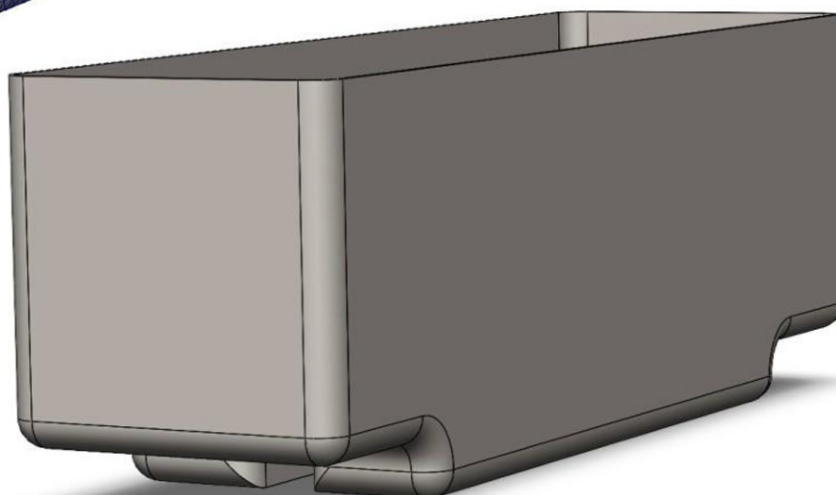
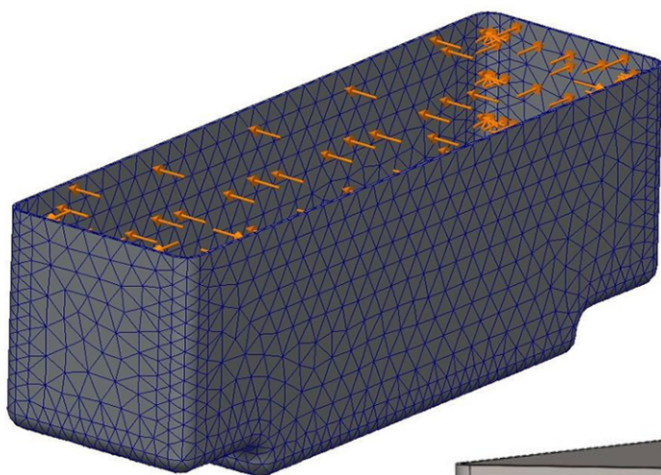


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# **CONCEPTUAL SOLUTIONS FOR THE MANUFACTURE OF CARGO WAGON BEARING SYSTEMS FROM COMPOSITES (PART 2)**

*Monograph*

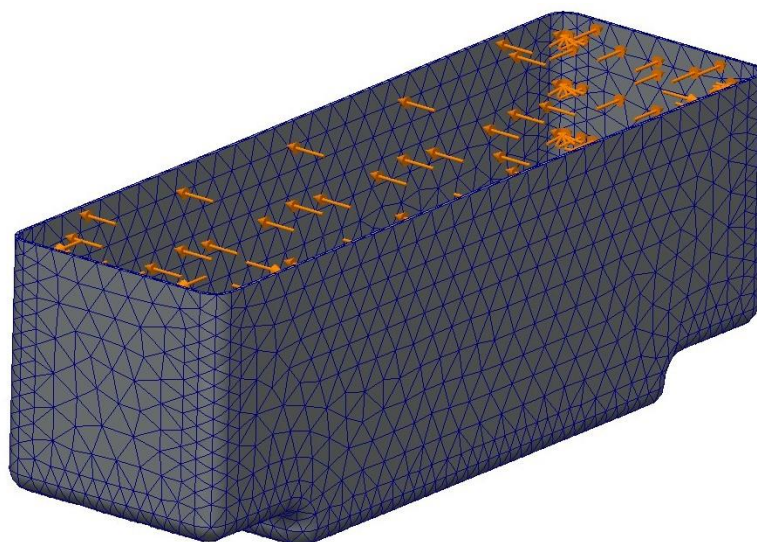


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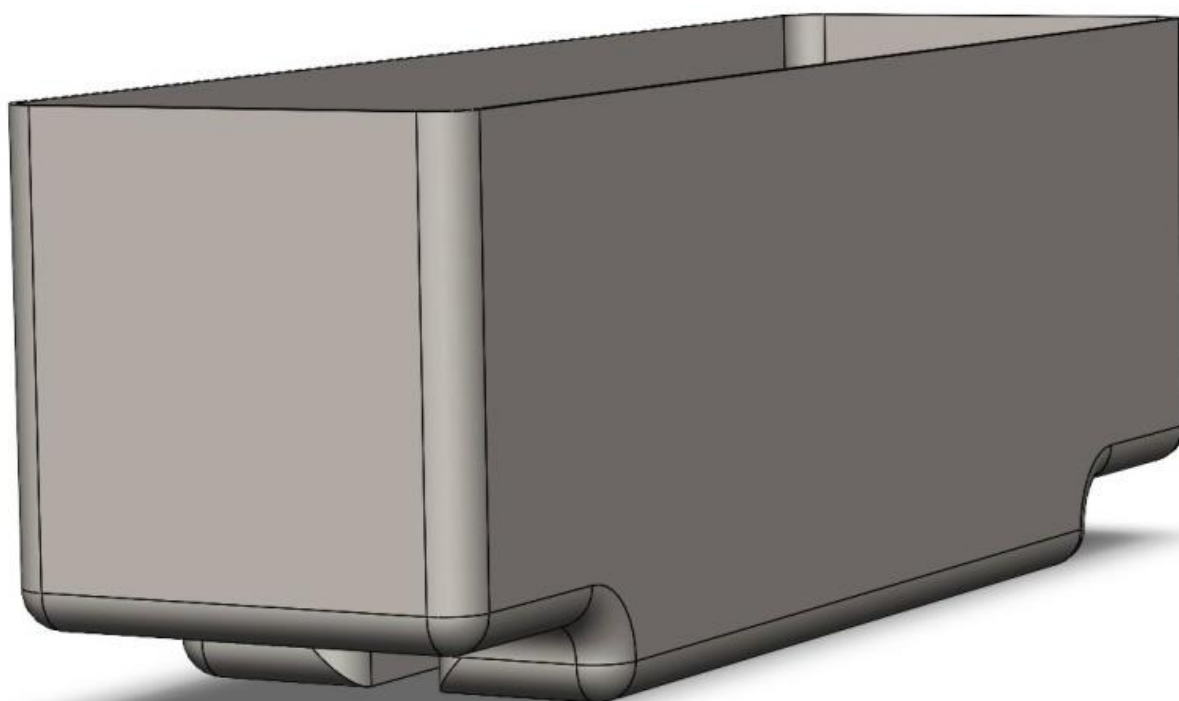
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### **Monograph**



Shawnee, USA:  
Primedia eLaunch LLC  
**2024**



**UDC 629.4.02.001.76**

**F 71**

Fomin O., Fomina A., Medvedev I., Cherkashin O. (2024). *Conceptual solutions for the manufacture of cargo wagon bearing systems from composites (Part 2)*.

Shawnee, USA: Primedia eLaunch LLC, 150 p.

ISBN 979-8-89217-808-2

DOI 10.36074/csftmocwbsfc-monograph.2024

*This monograph is recommended for printing by the Science Council  
of Volodymyr Dahl East Ukrainian National University  
(protocol No 11 dd 27.06.2024)*

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The monograph is the second part of the corresponding series of books. And it will be useful for scientists, designers, engineers whose activities are related to improving the technical, economic and operational indicators of non-traction rolling stock at various stages of its life cycle.

In particular, the issue of the possibility and expediency of introducing various types of structural hierarchy of composite components in the construction of wagons. What can happen when creating new models of them or modernizing existing ones.

To date, the traditional approach to creating a structure of freight wagons from steel has almost completely exhausted the potential for improving their technical, economic and operational indicators. At the same time, the experience of the development of composite materials and technologies for their creation in other branches of light and heavy engineering and instrument building indicates the prospect of deploying relevant research and development works on the use of such materials in railcar construction.

The purpose of the monograph is to highlight the results obtained from the creation of conceptual solutions for the manufacture of component load-carrying systems of freight cars from composites. The book also presents the results of works of a theoretical and practical nature. In particular, it is given. Model of deformation of space-reinforced fibrous materials. Analysis of the temperature effect on the stress-strain state of the tank wagon composite boiler during steaming. Separate issues of creating conceptual solutions for the manufacture of component freight wagons from composites. Analysis of the strength of the composite module of the body of a coal wagon.

The book can be used as a study guide for the preparation of bachelors, masters, doctors of philosophy and doctors of sciences in various specialties of transport mechanics. Including from specialties: railway transport, transport technologies, mechanical engineering, materials science and others.

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## **INTRODUCTION**

Composite materials of various types of reinforcement have become widespread in various industries. Therefore, it is relevant to study the mechanical behavior of composite materials during loading. Currently, theories dedicated to the study of deformation and destruction of composite materials are intensively developed. Methods for determining the stress-strain state, predicting physical and mechanical properties, and choosing the optimal structure of composite materials are being developed. This will significantly reduce expensive experimental research.

Composite materials based on continuous fibers and their binding matrix can be divided into three groups according to the nature of fiber orientation: unidirectional, multidirectional in one plane, and spatially oriented. The multidirectional nature of the fibers allows you to ensure the necessary stiffness and strength of the composite in different directions, which favorably distinguishes these materials from unidirectional ones. Therefore, fibrous materials with fibers disoriented in the plane, i.e. layered fibrous materials, as well as more priority and less researched spatially disoriented materials are widely used in many industries where light and strong structures are required.

Fibrous and spatially reinforced fibrous composite materials have been



studied by many authors. A number of works are devoted to experimental studies of composite materials. Effective material properties within the fully elastic range were studied by CLChoy et al. [7], and ALGeiger, P. Weich [8] determined its ultimate bearing capacity. Damage models of fibrous composites were built in the work of GZWoyiadjis, PIKattan [9]. T.Chen et al [10], HLDuan et al [11], RMGray [12], Z.Hashin [13, 14], HTLiu [20], L.V. Nazarenko [14, 15, 24], Maslov B.P. [4, 21-23], L.P. Horoshuna, O.M. Shikuly [5, 6, 16-19] and others. The solution to the linear problem of the deformation of stochastically inhomogeneous fibrous materials of spatial reinforcement was obtained in the works of L.V. Nazarenko [16, 25, 26], L.P. Khoroshun, and O.M. Shikula [4].

The purpose of this work is to build a model and study the deformation and thermoelastic properties of spatially reinforced fibrous materials. It is based on the stochastic differential equations of the theory of elasticity of L.P. Khoroshun [1, 4].

Geographically, Ukraine has a favorable transport location. This is explained by its location in the middle of the Euro-Asian transport routes, which ensures its advantages in interstate transportation. Today, three Pan-European international transport corridors pass through the territory of Ukraine, connecting it with Bulgaria, Georgia, Turkey and other countries.

At the same time, meeting the growing needs in transportation requires a significant increase in the working fleet of freight wagons. This can be done through the purchase of serial models of freight wagons, or through the creation and introduction into production of their more advanced designs. It should be noted that the second direction is more promising. One of the main directions of creating freight wagons with improved technical and economic indicators is the use of the latest materials, in particular composites.

Unfortunately, in recent years, the fleet of freight wagons has been replenished to a small extent. Which is explained by the need for significant costs for its replenishment.

It should also be noted that today the technical facilities of the domestic railway transport are in a critical state of wear and tear. Outdated freight wagons have a negative impact on the infrastructure and, accordingly, negatively affect the level of safety of railway transportation. They do not meet modern requirements for transportation efficiency. The urgent need to significantly improve the efficiency of rail freight transportation requires solving the scientific and technical problem of creating a fundamentally new generation of freight wagons made of composite materials.

## SECTION 1

### MODEL OF DEFORMATION OF SPATIALLY REINFORCED FIBROUS MATERIALS

#### 1.1 Research materials and methods

Consider a spatially reinforced fibrous material with a stochastic structure, which is a system of fibers  $N$  directions connected by the matrix. We will consider this material as a multi-component composite material, considering the matrix and fibers of each direction as separate components. We will assume that there is a sufficiently large number of stochastically located fibers in each direction, the material of the fibers is transversely isotropic with the axis of symmetry along the fibers, the material of the matrix is isotropic and physically nonlinear. Fibers  $k$ -th direction are characterized by direction cosines (Figure 1.1)

$$\gamma_1^{(k)} = \sin \theta_k \cos \varphi_k; \gamma_2^{(k)} = \sin \theta_k \sin \varphi_k; \gamma_3^{(k)} = \cos \theta_k$$

$$(0 \leq \theta_k \leq \pi/2; 0 \leq \varphi_k \leq 2\pi; k = 1, 2, \dots, N). \quad (1.1)$$

