{\sigma_m}{R_m} + \frac{\sigma_t}{R_t} = \frac{P}{L_0},
\]

where \( \sigma_m \) – meridian stress, Pa; \( \sigma_t \) – parallel (tangential) stress, Pa; \( R_m \) – radius of curvature in the meridian, mm; \( R_t \) – radius of curvature about the axis, mm; \( L_0 \) – shell thickness, mm.

For real conditions of tension, the full symmetry of the shell (as it is often assumed in such calculations) will be only a special case of deformation of anisotropic materials. Therefore, radius of curvature in the meridian \( R_m \) and about the axis of the figure \( R_t \) will differ in most cases. If we assume that \( R_m = \infty \), \( R_t = R \) (Fig. 2), the task to find the deformations and stresses in the shell is reduced to two-dimensional model and, therefore:

\[
\frac{\sigma_t}{R_t} = \frac{P}{L_0}. \tag{5}
\]

In this case, to estimate stresses, it is necessary to know the initial thickness of the shell. Provided that the shell volume is preserved \( V_\ell = V_0 \), the finite thickness of the shell \( L_\ell \):

\[
L_\ell = \frac{V_\ell}{S_\ell} = \frac{\pi R^2 L_0}{S_1 + S_2}. \tag{6}
\]
However, for the real objects, the condition of preserving their volume under tension is not satisfied; therefore, the correction coefficient $k<1$, ($V_k = kV_0$) has been included in the equation (6). Then, the relative deformation is as follows:

$$\varepsilon = \frac{L_0 - L_k}{L_0} = 1 - k \cdot \frac{L_k}{L_0} = \varepsilon_m + \varepsilon_\tau. \quad (7)$$

For anisotropic flexible materials, the interconnection between stress and deformation under tension is non-linear. But within the limits of elasticity for the elementary section of the shell $e$ (Fig. 2), it is possible to write according to the Hook's law:

$$\varepsilon_m = \frac{1}{E} \left( \sigma_m - \mu \sigma_\tau \right), \quad (8)$$

$$\varepsilon_\tau = \frac{1}{E} \left( \sigma_\tau - \mu \sigma_m \right)$$

where $E$ – the elasticity modulus of the 1st kind (Young modulus) under tension, Pa; $\sigma_m$, $\sigma_\tau$ – meridian and parallel (tangential) stresses, Pa; $\mu$ – the lateral contraction ratio (Poisson’s ratio).

Having solved the system of equations (8), we have determined the meridian deformation $\varepsilon_m$:

$$\varepsilon_m = \sqrt{\left( R_1 + \sqrt{r_1^2 - r_2^2} \right)^2 + (R_l - r_2)^2 + r \cdot \arccos \frac{r_1}{r} - 1}. \quad (9)$$

Parallel deformations $\varepsilon_\tau$ are found from the equation (7) by the substitution of $\varepsilon_m$.

Under the condition of homogeneity of the shell cross-section, the average values of $\sigma_m$ and $\sigma_\tau$, are:

$$\begin{align*}
E \cdot \varepsilon_m &= \sigma_m - \mu \sigma_\tau \\
E \cdot \varepsilon_\tau &= \sigma_\tau - \mu \sigma_m
\end{align*} \quad (10)$$

Meridian and parallel stresses are determined by solving the system (10)

$$\sigma_\tau = \frac{E \left( \mu \varepsilon_m + \varepsilon_\tau \right)}{1 - \mu^2}, \quad (11)$$

$$\sigma_m = \frac{E \left( \mu \varepsilon_\tau + \varepsilon_m \right)}{1 - \mu^2}. \quad (12)$$

To solve the equations (8), (11), (12), the Poisson's ratio and the modulus of the 1st kind (elasticity) under tension $E$ are used, which are determined experimentally or specified, taking into consideration the purpose function.

The developed deformation equations allow estimating the elastic deformations and the resulting stresses in the material under the influence of external force actions. On the one hand, the equations (11) and (12) allow predicting the force that should be applied to the material during molding (molding ability). On the other hand, the specified equations allow determining the force, at which elastic deformations occur in the object and its shape and size (shape stability) are preserved.

The comparative analysis of the experimental results of the material testing using the developed device with the data obtained theoretically [7] has confirmed the adequacy of the developed model within the elastic deformation.