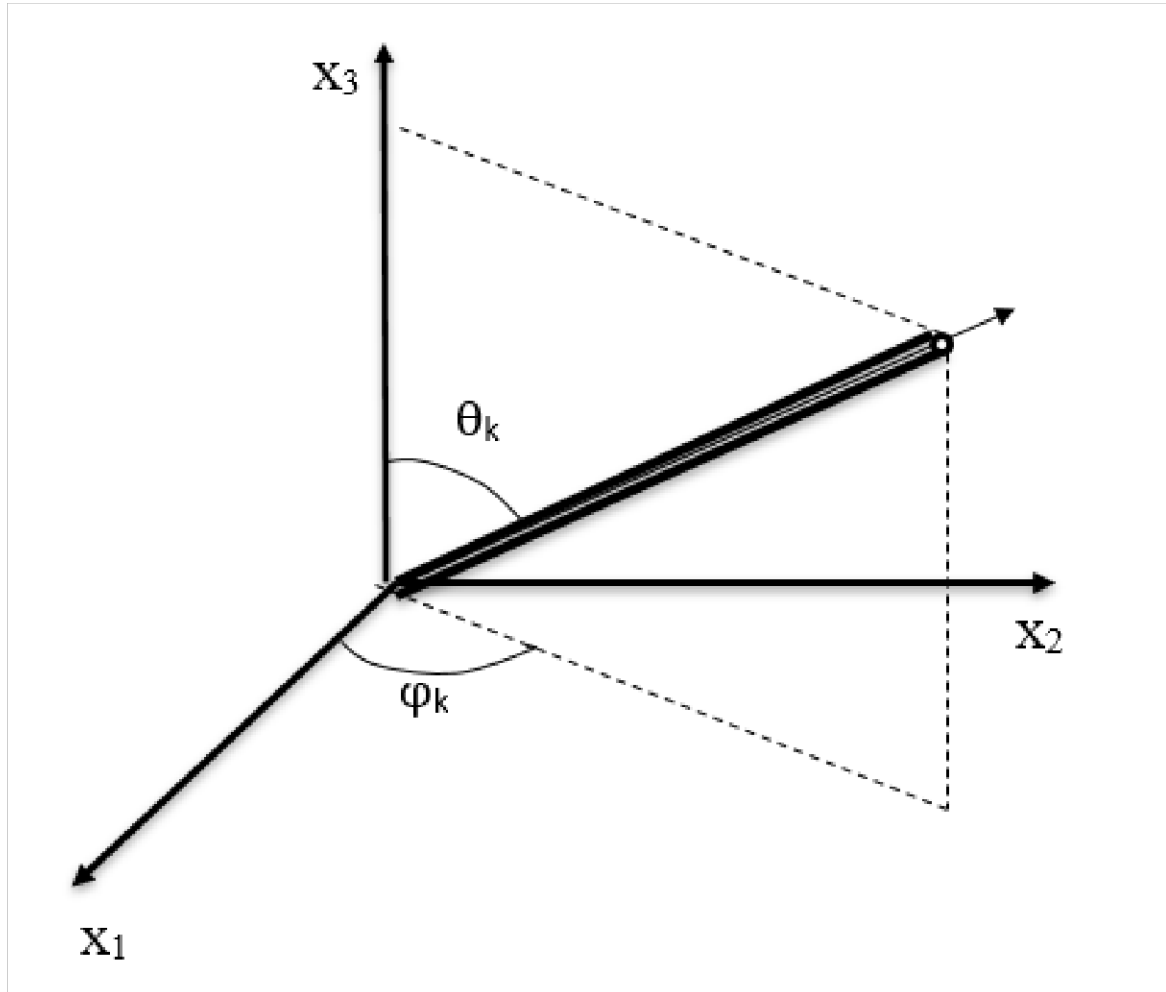


Figure 1.1

Let the volumetric contents of fibers  $k$ -th direction and the matrix are equal, respectively  $c_1^{(k)}$  and  $c_2$ . Total fiber concentration  $c_1 = \sum_{k=1}^N c_1^{(k)}$ , with  $c_1 + c_2 = 1$ . The paper considers the case of spatial reinforcement: the fibers are located in a plane  $x_1x_2$  along the sides of the square and its diagonals. Determination of the effective thermoelastic characteristics of the material will be carried out in two stages. At the first stage, the effective properties of the subsystem, which is a unidirectional fibrous material formed by fibers, are

determined  $k$ -th direction and part of the matrix with volumetric content

$c_2^{(k)} = \frac{c_2}{c_1} c_1^{(k)}$ . The solution of the problem of the first stage is carried out on the

basis of the model of unidirectional fibrous material of stochastic structure [1, 4-6]. Stochastic differential equations of the theory of elasticity are the basis, the solution is constructed using the method of conditional moments [1, 4]. At the second stage, the effective properties of the entire system are determined based on the calculated properties of the subsystems. The solution of the problem of the second stage is built on the basis of Voigt's scheme.

## 1.2 Determination of effective deformation properties of spatially reinforced fibrous materials. Formulation of the problem

Let the macrovolume of the spatially reinforced fibrous material be under conditions of uniform loading. Let's denote thermoelastic steel fibers  $k$ -th direction  $\lambda_{ij}^{(k)}$ ,  $\beta_i^{(k)}$ , and matrices— $\lambda_2$ ,  $\mu_2$ ,  $\beta_2$ . We will proceed from the equilibrium equations at the micropoint

$$\sigma_{ij,j}^{(k)} = 0, \quad (1.2)$$

relations between stresses and strains in the component

$$\begin{aligned} \sigma_{pq}^{(k)} &= (\lambda_{11}^{(k)} - \lambda_{12}^{(k)}) \varepsilon_{pq}^{(k)} + (\lambda_{12}^{(k)} \varepsilon_{rr}^{(k)} + \lambda_{13}^{(k)} \varepsilon_{33}^{(k)}) \delta_{pq} - \beta_1^{(k)} \theta \delta_{pq}; \\ \sigma_{33}^{(k)} &= \lambda_{13}^{(k)} \varepsilon_{rr}^{(k)} + \lambda_{33}^{(k)} \varepsilon_{33}^{(k)} - \beta_3^{(k)} \theta; \quad \sigma_{p3}^{(k)} = 2\lambda_{44}^{(k)} \varepsilon_{p3}^{(k)} \quad (p, q, r = 1, 2), \end{aligned} \quad (1.3)$$

and Cauchy ratios

$$\varepsilon_{ij}^{(k)} = u_{(i,j)}^{(k)} = \frac{1}{2} (u_{i,j}^{(k)} + u_{j,i}^{(k)}). \quad (1.4)$$

Substituting (1.3), (1.4) into (1.2), we arrive at statistically nonlinear equilibrium equations with respect to movements  $u_i^{(k)}$  in the subsystem

$$\begin{aligned} & [(\lambda_{11}^{(k)} - \lambda_{12}^{(k)}) u_{m,r}^{0(k)}]_{,r} + [(\lambda_{11}^{(k)} + \lambda_{12}^{(k)}) u_{r,r}^{0(k)}]_{,m} = \\ & = -2[\lambda_{12}^{(k)} < \varepsilon_{rr} >^{(k)} \delta_{ml} + (\lambda_{11}^{(k)} - \lambda_{12}^{(k)}) < \varepsilon_{ml} >^{(k)} + \lambda_{13}^{(k)} < \varepsilon_{33} >^{(k)} \delta_{ml} - \beta_1^{(k)} \theta \delta_{ml}]_{,l}; \end{aligned}$$

$$(\lambda_{44}^{(k)} u_{3,r}^{0(k)})_{,r} = -(2\lambda_{44}^{(k)} \langle \varepsilon_{m3} \rangle^{(k)})_{,m} \quad (l, m, r = 1, 2). \quad (1.5)$$

Fluctuations of movements are very small compared to their average values at  $x_j \rightarrow \infty$ , therefore, at infinity, we take the fluctuation of displacements to be zero.

Averaging the ratio (1.3), we obtain expressions for the average stresses in the form

$$\begin{aligned} \langle \sigma_{pq} \rangle^{(k)} &= c_1^{(k)} (\lambda_{11}^{(k)} - \lambda_{12}^{(k)}) \langle \varepsilon_{pq}^1 \rangle^{(k)} + c_1^{(k)} (\lambda_{12}^{(k)} \langle \varepsilon_{rr}^1 \rangle^{(k)} + \lambda_{13}^{(k)} \langle \varepsilon_{33}^1 \rangle^{(k)}) \delta_{pq} + \\ &+ c_2^{(k)} \lambda_2 \langle \varepsilon_{ss}^2 \rangle^{(k)} \delta_{pq} + 2c_2^{(k)} \mu_2 \langle \varepsilon_{pq}^2 \rangle^{(k)} - (c_1^{(k)} \beta_1^{(k)} + c_2^{(k)} \beta_2) \theta \delta_{pq}; \\ \langle \sigma_{33} \rangle^{(k)} &= c_1^{(k)} \lambda_{13}^{(k)} \langle \varepsilon_{rr}^1 \rangle^{(k)} + c_1^{(k)} \lambda_{33}^{(k)} \langle \varepsilon_{33}^1 \rangle^{(k)} + \\ &+ c_2^{(k)} \lambda_2 \langle \varepsilon_{ss}^2 \rangle^{(k)} + 2c_2^{(k)} \mu_2 \langle \varepsilon_{33}^2 \rangle^{(k)} - (c_1^{(k)} \beta_3^{(k)} + c_2^{(k)} \beta_2) \theta; \\ \langle \sigma_{p3} \rangle^{(k)} &= 2c_1^{(k)} \lambda_{44}^{(k)} \langle \varepsilon_{p3}^1 \rangle^{(k)} + 2c_2^{(k)} \mu_2 \langle \varepsilon_{p3}^2 \rangle^{(k)} \\ &(p, q, r = 1, 2, \quad s = 1, 2, 3), \end{aligned} \quad (1.6)$$

Let's determine from equations (1.5) the average deformations of subsystem components  $\langle \varepsilon_{ij}^1 \rangle^{(k)}$  and  $\langle \varepsilon_{ij}^2 \rangle^{(k)}$  as functions of the average deformations of the subsystem  $\langle \varepsilon_{ij} \rangle^{(k)}$  and substituting them into the ratio (1.6), we will obtain the expressions for the effective characteristics.

Equation (1.5) will be reduced to the integral form. To do this, we select the coefficients from the matrix  $\lambda_{ij}^{(k)}$  of the left part some matrix of modules  $\lambda_{ij}^{c(k)}$  with coordinate-independent elements, giving the equation in the form

$$\begin{aligned} &(\lambda_{11}^{c(k)} - \lambda_{12}^{c(k)}) u_{m,rr}^{0(k)} + (\lambda_{11}^{c(k)} + \lambda_{12}^{c(k)}) u_{r,rm}^{0(k)} = \\ &= -2[\bar{\lambda}_{12}^{(k)} \varepsilon_{rr}^{(k)} \delta_{ml} + (\bar{\lambda}_{11}^{(k)} - \bar{\lambda}_{12}^{(k)}) \varepsilon_{ml}^{(k)} + \lambda_{13}^{(k)} \langle \varepsilon_{33} \rangle^{(k)} \delta_{ml} - \beta_1^{(k)} \theta \delta_{ml}]_{,l}; \end{aligned}$$



$$\lambda_{44}^{c(k)} u_{3,rr}^{0(k)} = -(2\bar{\lambda}_{44}^{(k)} \varepsilon_{m3}^{(k)})_{,m} \quad (m, l, r = 1, 2, \quad p = 1, 2, 3).$$

$$(\bar{\lambda}_{ij}^{(k)} = \lambda_{ij}^{(k)} - \lambda_{ij}^{c(k)}) \quad (1.7)$$

and use the Green's function that satisfies the equation

$$(\lambda_{11}^{c(k)} - \lambda_{12}^{c(k)}) G_{jm,ll}^{(k)}(x_r) + (\lambda_{11}^{c(k)} + \lambda_{12}^{c(k)}) G_{jl,lm}^{(k)}(x_r) = -\delta(x_r) \delta_{jm};$$

$$\lambda_{44}^{c(k)} G_{,mm}^{(k)}(x_r) = -\delta(x_r) \quad (l, m, r = 1, 2). \quad (1.8)$$

Based on Betti's formulas from equations (1.7), (1.8) we have

$$u_m^{0(k)}(x_j^{(1)}) = 2 \int_{\Delta \tilde{s}^{(2)}} G_{ml}^{(k)}(x_j^{(1)} - x_j^{(2)}) \times \\ \times [\bar{\lambda}_{12}^{(2)(k)} \varepsilon_{rr}^{(2)(k)} \delta_{lq} + (\bar{\lambda}_{11}^{(2)(k)} - \bar{\lambda}_{12}^{(2)(k)}) \varepsilon_{lq}^{(2)(k)} + \lambda_{13}^{(2)(k)} < \varepsilon_{33} >^{(k)} \delta_{lq} - \beta_1^{(2)(k)} \theta \delta_{lq}]_{,q} d\tilde{s}^{(2)};$$

$$u_3^{0(k)}(x_j^{(1)}) = 2 \int_{\Delta \tilde{s}^{(2)}} G^{(k)}(x_j^{(1)} - x_j^{(2)}) (\bar{\lambda}_{44}^{(2)(k)} \varepsilon_{m3}^{(2)(k)})_{,m} d\tilde{s}^{(2)}$$

$$(l, m, q, r = 1, 2). \quad (1.9)$$

By differentiating expression (1.9) and integrating it by parts, we obtain the integral equation with respect to deformations

$$\varepsilon_{ml}^{(k)}(x_j^{(1)}) = < \varepsilon_{ml} >^{(k)} + \int_{\Delta \tilde{s}^{(2)(k)}} [G_{mm,l}^{(k)}(x_j^{(1)} - x_j^{(2)}) + G_{ln,m}^{(k)}(x_j^{(1)} - x_j^{(2)})]_{,q} \times$$

$$\begin{aligned}
 & \times [\bar{\lambda}_{12}^{(2)(k)} \varepsilon_{rr}^{(2)(k)} \delta_{nq} + (\bar{\lambda}_{11}^{(2)(k)} - \bar{\lambda}_{12}^{(2)(k)}) \varepsilon_{nq}^{(2)(k)} + \lambda_{13}^{(2)(k)} < \varepsilon_{33} >^{(k)} \delta_{nq} - \beta_1^{(2)(k)} \theta \delta_{nq}]_{,q} d\tilde{s}^{(2)(k)} - \\
 & - \int_{\Delta \tilde{l}^{(2)(k)}} [G_{mn,l}^{(k)} (x_j^{(1)} - x_j^{(2)}) + G_{ln,m}^{(k)} (x_j^{(1)} - x_j^{(2)})] \tilde{n}_q^{(k)} \times \\
 & \times [\bar{\lambda}_{12}^{(2)(k)} \varepsilon_{rr}^{(2)(k)} \delta_{nq} + (\bar{\lambda}_{11}^{(2)(k)} - \bar{\lambda}_{12}^{(2)(k)}) \varepsilon_{nq}^{(2)(k)} + \lambda_{13}^{(2)(k)} < \varepsilon_{33} >^{(k)} \delta_{nq} - \beta_1^{(2)(k)} \theta \delta_{nq}]_{,q} d\tilde{l}^{(2)(k)}; \\
 & \varepsilon_{m3}^{(k)} (x_j^{(1)}) = < \varepsilon_{m3} >^{(k)} + \int_{\Delta \tilde{s}^{(2)(k)}} G_{,mq}^{(k)} (x_j^{(1)} - x_j^{(2)}) (\bar{\lambda}_{44}^{(2)(k)} \varepsilon_{q3}^{(2)(k)}) d\tilde{s}^{(2)(k)} - \\
 & - \int_{\Delta \tilde{l}^{(2)(k)}} G_{,k}^{(k)} (x_j^{(1)} - x_j^{(2)}) \tilde{n}_q^{(k)} (\bar{\lambda}_{44}^{(2)(k)} \varepsilon_{q3}^{(2)(k)}) d\tilde{l}^{(2)(k)} \\
 & (l, m, n, q, r = 1, 2).
 \end{aligned} \tag{1.10}$$

Here  $\tilde{n}_q^{(k)}$  is the normal to the infinitely distant border of the area under consideration, the upper numerical indices indicate the corresponding point of the plane area or the curve that limits it.

To determine the Green's functions included in equation (1.10), we apply the integral Fourier transform of the plane domain to equations (1.8). As a result, we get

$$(\lambda_{11}^{c(k)} - \lambda_{12}^{c(k)}) \xi^2 G_{jm}^{(k)F} + (\lambda_{11}^{c(k)} + \lambda_{12}^{c(k)}) \xi_m \xi_l G_{jl}^{(k)F} = \delta_{jm}; \tag{1.11}$$

$$\lambda_{44}^{c(k)} \xi^2 G^{(k)F} = 1, \tag{1.12}$$

where

$$G_{jm}^{(k)F} = \int G_{jm}^{(k)}(x_r) e^{i\xi_j x_j} dx;$$

$$G^{(k)F} = \int G^{(k)}(x_r) e^{i\xi_j x_j} dx \quad (\xi^2 = \xi_j \xi_j). \quad (1.13)$$

Multiplying both parts of equation (1.11) by  $\xi_m$  and summing by index  $m$ , we find

$$\lambda_{11}^{c(k)} \xi^2 \xi_l G_{jl}^{(k)F} = \xi_j. \quad (1.14)$$

From the obtained ratios and from (1.11), (1.12) we obtain

$$\frac{\lambda_{11}^{c(k)} + \lambda_{12}^{c(k)}}{\lambda_{11}^{c(k)}} \frac{\xi_m \xi_l}{\xi^2} + (\lambda_{11}^{c(k)} - \lambda_{12}^{c(k)}) \xi^2 G_{ml}^{(k)F} = \delta_{ml};$$

$$\lambda_{44}^{c(k)} \xi^2 G^{(k)F} = 1, \quad (1.15)$$

where

$$G_{ml}^{(k)F} = \frac{1}{\lambda_{11}^{c(k)} - \lambda_{12}^{c(k)}} \left( \frac{\delta_{ml}}{\xi^2} - \frac{\lambda_{11}^{c(k)} + \lambda_{12}^{c(k)}}{\lambda_{11}^{c(k)}} \frac{\xi_m \xi_l}{\xi^4} \right);$$

$$G^{(k)F} = \frac{1}{\lambda_{44}^{c(k)} \xi^2}. \quad (1.16)$$

Taking into account that

$$\frac{1}{\pi} \int \frac{1}{\xi^2} e^{-i\xi_j x_j} d\xi = -2 \ln \frac{1}{r};$$

$$\frac{1}{\pi} \int \frac{\xi_m \xi_l}{\xi^4} e^{-i\xi_j x_j} d\xi = -\ln \frac{1}{r} \delta_{ml} + \frac{x_m x_l}{r^2} \quad (r^2 = x_j x_j), \quad (1.17)$$

it is easy to find the original Fourier image  $G_{ml}^{(k)}$  and  $G^{(k)}$  of Green's functions

$$G_{ml}^{(k)} = \frac{1}{4\pi^2} \int G_{ml}^{(k)F} e^{-i\xi_j x_j} d\xi =$$

$$= \frac{1}{4\pi\lambda_{11}^{c(k)}(\lambda_{11}^{c(k)} - \lambda_{12}^{c(k)})} \left[ (3\lambda_{11}^{c(k)} - \lambda_{12}^{c(k)}) \ln \frac{1}{r} \delta_{ml} \right.$$

$$\left. + (\lambda_{11}^{c(k)} + \lambda_{12}^{c(k)}) \frac{(x_m^{(1)} - x_m^{(2)})(x_l^{(1)} - x_l^{(2)})}{r^2} \right]$$

$$G^{(k)}(x_i^{(1)} - x_i^{(2)}) = \frac{1}{4\pi^2} \int G^{(k)F} e^{-i\xi_j x_j} d\xi = \frac{1}{2\pi\lambda_{44}^{c(k)}} \ln \frac{1}{r} \quad (l, m = 1, 2). \quad (1.18)$$

We will use the method of conditional moments [1, 4]. In order to shorten further explanations, we will present equation (1.10) in symbolic form

$$\varepsilon^{(1)(k)} = \langle \varepsilon \rangle^{(k)} + \int K^{(k)}(x^{(1)} - x^{(2)}) (\bar{\lambda}^{(2)(k)} \varepsilon^{(2)(k)} - \beta^{(2)(k)} \theta) dx^{(2)}. \quad (1.19)$$

Let's multiply (1.19) by the conditional density  $f(\varepsilon^{(1)(k)}, \varepsilon^{(2)(k)}, \lambda^{(2)(k)} |_{\nu}^{(1)(k)})$  (density of distribution of deformations at a point  $x^{(1)}$  subsystems, deformations and characteristics at a point  $x^{(2)}$  subsystems under the condition that at a point  $x^{(1)}$  is located  $\nu$ -subsystem component) and perform statistical averaging. As a result, we get

$$\langle \varepsilon^\nu \rangle^{(k)} = \langle \varepsilon \rangle^{(k)} + \int K^{(k)}(x) \sum_{s=1}^2 p_{\nu s} [\bar{\lambda}_s^{(k)} \varepsilon^{s\nu(k)}(x) - \beta_s^{(k)} \theta] dx \quad (\nu = 1, 2), \quad (1.20)$$

where  $\langle \varepsilon^\nu \rangle^{(k)}$  – average deformation  $\nu$ -subsystem component;  
 $\varepsilon^{s\nu(k)}(x^{(1)} - x^{(2)}) = \langle \varepsilon^{(1)(k)} |_{s, \nu}^{(1)(k)}, (2)(k)} \rangle$  – mathematical expectation at a point  $x^{(1)}$  subsystems provided that the point  $x^{(1)}$  is located  $s$ -components of the subsystem,

and the point  $x^{(2)}$  - in  $\nu$ -subsystem components;  $p_{\nu s}^{(k)}(x^{(1)} - x^{(2)}) = f_s^{(1)(k)} |_{\nu}^{(2)(k)}$  is the probability of finding a point  $x^{(1)}$  in  $s$ -components of the subsystem, provided that  $x^{(2)}$  is located in  $\nu$ -subsystem components.

We will neglect deformation fluctuations within the subsystem component. In this case, conditional two-point moments  $\varepsilon^{s\nu(k)}(x)$ , included in equation (1.20), degenerate at one point, i.e

$$\varepsilon^{s\nu(k)}(x) \approx \varepsilon^s >^{(k)}. \quad (1.21)$$

Then equations (1.20) are reduced to a system of algebraic equations with respect to the average deformations of the components

$$\langle \varepsilon^\nu \rangle^{(k)} = \langle \varepsilon \rangle^{(k)} + \sum_{s=1}^2 \int K^{(k)}(x) p_{\nu s}(x) dx \times (\bar{\lambda}_s^{(k)} \langle \varepsilon^s \rangle^{(k)} - \beta_s^{(k)} \theta) \quad (\nu = 1, 2). \quad (1.22)$$

If the properties of the composite material of the subsystem are statistically isotropic in the plane perpendicular to the direction of the fibers, then the conditional probabilities  $p_{\nu s}^{(k)}(x^{(1)} - x^{(2)})$  depend only on the distance between the points  $x^{(1)}$  and  $x^{(2)}$ . In this case, after integration in (1.23), we obtain

$$\langle \varepsilon^\nu \rangle^{(k)} = \langle \varepsilon \rangle^{(k)} + A^{(k)} \sum_{s=1}^2 (\delta_{\nu s} - c_s^{(k)}) (\bar{\lambda}_s^{(k)} \langle \varepsilon^s \rangle^{(k)} - \beta_s^{(k)} \theta) \quad (1.23)$$

or in index form

$$\begin{aligned} \langle \varepsilon_{ij}^\nu \rangle^{(k)} = & \langle \varepsilon_{ij} \rangle^{(k)} + A_{ijnq}^{(k)} \sum_{s=1}^2 (\delta_{\nu s} - c_s^{(k)}) [\bar{\lambda}_{12}^{s(k)} \langle \varepsilon_{rr}^s \rangle^{(k)} \delta_{nq} + \\ & + (\bar{\lambda}_{11}^{s(k)} - \bar{\lambda}_{12}^{s(k)}) \langle \varepsilon_{nq}^s \rangle^{(k)} + \lambda_{13}^{s(k)} \langle \varepsilon_{33}^s \rangle^{(k)} \delta_{nq} - \beta_1^{s(k)} \theta \delta_{nq}]; \end{aligned}$$

$$\langle \varepsilon_{i3}^{\nu} \rangle^{(k)} = \langle \varepsilon_{i3} \rangle^{(k)} + A_{i3n3}^{(k)} \sum_{s=1}^2 (\delta_{\nu s} - c_s^{(k)}) \bar{\lambda}_{44}^{s(k)} \langle \varepsilon_{q3}^s \rangle^{(k)}$$

$$(i, j, n, q, r = 1, 2), \quad (1.24)$$

where the nonzero components  $A_{ijnq}^{(k)}$  are determined by formulas

$$A_{1111}^{(k)} = A_{2222}^{(k)} = -\frac{5\lambda_{11}^{c(k)} - 3\lambda_{12}^{c(k)}}{8(\lambda_{11}^{c(k)} - \lambda_{12}^{c(k)})\lambda_{11}^{c(k)}}; \quad A_{1122}^{(k)} = A_{2211}^{(k)} = \frac{\lambda_{11}^{c(k)} + \lambda_{12}^{c(k)}}{8(\lambda_{11}^{c(k)} - \lambda_{12}^{c(k)})\lambda_{11}^{c(k)}};$$

$$A_{1212}^{(k)} = A_{2121}^{(k)} = A_{1221}^{(k)} = A_{2112}^{(k)} = -\frac{3\lambda_{11}^{c(k)} - \lambda_{12}^{c(k)}}{8(\lambda_{11}^{c(k)} - \lambda_{12}^{c(k)})\lambda_{11}^{c(k)}};$$

$$A_{1313}^{(k)} = A_{2323}^{(k)} = A_{3131}^{(k)} = A_{3232}^{(k)} = A_{1331}^{(k)} = A_{2332}^{(k)} = A_{3113}^{(k)} = A_{3223}^{(k)} = -\frac{1}{\lambda_{44}^{c(k)}}. \quad (1.25)$$

Solving equation (1.24) relatively  $\langle \varepsilon_{ij}^{\nu} \rangle^{(k)}$  ( $\nu = 1, 2$ ), we get an expression for the average component deformations in the subsystem  $\langle \varepsilon_{ij} \rangle^{(k)}$  and temperature  $\theta$

$$\langle \varepsilon^1 \rangle^{(k)} = [I + c_2^{(k)} Q^{(k)} (\lambda_1^{(k)} - \lambda_2^{(k)})] \langle \varepsilon \rangle^{(k)} - c_2^{(k)} Q^{(k)} (\beta_1^{(k)} - \beta_2^{(k)}) \theta;$$

$$\langle \varepsilon^2 \rangle^{(k)} = [I - c_1^{(k)} Q^{(k)} (\lambda_1^{(k)} - \lambda_2^{(k)})] \langle \varepsilon \rangle^{(k)} + c_1^{(k)} Q^{(k)} (\beta_1^{(k)} - \beta_2^{(k)}) \theta, \quad (1.26)$$

where  $I$  – unitary operator of the fourth rank, or in index form

$$\begin{aligned} \langle \varepsilon_{ij}^1 \rangle^{(k)} = & \langle \varepsilon_{ij} \rangle^{(k)} + c_2^{(k)} [(\lambda_{12}^{(k)} - \lambda_2) \langle \varepsilon_{rr} \rangle^{(k)} + (\lambda_{13}^{(k)} - \lambda_2) \langle \varepsilon_{33} \rangle^{(k)}] Q_{ijll}^{(k)} \delta_{ij} + \\ & + c_2^{(k)} [(\lambda_{11}^{(k)} - \lambda_{12}^{(k)}) - 2\mu_2] Q_{ijmn}^{(k)} \langle \varepsilon_{mn} \rangle^{(k)} - c_2^{(k)} (\beta_1^{(k)} - \beta_2) Q_{ijll}^{(k)} \theta \delta_{ij}; \end{aligned}$$

$$\langle \varepsilon_{i3}^1 \rangle^{(k)} = \langle \varepsilon_{i3} \rangle^{(k)} + 2c_2^{(k)} (\lambda_{44}^{(k)} - \mu_2) Q_{i3m3}^{(k)} \langle \varepsilon_{m3} \rangle^{(k)};$$

$$\begin{aligned} \langle \varepsilon_{ij}^2 \rangle^{(k)} = & \langle \varepsilon_{ij} \rangle^{(k)} - c_1^{(k)} [(\lambda_{12}^{(k)} - \lambda_2) \langle \varepsilon_{rr} \rangle^{(k)} + (\lambda_{13}^{(k)} - \lambda_2) \langle \varepsilon_{33} \rangle^{(k)}] Q_{ijll}^{(k)} \delta_{ij} - \\ & - c_1^{(k)} [(\lambda_{11}^{(k)} - \lambda_{12}^{(k)}) - 2\mu_2] Q_{ijmn}^{(k)} \langle \varepsilon_{mn} \rangle^{(k)} + c_1^{(k)} (\beta_1^{(k)} - \beta_2) Q_{ijll}^{(k)} \theta \delta_{ij}; \end{aligned}$$

$$\langle \varepsilon_{i3}^2 \rangle^{(k)} = \langle \varepsilon_{i3} \rangle^{(k)} - 2c_1^{(k)} (\lambda_{44}^{(k)} - \mu_2) Q_{i3m3}^{(k)} \langle \varepsilon_{m3} \rangle^{(k)}$$

$$(i, j, l, m, n, r = 1, 2), \quad (1.27)$$

where the nonzero components of the transverse isotropic tensor  $Q_{ijmn}^{(k)}$  have the appearance

$$\begin{aligned} Q_{1111}^{(k)} + Q_{1122}^{(k)} = Q_{2211}^{(k)} + Q_{2222}^{(k)} = & - \frac{1}{2c_1^{(k)} (\lambda_2 + \mu_2) + c_2^{(k)} (\lambda_{11}^{(k)} + \lambda_{12}^{(k)}) + (\lambda_{11}^{c(k)} - \lambda_{12}^{c(k)})}; \\ Q_{1212}^{(k)} = Q_{2121}^{(k)} = Q_{2112}^{(k)} = Q_{1221}^{(k)} = \\ = & - \frac{1}{2 \left[ 2c_1^{(k)} \mu_2 + c_2^{(k)} (\lambda_{11}^{(k)} - \lambda_{12}^{(k)}) + \frac{(\lambda_{11}^{c(k)} - \lambda_{12}^{c(k)}) (\lambda_{11}^{(k)} + \lambda_{12}^{c(k)})}{3\lambda_{11}^{c(k)} - \lambda_{12}^{c(k)}} \right]}; \\ Q_{1313}^{(k)} = Q_{2323}^{(k)} = Q_{1331}^{(k)} = Q_{2332}^{(k)} = Q_{3113}^{(k)} = Q_{3223}^{(k)} = Q_{1331}^{(k)} = Q_{2332}^{(k)} = \\ = & - \frac{1}{4(2c_1^{(k)} \mu_2 + c_2^{(k)} \lambda_{44}^{(k)} + \lambda_{44}^{c(k)})}. \end{aligned} \quad (1.28)$$