3. Developing a method for assessing the deformation of fibroreticulate materials under spatial tension

To carry out the tests, a method and a device for cyclic spatial tension have been developed (RF Patent No. 2354953) [8], the fundamental difference of which lies in the possibility to measure the deformation components of material samples after the specified number of cycles of their spatial tension.

It allows us to study the dynamics of changes in the deformation indicators of materials under the conditions of the sample testing that simulate the impact of technological and operational factors.
A method for estimating the deformation of flexible materials is proposed, based on the use of analytical-type tool, which makes it possible to implement a comprehensive and more accurate control of all input and output parameters.

The principle of operation of this device lies in the fact that the test material is fixed along the ring circuit and is loaded by the indenter using an automatically specified multi-cycle mechanical force.

Therewith, the material is subjected to multi-axial spatial tension, obtaining equal deformations along all elements of the cone. The load on the indenter is integral from the loads in all directions and, therefore, it is independent of the leather position relative to the device. Thus, during the extrusion test of the sample clamped along the ring circuit, the average characteristics of the anisotropic material are obtained, regardless of its position.

In the proposed device, the movement of the indenter after the unloading is converted by means of a linear increment encoder into an electrical signal and transmitted to the computer in real time digitally. Further, the obtained information is processed by a special program that calculates the main deformation characteristics.

The proposed method allows measuring the deformation directly in semi-finished or finished products. The device has easy design and is simple to operate. At the same time, it allows to obtain more accurate and objective measurement results.

The subject matter of the method consists in estimating the complete, reversible, irreversible deformation component (in % and fractions), the calculation of which uses the measurement data of the material sample deflection under the loading $h_{\text{max}}$, after the unloading $h_1$ and after the rest $h_{\text{rest}}$ (Fig. 3).

![Figure. 3. The position of the sample material before testing (1) and in the conditions of spatial tension (2)](image)

The measuring system of the device (Figs. 4, no. 1–9) allows to: automate the control and operation of all mechanisms of the device; automatically measure and consider the value of the initial sample deflection relative to the zero level $\Delta h$ under the current measurements (see Fig. 14); simulate test conditions. High accuracy of the measurement results of the sample deflection value (instrument measurement error is not more than 10 μm) is provided by differential photosensors (see. Figs. 4, no. 5–6).

The number of papers, including [8, 9], have experimentally determined the optimal parameters for testing fibroreticulate materials of different fibrous composition and structure: the time of sample loading/rest in a cycle is 5–20/5–10 s; cyclic load on samples of fabric, leather and packages is 1.0...2.0 daN, on knitted fabrics is 0.5 daN.

The dynamics of changes in the properties of materials under the influence of external factors is analysed on the basis of determining the indicators of plasticity (%), elasticity (%), conditional stiffness (N). The calculation of the relative deformation (%), average stress $\sigma$ (MPa), the equilibrium elastic modulus $E_3$ (MPa) is performed using the equations (7) - (11) in the MathCAD system.

The paper [9] and other studies have performed the experimental verification of the theoretically developed method of spatial deformation during the study of samples of leather, fabrics, knitted fabrics, as well as packages obtained by molding the parts of fabrics and leather by means of doubling and processing with polymer dispersions.
Figure. 4. The device scheme for cyclic spatial tension: measuring system (1–9), including: 1 – spring contact probe, 2 – antibacklash plug, 3 – guidance, 4 – balancing lever, 5 – probe photosensor, 6 – differential photosensor, 7 – carriage, 8 – lead screw, 9 – measuring device; 10 – the supporting point for the placement of goods; 11 – electric motor; 12 – loading device; 13 – clamping rings to fix the sample; 14 – carriage moving over the table 15; 16 – step motor; 17 – electronic assembly with input panel and data display.

4. Conclusion
1. The equations of the elastic state of the flexible fibroreticulate materials are obtained under the spatial tension in stresses and deformations.
2. The geometric parameters of elastic deformations in the material during in the material in the design, processing treatment (molding process) and operation (shape stability) of the products.
3. The advantage of the developed method of spatial cyclic tension of flexible fibroreticulate materials is the ability to model test conditions that simulate operating conditions. This capability of the test method allows to examine the dynamics of changes in the markers of the molding properties and shape stability of materials and to predict their behaviour during operation.

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