Let's determine from this system the average deformations of the components in the subsystem  $\langle \varepsilon_{ij}^1 \rangle^{(k)}$  and  $\langle \varepsilon_{ij}^2 \rangle^{(k)}$  as functions of average deformations of the composite  $\langle \varepsilon_{ij} \rangle^{(k)}$  and substitute in expression (1.6). As a result, we will obtain the dependence of macrostresses in the subsystem on macrodeformations in it

Let's substitute the expressions (1.27) for the average deformations of subsystem components  $\langle \varepsilon_{ij}^1 \rangle^{(k)}$  and  $\langle \varepsilon_{ij}^2 \rangle^{(k)}$  into expressions (1.6), we will find the dependences between the average stresses  $\langle \sigma_{ij} \rangle^{(k)}$ , deformations  $\langle \varepsilon_{ij} \rangle^{(k)}$  and temperature  $\theta$  in the subsystem

$$\begin{aligned} \langle \sigma_{pq} \rangle^{(k)} &= (\lambda_{11}^{*(k)} - \lambda_{12}^{*(k)}) \langle \varepsilon_{pq} \rangle^{(k)} + (\lambda_{12}^{*(k)} \langle \varepsilon_{rr} \rangle^{(k)} + \lambda_{13}^{*(k)} \langle \varepsilon_{33} \rangle^{(k)} - \beta_1^{*(k)} \theta) \delta_{pq}; \\ \langle \sigma_{33} \rangle^{(k)} &= \lambda_{13}^{*(k)} \langle \varepsilon_{rr} \rangle^{(k)} + \lambda_{33}^{*(k)} \langle \varepsilon_{33} \rangle^{(k)} - \beta_3^{*(k)} \theta; \\ \langle \sigma_{p3} \rangle^{(k)} &= 2\lambda_{44}^{*(k)} \langle \varepsilon_{p3} \rangle^{(k)} \quad (p, q, r = 1, 2), \end{aligned} \quad (1.29)$$

and the expressions for the effective thermoelastic characteristics of the subsystem have the form [1, 4]

$$\begin{aligned} \lambda_{11}^{*(k)} + \lambda_{12}^{*(k)} &= c_1^{(k)} (\lambda_{11}^{(k)} + \lambda_{12}^{(k)}) + 2c_2^{(k)} (\lambda_2 + \mu_2) - \\ &\quad - \frac{c_1^{(k)} c_2^{(k)} (\lambda_{11}^{(k)} + \lambda_{12}^{(k)} - 2\lambda_2 - 2\mu_2)^2}{2c_1^{(k)} (\lambda_2 + \mu_2) + c_2^{(k)} (\lambda_{11}^{(k)} + \lambda_{12}^{(k)}) + 2m^{(k)}}; \\ \lambda_{11}^{*(k)} - \lambda_{12}^{*(k)} &= c_1^{(k)} (\lambda_{11}^{(k)} - \lambda_{12}^{(k)}) + 2c_2^{(k)} \mu_2 - \frac{c_1^{(k)} c_2^{(k)} (\lambda_{11}^{(k)} - \lambda_{12}^{(k)} - 2\mu_2)^2}{2c_1^{(k)} \mu_2 + c_2^{(k)} (\lambda_{11}^{(k)} - \lambda_{12}^{(k)}) + \frac{2m^{(k)} n^{(k)}}{n^{(k)} + 2m^{(k)}}}; \\ \lambda_{13}^{*(k)} &= c_1^{(k)} \lambda_{13}^{(k)} + c_2^{(k)} \lambda_2 - \frac{c_1^{(k)} c_2^{(k)} (\lambda_{11}^{(k)} + \lambda_{12}^{(k)} - 2\lambda_2 - 2\mu_2) (\lambda_{13}^{(k)} - \lambda_2)}{2c_1^{(k)} (\lambda_2 + \mu_2) + c_2^{(k)} (\lambda_{11}^{(k)} + \lambda_{12}^{(k)}) + 2m^{(k)}}; \end{aligned}$$

$$\lambda_{33}^{*(k)} = c_1^{(k)} \lambda_{33}^{(k)} + c_2^{(k)} (\lambda_2 + 2\mu_2) - \frac{2c_1^{(k)} c_2^{(k)} (\lambda_{13}^{(k)} - \lambda_2)^2}{2c_1^{(k)} (\lambda_2 + \mu_2) + c_2^{(k)} (\lambda_{11}^{(k)} + \lambda_{12}^{(k)}) + 2m^{(k)}};$$

$$\lambda_{44}^{*(k)} = c_1^{(k)} \lambda_{44}^{(k)} + c_2^{(k)} \mu_2 - \frac{c_1^{(k)} c_2^{(k)} (\lambda_{44}^{(k)} - \mu_2)^2}{c_1^{(k)} \mu_2 + c_2^{(k)} \lambda_{44}^{(k)} + s^{(k)}};$$

$$\beta_1^{*(k)} = c_1^{(k)} \beta_1^{(k)} + c_2^{(k)} \beta_2 - \frac{c_1^{(k)} c_2^{(k)} (\lambda_{11}^{(k)} + \lambda_{12}^{(k)} - 2\lambda_2 - 2\mu_2)(\beta_1^{(k)} - \beta_2)}{2c_1^{(k)} (\lambda_2 + \mu_2) + c_2^{(k)} (\lambda_{11}^{(k)} + \lambda_{12}^{(k)}) + 2m^{(k)}};$$

$$\beta_3^{*(k)} = c_1^{(k)} \beta_3^{(k)} + c_2^{(k)} \beta_2 - \frac{2c_1^{(k)} c_2^{(k)} (\lambda_{13}^{(k)} - \lambda_2)(\beta_1^{(k)} - \beta_2)}{2c_1^{(k)} (\lambda_2 + \mu_2) + c_2^{(k)} (\lambda_{11}^{(k)} + \lambda_{12}^{(k)}) + 2m^{(k)}}, \quad (1.30)$$

Where

$$2m^{(k)} = c_1^{(k)} (\lambda_{11}^{(k)} - \lambda_{12}^{(k)}) + 2c_2^{(k)} \mu_2; \quad 2n^{(k)} = c_1^{(k)} (\lambda_{11}^{(k)} + \lambda_{12}^{(k)}) + 2c_2^{(k)} (\lambda_2 + \mu_2);$$

$$s^{(k)} = c_1^{(k)} \lambda_{44}^{(k)} + c_2^{(k)} \mu_2, \quad (1.31)$$

if the stiffness of the matrix is greater than the stiffness of the fibers, and

$$2m^{(k)} = \left( \frac{c_1^{(k)}}{\lambda_{11}^{(k)} - \lambda_{12}^{(k)}} + \frac{c_2^{(k)}}{2\mu_2} \right)^{-1}; \quad 2n^{(k)} = \left( \frac{c_1^{(k)}}{\lambda_{11}^{(k)} + \lambda_{12}^{(k)}} + \frac{c_2^{(k)}}{2(\lambda_2 + \mu_2)} \right)^{-1};$$

$$s^{(k)} = \left( \frac{c_1^{(k)}}{\lambda_{44}^{(k)}} + \frac{c_2^{(k)}}{\mu_2} \right)^{-1}, \quad (1.32)$$

if the stiffness of the fibers is greater than the stiffness of the matrix.

If the properties of fibers in all directions are the same, then

$$\lambda_{ij}^{(k)} = \lambda_{ij}^1; \quad \beta_i^{(k)} = \beta_i^1, \quad (1.33)$$

and expressions (1.30) – (1.32) from the index  $k$  do not depend

Effective characteristics (1.30) – (1.32) are the components of tensors of effective deformation characteristics in the local coordinate system  $x_i^{(k)}$ , where is  $x_3^{(k)}$  parallel to the fibers  $k$ -th direction Let's go to the general coordinate system according to the transformation

$$x_i = \alpha_{ij}^{(k)} x_j^{(k)}; \quad x_i^{(k)} = \alpha_{ji}^k x_j; \quad (1.34)$$

where

$$\alpha_{11}^{(k)} = \cos \theta_k \cos \varphi_k; \quad \alpha_{12}^{(k)} = -\sin \varphi_k; \quad \alpha_{13}^{(k)} = \sin \theta_k \cos \varphi_k;$$

$$\alpha_{21}^{(k)} = \cos \theta_k \sin \varphi_k; \quad \alpha_{22}^k = \cos \varphi_k; \quad \alpha_{23}^k = \sin \theta_k \sin \varphi_k;$$

$$\alpha_{31}^{(k)} = -\sin \theta_k; \quad \alpha_{32}^{(k)} = 0; \quad \alpha_{33}^{(k)} = \cos \theta_k. \quad (1.35)$$

Then the tensors of the effective deformation characteristics  $\lambda_{ijlm}^{*(k)}$  and thermal stresses  $\beta_{ij}^{*(k)}$  in the general coordinate system are expressed through the corresponding tensors  $\lambda_{ijlm}^{*(k)}$ ,  $\beta_{ij}^{*(k)}$  in the local coordinate system by ratios

$$\lambda_{ijlm}^{*(k)} = \alpha_{ip}^{(k)} \alpha_{jq}^{(k)} \alpha_{lr}^{(k)} \alpha_{ms}^{(k)} \lambda_{pqrs}^{*(k)}; \quad \beta_{ij}^{*(k)} = \alpha_{ip}^{(k)} \alpha_{jq}^{(k)} \beta_{pq}^{*(k)}. \quad (1.36)$$

The effective characteristics of the entire system according to the Voigt scheme are determined by formulas

$$\lambda_{ijlm}^{**(k)} = \frac{1}{c_1} \sum_{k=1}^N c_1^{(k)} \lambda_{ijlm}^{*(k)}; \quad \beta_{ij}^{**(k)} = \frac{1}{c_1} \sum_{k=1}^N c_1^{(k)} \beta_{ij}^{*(k)}. \quad (1.37)$$

Substituting (1.36) into (1.37) and passing to matrix notation, we obtain

$$\begin{aligned} \lambda_{ijlm}^{**} = & \frac{1}{c_1} \sum_{k=1}^N c_1^{(k)} \{ [\alpha_{i1}^{(k)} \alpha_{j1}^{(k)} \alpha_{l1}^{(k)} \alpha_{m1}^{(k)} + \alpha_{i2}^{(k)} \alpha_{j2}^{(k)} \alpha_{l2}^{(k)} \alpha_{m2}^{(k)} + \\ & + \frac{1}{2} (\alpha_{i1}^{(k)} \alpha_{j2}^{(k)} + \alpha_{i2}^{(k)} \alpha_{j1}^{(k)}) (\alpha_{l1}^{(k)} \alpha_{m2}^{(k)} + \alpha_{l2}^{(k)} \alpha_{m1}^{(k)}) ] \lambda_{11}^{*(k)} + \\ & + [\alpha_{i1}^{(k)} \alpha_{j1}^{(k)} \alpha_{l2}^{(k)} \alpha_{m2}^{(k)} + \alpha_{i2}^{(k)} \alpha_{j2}^{(k)} \alpha_{l1}^{(k)} \alpha_{m1}^{(k)} - \\ & - \frac{1}{2} (\alpha_{i1}^{(k)} \alpha_{j2}^{(k)} + \alpha_{i2}^{(k)} \alpha_{j1}^{(k)}) (\alpha_{l1}^{(k)} \alpha_{m2}^{(k)} + \alpha_{l2}^{(k)} \alpha_{m1}^{(k)}) ] \lambda_{12}^{*(k)} + \\ & + \alpha_{i3}^{(k)} \alpha_{j3}^{(k)} \alpha_{l3}^{(k)} \alpha_{m3}^{(k)} \lambda_{33}^{*(k)} + \\ & + [ (\alpha_{i1}^{(k)} \alpha_{j1}^{(k)} + \alpha_{i2}^{(k)} \alpha_{j2}^{(k)}) \alpha_{l3}^{(k)} \alpha_{m3}^{(k)} + \alpha_{i3}^{(k)} \alpha_{j3}^{(k)} (\alpha_{l1}^{(k)} \alpha_{m1}^{(k)} + \alpha_{l2}^{(k)} \alpha_{m2}^{(k)}) ] \lambda_{13}^{*(k)} + \\ & + [ (\alpha_{i1}^{(k)} \alpha_{j3}^{(k)} + \alpha_{i3}^{(k)} \alpha_{j1}^{(k)}) (\alpha_{l1}^{(k)} \alpha_{m3}^{(k)} + \alpha_{l3}^{(k)} \alpha_{m1}^{(k)}) + \\ & + (\alpha_{i2}^{(k)} \alpha_{j3}^{(k)} + \alpha_{i3}^{(k)} \alpha_{j2}^{(k)}) (\alpha_{l2}^{(k)} \alpha_{m3}^{(k)} + \alpha_{l3}^{(k)} \alpha_{m2}^{(k)}) ] \lambda_{44}^{*(k)} \}; \\ \beta_{ij}^{**} = & \frac{1}{c_1} \sum_{k=1}^N c_1^{(k)} [ (\alpha_{i1}^{(k)} \alpha_{j1}^{(k)} + \alpha_{i2}^{(k)} \alpha_{j2}^{(k)}) \beta_1^{*(k)} + \alpha_{i3}^{(k)} \alpha_{j3}^{(k)} \beta_3^{*(k)} ]. \end{aligned} \quad (1.38)$$

Formulas (1.30)– (1.32), (1.38) determine the effective deformation properties of the spatially reinforced material due to the properties of the fibers and the matrix. If the properties of the fibers and their volume content in each direction are the same, then

$$c_1^{(k)} = \frac{c_1}{N}; \quad \lambda_{ij}^{*(k)} = \lambda_{ij}^*; \quad \beta_i^{*(k)} = \beta_i^*, \quad (1.39)$$

which simplifies the calculation.

You can find deformations  $\langle \varepsilon_{ij}^v \rangle$  and tension  $\langle \sigma_{ij}^v \rangle$  in components at specified macrodeformations  $\langle \varepsilon_{ij} \rangle$  or macrostresses  $\langle \sigma_{ij} \rangle$ .

For this we will use:

relationships between macrostresses  $\langle \sigma_{ij} \rangle$ , macrodeformations  $\langle \varepsilon_{lm} \rangle$  and temperature  $\theta$

$$\langle \sigma_{ij} \rangle = \lambda_{ijlm}^{**} \langle \varepsilon_{lm} \rangle - \beta_{ij}^{**} \theta, \quad (1.40)$$

ratios between average stresses  $\langle \sigma_{ij}^1 \rangle$ , deformations  $\langle \varepsilon_{lm}^1 \rangle$  and temperature  $\theta$  in the system of spatially arranged fibers

$$\langle \sigma_{ij}^1 \rangle = \lambda_{ijlm}^{1*} \langle \varepsilon_{lm}^1 \rangle - \beta_{ij}^{1*} \theta, \quad (1.41)$$

ratios between average stresses  $\langle \sigma_{ij}^2 \rangle$ , deformities  $\langle \varepsilon_{lm}^2 \rangle$  and temperature  $\theta$  in the matrix

$$\langle \sigma_{ij}^2 \rangle = \lambda_{ijlm}^2 \langle \varepsilon_{lm}^2 \rangle - \beta_{ij}^2 \theta; \quad \lambda_{ijlm}^2 = \lambda_2 \delta_{ij} \delta_{lm} + \mu_2 (\delta_{il} \delta_{jm} + \delta_{im} \delta_{jl}), \quad (1.42)$$

relationships between macrostresses  $\langle \sigma_{ij} \rangle$  and average stresses in the fiber system  $\langle \sigma_{ij}^1 \rangle$  and in the matrix  $\langle \sigma_{ij}^2 \rangle$

$$\langle \sigma_{ij} \rangle = c_1 \langle \sigma_{ij}^1 \rangle + c_2 \langle \sigma_{ij}^2 \rangle, \quad (1.43)$$

ratios between macrodeformations  $\langle \varepsilon_{ij} \rangle$  and average deformations in the fiber system  $\langle \varepsilon_{ij}^1 \rangle$  and in the matrix  $\langle \varepsilon_{ij}^2 \rangle$

$$\langle \varepsilon_{ij} \rangle = c_1 \langle \varepsilon_{ij}^1 \rangle + c_2 \langle \varepsilon_{ij}^2 \rangle, \quad (1.44)$$

note that the dependences between the characteristics of the system of spatially arranged fibers and the characteristics of unidirectional fibers are described by the same law as the dependences between the effective characteristics of the material and the characteristics of the unidirectional fibrous material.

Using the relations (1.40) – (1.44), we obtain the dependences between the average deformations in the components  $\langle \sigma_{ij}^1 \rangle$  and macrodeformations  $\langle \varepsilon_{ij} \rangle$

$$\begin{aligned} c_1 \langle \varepsilon_{ij}^1 \rangle &= (\lambda_{ijpq}^{1*} - \lambda_{ijpq}^2)^{-1} [(\lambda_{pqlm}^{**} - \lambda_{pqlm}^2) \langle \varepsilon_{lm} \rangle - (\beta_{pq}^{**} - \langle \beta_{pq} \rangle) \theta], \\ c_2 \langle \varepsilon_{ij}^2 \rangle &= -(\lambda_{ijpq}^{1*} - \lambda_{ijpq}^2)^{-1} [(\lambda_{pqlm}^{**} - \lambda_{pqlm}^{1*}) \langle \varepsilon_{lm} \rangle - (\beta_{pq}^{**} - \langle \beta_{pq} \rangle) \theta]. \end{aligned} \quad (1.45)$$

and between the average stresses in the components  $\langle \sigma_{ij}^1 \rangle$ ,  $\langle \sigma_{ij}^2 \rangle$  and macrostresses  $\langle \sigma_{ij} \rangle$

$$\begin{aligned} c_1 \langle \sigma_{ij}^1 \rangle &= \lambda_{ijpq}^{1*} (\lambda_{ijpq}^{1*} - \lambda_{ijpq}^2)^{-1} [(\lambda_{pqlm}^{**} - \lambda_{pqlm}^2) \langle \varepsilon_{lm} \rangle - (\beta_{pq}^{**} - \langle \beta_{pq} \rangle) \theta] - \beta_{ij}^{1*} \theta, \\ c_2 \langle \sigma_{ij}^2 \rangle &= -\lambda_{ijpq}^2 (\lambda_{ijpq}^{1*} - \lambda_{ijpq}^2)^{-1} [(\lambda_{pqlm}^{**} - \lambda_{pqlm}^2) \langle \varepsilon_{lm} \rangle - (\beta_{pq}^{**} - \langle \beta_{pq} \rangle) \theta] - \beta_{ij}^2 \theta. \end{aligned} \quad (1.46)$$

### **1.3 Determination of the effective deformable properties of fibrous materials in the case of fibers located in a plane $x_1x_2$ along the sides of the square and its diagonals**

Consider a characteristic type of spatial reinforcement. Let all fibers have the same properties. Let's determine the effective elastic properties and stress-strain state of fibrous materials in a typical case of spatial reinforcement. Let the fibers be located along the sides of the square and its diagonals and have the same volume content in each direction, i.e.

$$N = 4; \quad c_1^{(1)} = c_1^{(2)} = c_1^{(3)} = c_1^{(4)} = \frac{1}{4}; \quad \theta_1 = \theta_2 = \theta_3 = \theta_4 = \frac{\pi}{2}; \quad \varphi_1 = 0; \quad \varphi_2 = \frac{\pi}{4}; \quad \varphi_3 = \frac{\pi}{2}; \quad \varphi_4 = \frac{3\pi}{4};$$

$$\alpha_{11}^{(1)} = 0; \quad \alpha_{12}^{(1)} = 0; \quad \alpha_{13}^{(1)} = 1;$$

$$\alpha_{21}^{(1)} = 0; \quad \alpha_{22}^{(1)} = 1; \quad \alpha_{23}^{(1)} = 0;$$

$$\alpha_{31}^{(1)} = -1; \quad \alpha_{32}^{(1)} = 0; \quad \alpha_{33}^{(1)} = 0.$$

$$\alpha_{11}^{(2)} = 0; \quad \alpha_{12}^{(2)} = -\frac{\sqrt{2}}{2}; \quad \alpha_{13}^{(2)} = \frac{\sqrt{2}}{2};$$

$$\alpha_{21}^{(2)} = 0; \quad \alpha_{22}^{(2)} = \frac{\sqrt{2}}{2}; \quad \alpha_{23}^{(2)} = \frac{\sqrt{2}}{2};$$

$$\alpha_{31}^{(2)} = -1; \quad \alpha_{32}^{(2)} = 0; \quad \alpha_{33}^{(2)} = 0.$$

$$\alpha_{11}^{(3)} = 0; \quad \alpha_{12}^{(3)} = -1; \quad \alpha_{13}^{(3)} = 0;$$

$$\alpha_{21}^{(3)} = 0; \quad \alpha_{22}^{(3)} = 0; \quad \alpha_{23}^{(3)} = 1;$$

$$\alpha_{31}^{(3)} = -1; \quad \alpha_{32}^{(3)} = 0; \quad \alpha_{33}^{(3)} = 0.$$

$$\alpha_{11}^{(4)} = 0; \quad \alpha_{12}^{(4)} = -\frac{\sqrt{2}}{2}; \quad \alpha_{13}^{(4)} = -\frac{\sqrt{2}}{2};$$

$$\alpha_{21}^{(4)} = 0; \quad \alpha_{22}^{(4)} = -\frac{\sqrt{2}}{2}; \quad \alpha_{23}^{(4)} = \frac{\sqrt{2}}{2};$$

$$\alpha_{31}^{(4)} = -1; \quad \alpha_{32}^{(4)} = 0; \quad \alpha_{33}^{(4)} = 0. \tag{1.47}$$

Substituting (1.47) into (1.38), we get

$$\lambda_{11}^{**} = \lambda_{22}^{**} = \frac{1}{8}(3\lambda_{11}^* + 2\lambda_{13}^* + 3\lambda_{33}^* + 4\lambda_{44}^*);$$

$$\lambda_{33}^{**} = \lambda_{11}^*;$$

$$\lambda_{12}^{**} = \frac{1}{8}(\lambda_{11}^* + 6\lambda_{13}^* + \lambda_{33}^* - 4\lambda_{44}^*);$$

$$\lambda_{13}^{**} = \lambda_{23}^{**} = \frac{1}{2}(\lambda_{12}^* + \lambda_{13}^*);$$



$$\lambda_{44}^{**} = \lambda_{55}^{**} = \frac{1}{4}(\lambda_{11}^{*} - \lambda_{12}^{*} + 2\lambda_{44}^{*}); \quad \lambda_{66}^{**} = \frac{1}{2}(\lambda_{11}^{*} - \lambda_{12}^{*});$$

$$\beta_{11}^{**} = \beta_{22}^{**} = \frac{1}{2}(\beta_1^{*} + \beta_3^{*}); \quad \beta_{33}^{**} = \beta_1^{*}, \quad (1.48)$$

where  $\lambda_{11}^{*}, \lambda_{12}^{*}, \lambda_{13}^{*}, \lambda_{33}^{*}, \lambda_{44}^{*}, \lambda_{66}^{*}, \beta_1^{*}, \beta_3^{*}$  are determined by formulas (1.30) – (1.33), (1.39). That is, the material has hexagonal symmetry and dependencies between macrostresses  $\langle \sigma_{ij} \rangle$ , macrodeformations  $\langle \varepsilon_{ij} \rangle$  and temperature  $\theta$  have the appearance

$$\langle \sigma_{pq} \rangle = (\lambda_{11}^{**} - \lambda_{12}^{**}) \langle \varepsilon_{pq} \rangle + (\lambda_{12}^{**} \langle \varepsilon_{rr} \rangle + \lambda_{13}^{**} \langle \varepsilon_{33} \rangle) \delta_{pq} - \beta_1^{**} \theta \delta_{pq};$$

$$\langle \sigma_{33} \rangle = \lambda_{13}^{**} \langle \varepsilon_{rr} \rangle + \lambda_{33}^{**} \langle \varepsilon_{33} \rangle - \beta_3^{**} \theta;$$

$$\langle \sigma_{p3} \rangle = 2\lambda_{44}^{**} \langle \varepsilon_{p3} \rangle$$

$$(p, q, r = 1, 2, s = 1, 2, 3), \quad (1.49)$$

Dependencies between stresses  $\langle \sigma_{ij}^1 \rangle$  deformations  $\langle \varepsilon_{ij}^1 \rangle$  and temperature  $\theta$  in components based on (1.29), (1.41), (1.42) have the form: in fibers

$$\langle \sigma_{pq}^1 \rangle = (\lambda_{11}^1 - \lambda_{12}^1) \langle \varepsilon_{pq}^1 \rangle$$

$$+ (\lambda_{12}^1 \langle \varepsilon_{rr}^1 \rangle + \lambda_{13}^1 \langle \varepsilon_{33}^1 \rangle - \beta_1^1 \theta) \delta_{pq};$$

$$\langle \sigma_{33}^1 \rangle = \lambda_{13}^1 \langle \varepsilon_{rr}^1 \rangle + \lambda_{33}^1 \langle \varepsilon_{33}^1 \rangle - \beta_3^1 \theta;$$

$$\langle \sigma_{p3}^1 \rangle = 2\lambda_{44}^1 \langle \varepsilon_{p3}^1 \rangle \quad (p, q, r = 1, 2), \quad (1.50)$$

in the matrix

$$\langle \sigma_{ij}^2 \rangle = \lambda_2 \langle \varepsilon_{kk}^2 \rangle \delta_{ij} + 2\mu_2 \langle \varepsilon_{ij}^2 \rangle - \beta_2 \theta \delta_{ij} \quad (i, j, k = 1, 2, 3). \quad (1.51)$$

Dependencies between average deformations in components  $\langle \varepsilon_{ij}^1 \rangle$ ,  $\langle \varepsilon_{ij}^2 \rangle$  and macrodeformations  $\langle \varepsilon_{ij} \rangle$  for a material with hexagonal symmetry, we obtain on the basis of the dependences (1.45) in fibers

$$\begin{aligned} \langle \varepsilon_{ij}^1 \rangle &= \frac{\lambda_{11}^{**} - \lambda_{12}^{**} - \lambda_{11}^{1*} + \lambda_{12}^{1*}}{c_1(\lambda_{11}^{1*} - \lambda_{12}^{1*} - 2\mu_2)} \langle \varepsilon_{ij} \rangle + \\ &+ \frac{1}{\Delta_1} \{ [(\lambda_{11}^{**} - \lambda_2 - 2\mu_2)a_1 - (\lambda_{12}^{**} - \lambda_2)a_2 - (\lambda_{13}^{**} - \lambda_2)a_3] \langle \varepsilon_{rr} \rangle + \\ &+ [(\lambda_{13}^{**} - \lambda_2)(a_1 - a_2) - (\lambda_{33}^{**} - \lambda_2 - 2\mu_2)a_3] \langle \varepsilon_{33} \rangle - \\ &- [(\beta_1^{**} - c_1\beta_1^{1*} - c_2\beta_2)(a_1 - a_2) - (\beta_{33}^{**} - c_1\beta_3^{1*} - c_2\beta_2)a_3] \theta \} \delta_{ij}; \\ \langle \varepsilon_{33}^1 \rangle &= \frac{1}{\Delta_1} \{ [(\lambda_{13}^{**} - \lambda_2)a_4 - (\lambda_{11}^{**} + \lambda_{12}^{**} - 2\lambda_2 - 2\mu_2)a_3] \langle \varepsilon_{rr} \rangle + \\ &+ [(\lambda_{33}^{**} - \lambda_2 - 2\mu_2)a_4 - 2(\lambda_{13}^{**} - \lambda_2)a_3] \langle \varepsilon_{33} \rangle - \\ &- [(\beta_{33}^{**} - c_1\beta_3^{1*} - c_2\beta_2)a_4 - 2(\beta_1^{**} - c_1\beta_1^{1*} - c_2\beta_2)a_3] \theta \}; \\ \langle \varepsilon_{i3}^1 \rangle &= \frac{\lambda_{44}^{**} - \mu_2}{c_1(\lambda_{44}^{1*} - \mu_2)} \langle \varepsilon_{i3} \rangle \quad (i, j, r = 1, 2); \end{aligned} \quad (1.52)$$

in the matrix

$$\begin{aligned}
 <\varepsilon_{ij}^2> = \frac{\lambda_{11}^{**} - \lambda_{12}^{**} - \lambda_{11}^{1*} + \lambda_{12}^{1*}}{c_2(2\mu_2 - \lambda_{11}^{1*} + \lambda_{12}^{1*})} <\varepsilon_{ij}> - \\
 &\frac{1}{\Delta_2} \{[(\lambda_{11}^{**} - \lambda_{11}^{1*})a_1 - (\lambda_{12}^{**} - \lambda_{12}^{1*})a_2 - (\lambda_{13}^{**} - \lambda_{13}^{1*})a_3] <\varepsilon_{rr}> + \\
 &+ [(\lambda_{13}^{**} - \lambda_{13}^{1*})(a_1 - a_2) - (\lambda_{33}^{**} - \lambda_{33}^{1*})a_3] <\varepsilon_{33}> - \\
 &- [(\beta_1^{**} - c_1\beta_1^{1*} - c_2\beta_2)(a_1 - a_2) - (\beta_{33}^{**} - c_1\beta_3^{1*} - c_2\beta_2)a_3]\theta\}\delta_{ij}; \\
 <\varepsilon_{33}^2> = -\frac{1}{\Delta_2} \{[(\lambda_{13}^{**} - \lambda_{13}^{1*})a_4 - (\lambda_{11}^{**} + \lambda_{12}^{**} - \lambda_{11}^{1*} - \lambda_{12}^{1*})a_3] <\varepsilon_{rr}> + \\
 &+ [(\lambda_{33}^{**} - \lambda_{33}^{1*})a_4 - 2(\lambda_{13}^{**} - \lambda_{13}^{1*})a_3] <\varepsilon_{33}> - \\
 &- [(\beta_{33}^{**} - c_1\beta_3^{1*} - c_2\beta_2)a_4 - 2(\beta_1^{**} - c_1\beta_1^{1*} - c_2\beta_2)a_3]\theta\}; \\
 <\varepsilon_{i3}^2> = \frac{\lambda_{44}^{**} - \lambda_{44}^{1*}}{c_2(\mu_2 - \lambda_{44}^{1*})} <\varepsilon_{i3}> \quad (i, j, r = 1, 2); \\
 &(1.53)
 \end{aligned}$$

$$\Delta_1 = -c_1(\lambda_{11}^{1*} - \lambda_{12}^{1*} - 2\mu_2) \times [(\lambda_{11}^{1*} + \lambda_{12}^{1*} - 2\lambda_2 - 2\mu_2)(\lambda_{33}^{1*} - \lambda_2 - 2\mu_2) - 2(\lambda_{13}^{1*} - \lambda_2)^2];$$

$$\begin{aligned}
 \Delta_2 &= c_2(\lambda_{11}^{1*} - \lambda_{12}^{1*} - 2\mu_2) \times [(\lambda_{11}^{1*} + \lambda_{12}^{1*} - 2\lambda_2 - 2\mu_2)(\lambda_{33}^{1*} - \lambda_2 - 2\mu_2) - 2(\lambda_{13}^{1*} - \lambda_2)^2]; \\
 a_1 &= (\lambda_{13}^{1*} - \lambda_2)^2 - (\lambda_{12}^{1*} - \lambda_2)(\lambda_{33}^{1*} - \lambda_2 - 2\mu_2);
 \end{aligned}$$

$$a_2 = (\lambda_{13}^{1*} - \lambda_2)^2 - (\lambda_{11}^{1*} - \lambda_2 - 2\mu_2)(\lambda_{33}^{1*} - \lambda_2 - 2\mu_2);$$

$$a_3 = (\lambda_{13}^{1*} - \lambda_2)(\lambda_{11}^{1*} - \lambda_{12}^{1*} - 2\mu_2);$$

$$a_4 = (\lambda_{11}^{1*} + \lambda_{12}^{1*} - 2\lambda_2 - 2\mu_2)(\lambda_{11}^{1*} - \lambda_{12}^{1*} - 2\mu_2), \quad (1.54)$$

Where

$$\lambda_{11}^{1*} = \lambda_{22}^{1*} = \frac{1}{8}(3\lambda_{11}^1 + 2\lambda_{13}^1 + 3\lambda_{33}^1 + 4\lambda_{44}^1); \quad \lambda_{33}^{1*} = \lambda_{11}^1;$$

$$\lambda_{12}^{1*} = \frac{1}{8}(\lambda_{11}^1 + 6\lambda_{13}^1 + \lambda_{33}^1 - 4\lambda_{44}^1);$$

$$\lambda_{13}^{1*} = \lambda_{23}^{1*} = \frac{1}{2}(\lambda_{12}^1 + \lambda_{13}^1);$$

$$\lambda_{44}^{1*} = \lambda_{55}^{1*} = \frac{1}{4}(\lambda_{11}^1 - \lambda_{12}^1 + 2\lambda_{44}^1);$$

$$\beta_{11}^{1*} = \beta_{22}^{1*} = \frac{1}{2}(\beta_1^1 + \beta_3^1); \quad \beta_{33}^{1*} = \beta_1^1, \quad (1.55)$$

Macro deformations  $\langle \varepsilon_{ij} \rangle$  associated with macrostresses  $\langle \sigma_{ij} \rangle$  and temperature  $\theta$  additions

$$\langle \varepsilon_{ij} \rangle = \frac{1 + \nu_{12}^{**}}{E_1^{**}} \langle \sigma_{ij} \rangle - \frac{\nu_{12}^{**}}{E_1^{**}} \langle \sigma_{rr} \rangle \delta_{ij} - \frac{\nu_{13}^{**}}{E_3^{**}} \langle \sigma_{33} \rangle \delta_{ij} + \alpha_1^{**} \theta \delta_{ij};$$

$$\langle \varepsilon_{33} \rangle = \frac{1}{E_3^{**}} \langle \sigma_{33} \rangle - \frac{\nu_{13}^{**}}{E_3^{**}} \langle \sigma_{rr} \rangle + \alpha_3^{**} \theta; \quad \langle \varepsilon_{i3} \rangle = \frac{1}{2G_{13}^{**}} \langle \sigma_{i3} \rangle$$

$$(i, j, r = 1, 2), \quad (1.56)$$

where technical steels are related to thermoelastic characteristics  $\lambda_{ijlm}^{**}$ ,  $\beta_{ij}^{**}$  ratios

$$E_1^{**} = \frac{4\Delta^{**} G_{12}^{**}}{2G_{12}^{**} \lambda_{33}^{**} + \Delta^{**}}; \quad E_3^{**} = \frac{\Delta^{**}}{\lambda_{11}^{**} + \lambda_{12}^{**}};$$

$$G_{12}^{**} = \lambda_{66}^{**} = \frac{1}{2}(\lambda_{11}^{**} - \lambda_{12}^{**}); \quad G_{13}^{**} = \lambda_{44}^{**};$$

$$\nu_{12}^{**} = \frac{E_1^{**}}{2G_{12}^{**}} - 1; \quad \nu_{12}^{**} = \frac{\lambda_{13}^{**}}{\lambda_{11}^{**} + \lambda_{12}^{**}};$$

$$\alpha_1^{**} = \frac{\beta_1^{**} \lambda_{33}^{**} - \beta_3^{**} \lambda_{13}^{**}}{\Delta^{**}}; \quad \alpha_3^{**} = \frac{\beta_3^{**} (\lambda_{11}^{**} + \lambda_{12}^{**}) - 2\beta_1^{**} \lambda_{13}^{**}}{\Delta^{**}};$$

$$\Delta^{**} = (\lambda_{11}^{**} + \lambda_{12}^{**})\lambda_{33}^{**} - 2(\lambda_{13}^{**})^2. \quad (1.57)$$

With the help of computer simulation, a numerical study of the dependence of the deformation of the fiber composite on the volume content of the components was carried out. High-modulus carbon fibers with the characteristics [3] are taken as components, respectively

$$E_1^1 = 8 \text{ GPa}; E_3^1 = 226 \text{ GPa}; \nu_{12}^1 = 0.3; \nu_{13}^1 = 0.2; G_{13}^1 = 60 \text{ GPa};$$

$$\alpha_1^1 = -1 \cdot 10^{-6}(\text{OC})^{-1}; \alpha_3^1 = 18 \cdot 10^{-6}(\text{OC})^{-1} \quad (1.58)$$

and epoxy matrix with characteristics [1, 3]

$$E_2 = 3 \text{ GPa}; \nu_2 = 0.35; \alpha_2 = 45 \cdot 10^{-6}(\text{OC})^{-1}; \sigma_{02} = 0.05 \text{ GPa} \quad (1.59)$$

where  $E_2$ ,  $\nu_2$ ,  $\alpha_2$  — Young's modulus, Poisson's ratio, and thermal deformation coefficient of the matrix, respectively;  $\sigma_{02}$  — the limit of its fluidity;  $E_1^1$  and  $E_3^1$ ,  $\nu_{12}^1$  and  $\nu_{13}^1$ ,  $G_{12}^1$  and  $G_{13}^1$ ,  $\alpha_1^1$  and  $\alpha_3^1$  — respectively transverse and longitudinal Young's

moduli, Poisson's ratios, fiber shear moduli and thermal deformation coefficients, which are associated with  $\lambda_{11}^1$ ,  $\lambda_{12}^1$ ,  $\lambda_{13}^1$ ,  $\lambda_{33}^1$ ,  $\lambda_{44}^1$ ,  $\beta_1^1$ ,  $\beta_3^1$  formulas

$$\lambda_{11}^1 + \lambda_{12}^1 = E_1^1 E_3^1 \left[ E_3^1 \left( 2 - \frac{E_1^1}{2G_{12}^1} \right) - 2E_1^1 (\nu_{13}^1)^2 \right]^{-1}; \quad \lambda_{11}^1 - \lambda_{12}^1 = 2G_{12}^1;$$

$$\lambda_{13}^1 = \nu_{13}^1 (\lambda_{11}^1 + \lambda_{12}^1); \quad \lambda_{33}^1 = (\lambda_{11}^1 + \lambda_{12}^1) \frac{E_3^1}{E_1^1} \left( 2 - \frac{E_1^1}{2G_{12}^1} \right); \quad \lambda_{44}^1 = G_{13}^1;$$

$$\beta_1^1 = (\lambda_{11}^1 + \lambda_{12}^1) \alpha_1^1 + \lambda_{13}^1 \alpha_3^1; \quad \beta_3^1 = 2\lambda_{13}^1 \alpha_1^1 + \lambda_{33}^1 \alpha_3^1. \quad (1.60)$$

Based on the obtained ratios, graphs of the dependence of the thermoelastic properties of the material on the volume concentration of fibers were constructed. In figures 2 – 9  $E_1^1$ ,  $E_3^1$ ,  $\nu_{12}^1$ ,  $\nu_{13}^1$ ,  $G_{12}^1$ ,  $G_{13}^1$ ,  $\alpha_1^1$ ,  $\alpha_3^1$  from  $c_1$ .

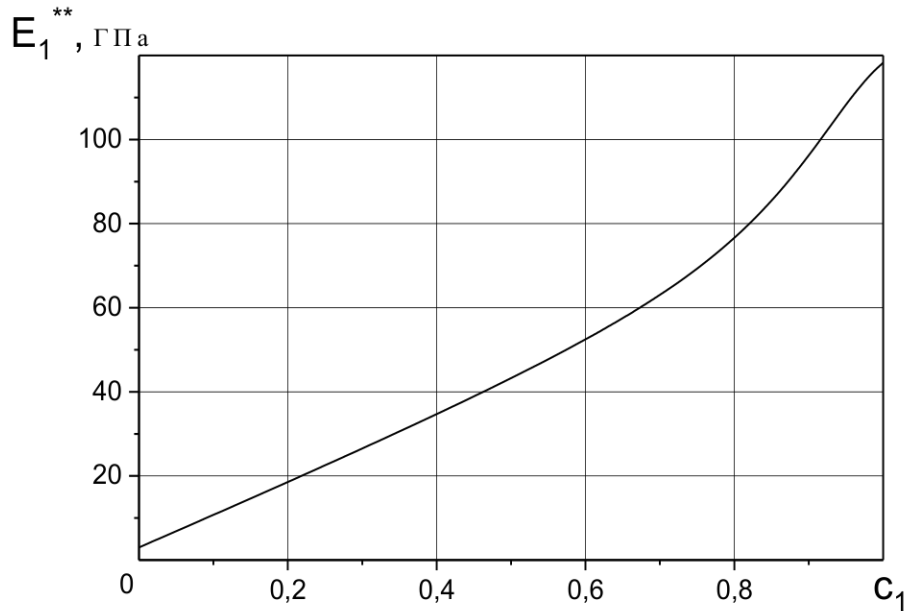


Figure 1.2.

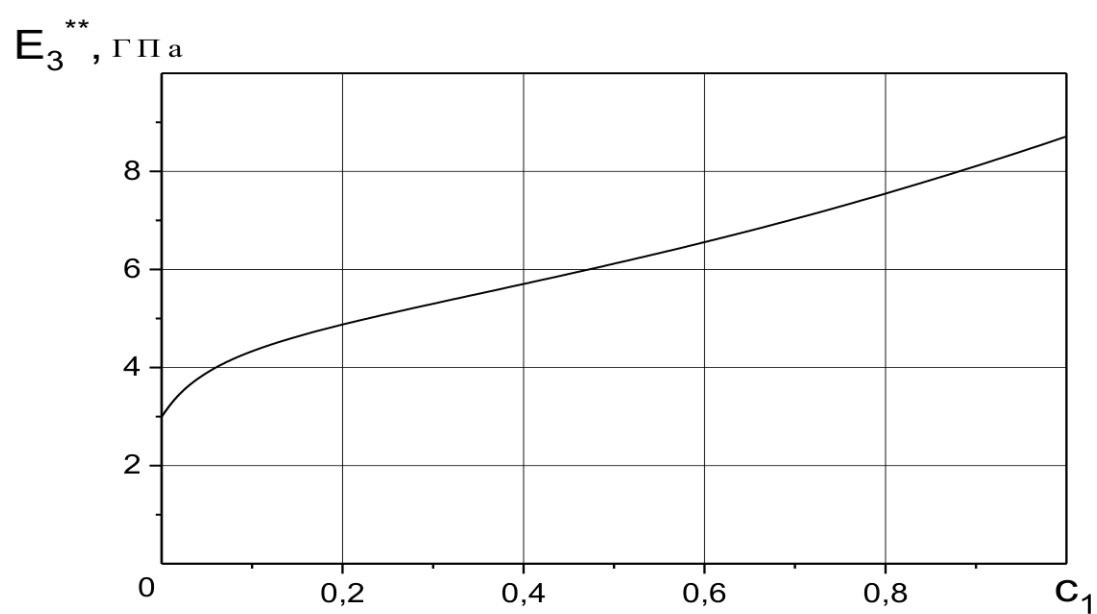


Figure 1.3.

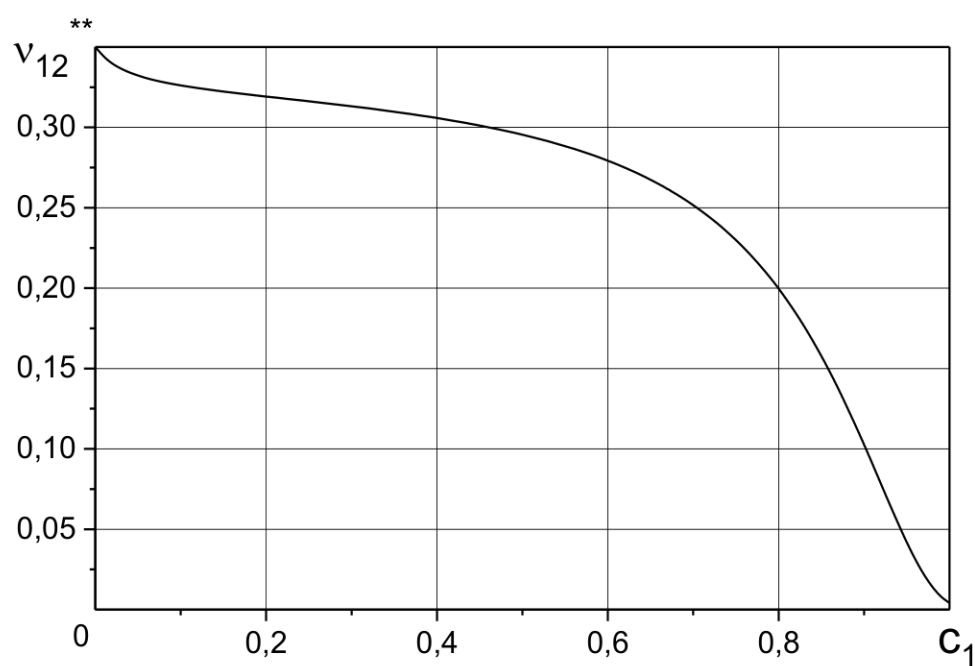


Figure 1.4.

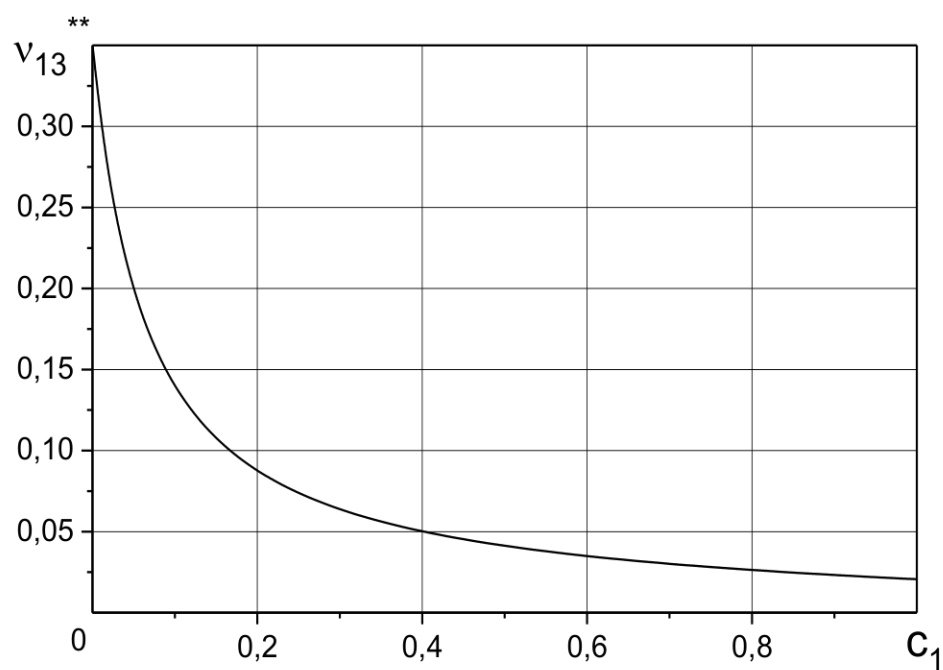


Figure 1.5.

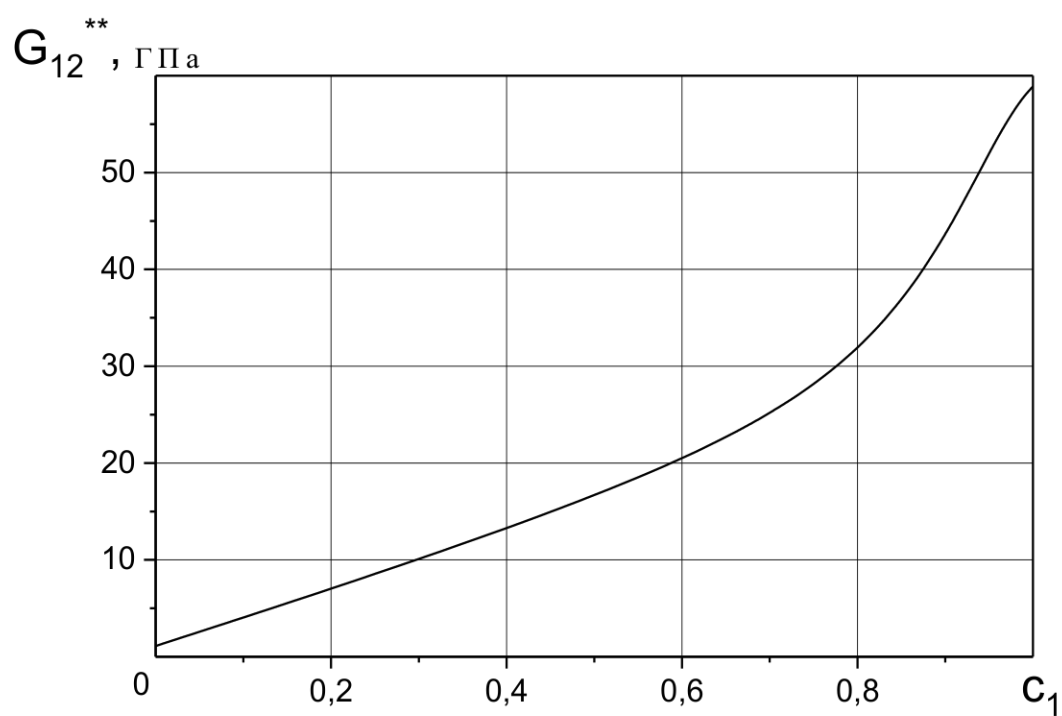


Figure 1.6.



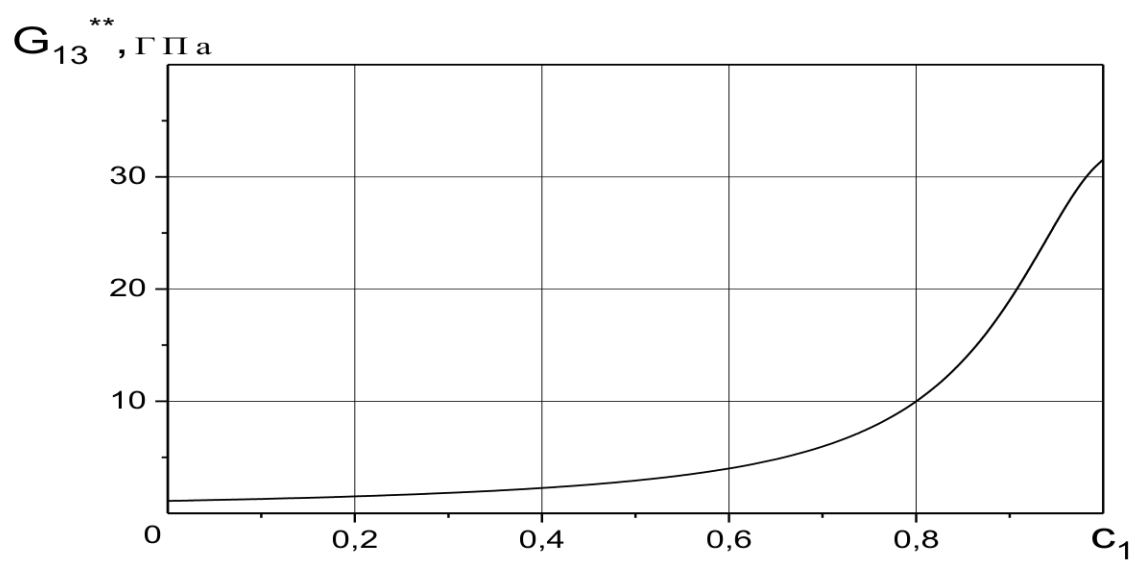


Figure 1.7.

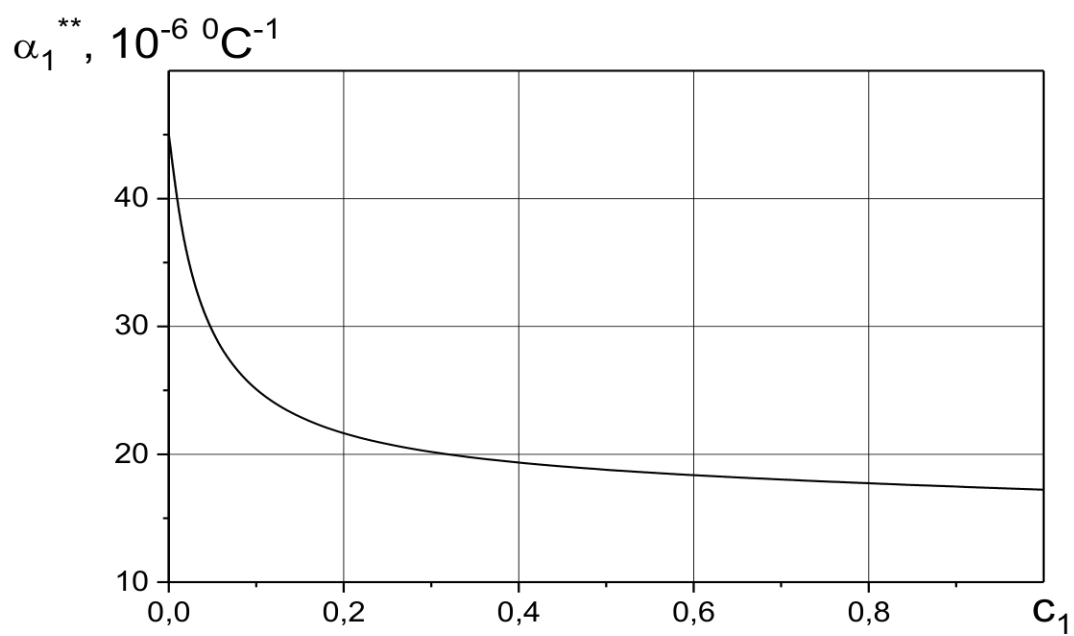


Figure 1.8.

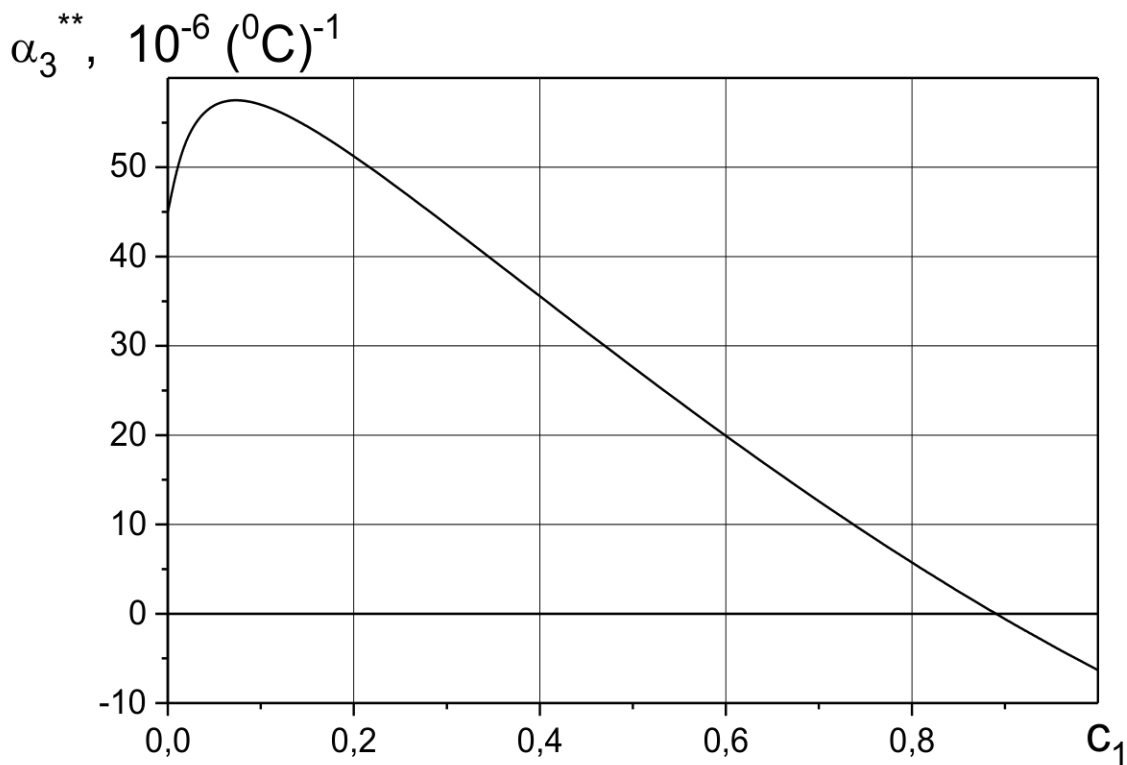


Figure 1.9.

Formulas (1.51), (1.53) – (1.56) make it possible to determine the average stresses in the matrix of the composite at given macrostresses. This makes it possible to predict the strength of the composite. That is, setting the macrostress in the composite with a certain concentration of fibers  $c_1$ , it is possible to determine whether the average stresses in the matrix reach its yield point  $\sigma_{02} = 0.05$  GPa, and draw a conclusion about the strength of the composite as a whole. In Figure 1.10, at different concentrations of fibers  $c_1$  loads on the composite are shown  $\sigma_0$ , corresponding to the yield strength of the matrix.

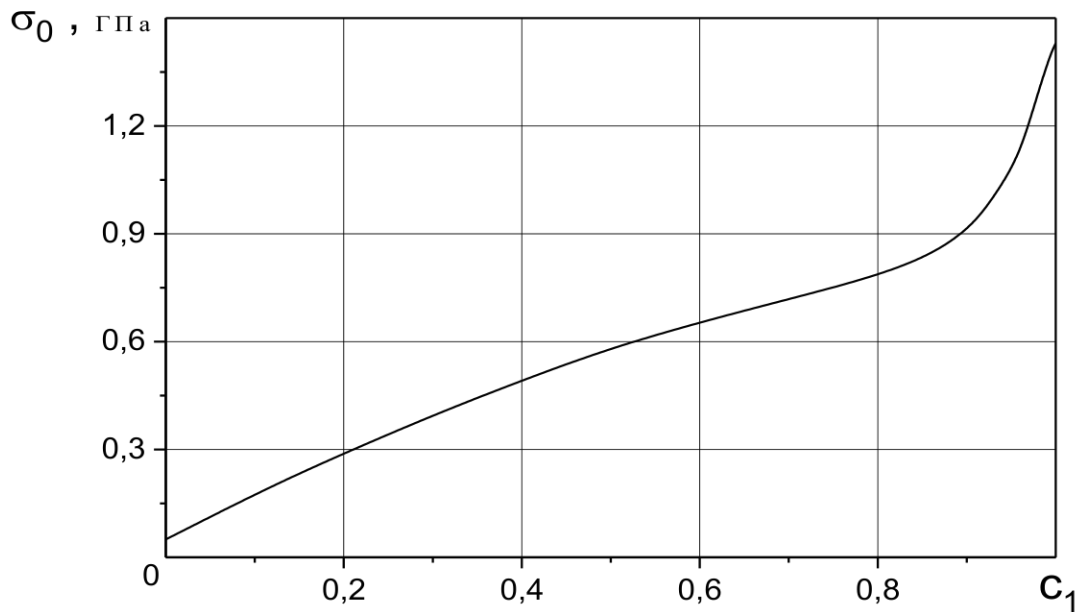


Figure 1.10.

The study of space-reinforced fibrous materials was carried out in the work for the case of fibers located in a plane  $x_1x_2$  along the sides of the square and its diagonals. The effective thermoelastic properties of the material were determined and the laws of the relationship between macrostresses and macrodeformations in the material and the dependence of the average deformations and stresses in the matrix of the material on macrodeformations or macrostresses, as well as the dependence of the material characteristics on the concentration of fibers, were established. An algorithm was built to determine the strength of the composite, based on the known strength of the matrix. The thermoelastic characteristics of the material and its strength were studied.

## **SECTION 2**

### **ANALYSIS OF THE TEMPERATURE EFFECT ON THE STRESS-STRAIN STATE OF THE TANK WAGON COMPOSITE BOILER DURING STEAMING**

#### **2.1 Analysis of existing developments on issues of influence on the stress-strain state of various machine-building structures**

The search for information sources was aimed at finding works that are devoted to highlighting the achievements and results of research on: determination of temperature effects on mechanical engineering structures, mathematical and computer modeling of processes in mechanical systems, analysis of stress-strain states in transport structures and, in particular, in freight wagons.

In work [30,31], it was found that a specific factor in the production of cellular aggregate of transport structures made of polymer materials is multi-stage impregnation with the composition of the dressing, and then the binder in the final operations, followed by drying and heat treatment of the cellular blocks. Which leads to uneven heat transfer of the binder from the central part of the panel to its peripheral end zones. The regularities of this non-uniform heat migration of the binder along the length of the cellular channel have been created and analyzed. It was found that these phenomena are caused by the hydrodynamic movement of the binder, which is mainly caused by temperature gradients. Taking this into account, a method of determining the thickness of the binder layer along the channels of the honeycombs was created with the given

input data of changes in density and surface tension along the length of the honeycomb aggregate.

In the scientific work [32-35], the approach to mass optimization of shell transport structures was further developed. Which includes significantly improved components of fragments of known analogues, as well as new fragments that were not taken into account before. This approach made it possible to solve the complex multi-parameter problem of optimal design of the considered class of shell transport structures with almost no loss of accuracy. For this, the optimization process was divided into several stages according to the justified significance levels of the parameters included in the objective function - minimum mass. The analysis of the effectiveness of the structure of the reinforcement of the load-bearing skins and the preliminary optimization of the properties of the cellular aggregate were carried out, which significantly simplified the choice of their optimal parameters. It is shown that with a minimal gain in mass due to the optimal reinforcement scheme, which is approximately 5% compared to a quasi-homogeneous shell, there is a real risk of doubling the mass of the shell when choosing a significantly suboptimal shell structure.

Scientific research [36-42] is devoted to highlighting the results of the analysis and substantiating the fields of tolerances for the relevant types of technological defects in transport engineering structures. The tolerances for the deviation of the thickness of the formed product from the design value are determined. It was found that the input control determines the deviation of the thickness from the nominal value for a single-layer semi-finished product realized in the prepreg. Deviation in thickness from the nominal value includes components that arise during its formation. These components are associated with integral deviations of the technological mode of formation (including temperature) from that regulated by the relevant documentation. Analytical

dependences on the reasonable assignment of tolerance fields for the physical and mechanical characteristics of the material with deviations in thickness, in the presence of local integrity violations in the form of voids, were obtained. In contrast to the existing models, the obtained dependencies made it possible to assess the quality of the technological processes of forming semi-finished products and products from polymer composite materials according to the level of defects of the considered class.

The authors of the study [43] proposed a new approach to diagnosing the technical condition of structures that transmit mechanical energy. At the same time, the impact on their stress-strain state was considered. And dependencies were developed accordingly, the publication is dedicated to highlighting their features.

The work [44, 45] presents the design calculation of the automatic electro-hydraulic drive for the rotary movement of technological equipment. At the same time, special attention was paid to the influence of temperatures on the corresponding properties. However, such studies did not consider the possibility of using the developed method for non-load-bearing transport metal structures.

Research [46-50] is devoted to the modeling of the dynamics of a node of an element of a general design by the method of spectral analysis. At the same time, the influence of various factors on the stress state of the general structure was investigated. However, special attention was not paid to the issue of temperature influence, which is initially explained by the lack of such a task.

The authors of the scientific research [51-55] studied, among other things, the temperature effect on the driving components of the power plants of transport. For this purpose, appropriate mathematical and computer models were developed and researched. However, their decisive component is compliance with the tasks of electrical equipment research.



In scientific and applied work [56-60], the main attention is also paid to the problems of researching the electrical equipment of vehicles. At the same time, the results of the conducted simulations, on the diagnosis of thermal effects, will be useful in solving similar problems for other structural components.

The scientific research [61] presents the results of an analysis of the influence of the existing stress-deformed state of freight wagons and the possibility of extending their service life. However, the possibility of their accident-free operational temperature loads was not considered.

The scientific study [62] is devoted to the analysis of the influence of the bending deformations of the wagon body on the indicators of interaction with the railway track. However, not enough attention has been paid to temperature deformations.

Scientific research [63-71] highlights the results of research into the possibility of extending the service life of the bodies of universal semi-wagons that have exhausted their regulatory resource. However, it is not specified how their stressed-strained state will be formed from possible temperature loads from the corresponding cargo.

The authors of the scientific publication [72] presented the results of computational modeling of the dynamic load of containers placed on a platform wagon during railway ferry transportation. Which corresponds to the second calculation mode. However, another case of specific perception of loads, namely from temperature influence, was not considered.

Modeling and simulation of the decision support system structure of an intelligent locomotive and evaluation of the quality of operation are given in the work [73]. It presents complex mathematical models and a proposed computer method for solving them. However, the issue of the possibility of applying appropriate approaches to calculated mathematical strength cases is not given.

Scientific research [74, 75] is devoted to issues of theoretical and practical determination of the parameters of the on-board capacitive energy storage of metro rolling stock. However, the direction of their influence on the carrying capacity of the wagon body, or their temperature factors, were not investigated.

In works [76-79], the issue of safety of sea cargo transportation is comprehensively investigated. At the same time, the scientific research [80] proposed an integrated approach to assessing the vulnerability of critical ship equipment and systems. And in work [81], the results of the study of the environmental efficiency of the operation of ships from the point of view of ensuring the efficiency of cargo transportation are given. And finally, in scientific research [82], the issue of environmental efficiency of ship operation from the point of view of ensuring the efficiency of cargo transportation is considered. However, the considered models of stress-deformed vessels did not include the modes of temperature loads on their hulls.

Summarizing the above, it can be noted that in all the above-mentioned scientific works, the peculiarities of the temperature effect on the stress-strain state of load-bearing systems of vehicles, and in particular the boiler of a tank wagon during steaming, were not investigated.



## 2.2 Requirements for modern designs of domestic tank wagons and their boilers

One of the common models of tank wagons was chosen for the study. Which has the characteristics listed in Table 2.1.

Table 2.1 Characteristics of tank wagon

| Parameter name                                                       | Marking | Value |
|----------------------------------------------------------------------|---------|-------|
| Inner radius of the boiler, m                                        | R       | 1.60  |
| The length of the cylindrical custom, m                              | L       | 9,775 |
| Bottoms are elliptical:                                              |         |       |
| — inner height of the oval part, m                                   | hov     | 0.64  |
| — height of the cylindrical part, m                                  | Hz      | 0.06  |
| The length of the wagon along the coupling axes of auto couplings, m | 2 Lc    | 12.02 |
| Slope depth, m                                                       | hukl    | 0.03  |
| Slope volume, m <sup>3</sup>                                         | On      | 0.02  |
| Number of axles in the wagont                                        | n       | 2     |
| Carrying capacity, i.e                                               | Qgr     | 70.5  |
| The mass of the container and the tolerance on the container, i.e    | T±ΔT    | 23.3  |
| Acceleration of free fall, m/s <sup>2</sup>                          | g       | 9.81  |

The image of the boiler of the tank wagon under investigation is shown in Figure 2.1.

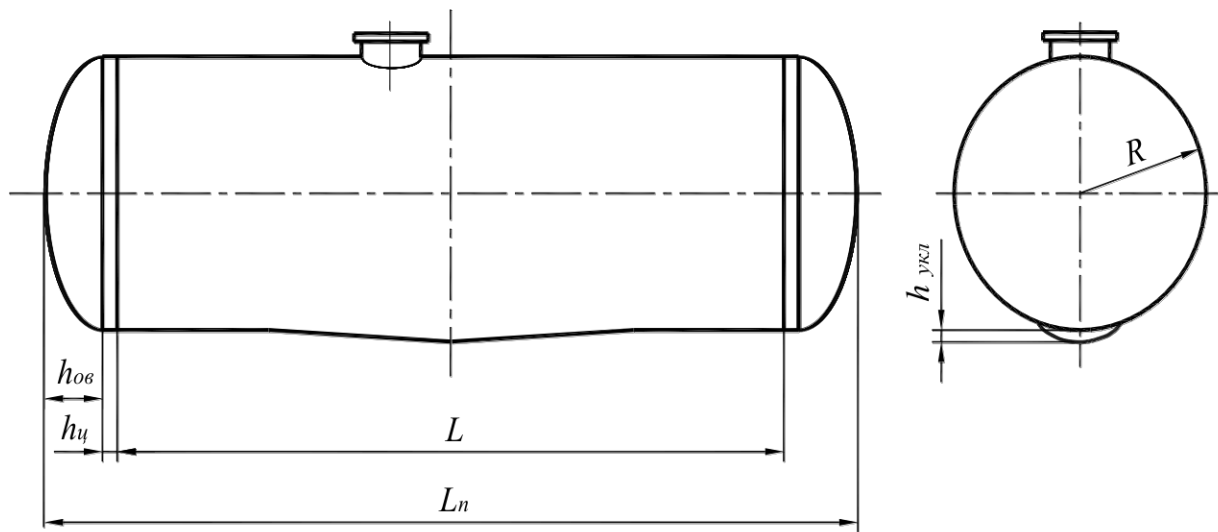


Figure 2.1 – Boiler of a tank wagon with elliptical bottoms

The tank wagon is intended for the transportation of petroleum products. Tank wagons should be used as intended in accordance with the rules of technical operation of railways and operational documentation. The use of tanks for the transportation of other dangerous goods must be agreed with the manufacturing plant, the main organization of the product being transported, and the bodies that control traffic safety and operation at the discharge-filling points. Operating loads should not exceed those established by current regulatory documents. It is not allowed to replace elements of the tank wagon with others, which differ in design or materials from those provided in the manufacturer's drawings, during operation, without his consent.

Sampling from tanks containing a dangerous petroleum product must be carried out without releasing the product into the atmosphere, unless it is stipulated by the standard for the transported product.

Tank wagons containing dangerous goods must have markings that characterize the transport danger of the goods. The marking should contain: danger sign, UN serial number, emergency card number.

The manufacturer guarantees the compliance of tank wagons with the requirements of the standard, subject to compliance with the rules of operation, maintenance and repair. The warranty period of operation of tank wagons is established in the technical conditions for specific models of tank wagons, but not less than 18 months from the day of commissioning. The warranty period for replaceable components, parts and accessories for tank wagons is established by relevant regulatory documents for specific products.

Tests of tank wagons should be performed under the values of climatic factors of the external performance environment "U" in accordance with the current regulatory documents.

Components of tank wagons and tank wagons as a whole that are manufactured must be checked for compliance with the requirements of regulatory and technical documentation during technical control.

During the control of tank wagons, measuring devices should be used in accordance with the requirements of the technical documentation.

Fitting into the dimensions is checked by passing tank wagons through the overall frame.

Assembly and installation of the boiler, frame, wagons, ladders, platforms, pouring and pouring fittings, safety devices, performance of the self-clutch mechanism, braking and other equipment of tank wagons, tightness of the boiler with pouring and pouring fittings and safety devices, marking, color and quality of painting are controlled visually and by measurements during tests of

tank wagons in accordance with the design documentation and technical conditions.

Quality control of welded joints of the boiler is carried out in accordance with current regulatory documents. Mechanical tests of welded joints of boilers of tank wagons are performed in accordance with current regulatory documents.

The quality of welded joints of boilers of tank wagons operating under excessive pressure over 0.07 MPa should be tested in accordance with current requirements.

Reliability requirements are monitored based on the results of reliability tests according to a specially developed and agreed program and methodology.

The capacity of the safety valves must be selected according to the calculation in accordance with the current regulatory documents.

The incoming control of materials and component products, which are received for the manufacture of tank wagons, must be carried out in the order established by the manufacturer in accordance with the current requirements.

Production, testing and acceptance of tank wagon boilers must meet the requirements of current regulatory documents.

The boiler should consist of a casing, two bottoms, a hatch, a hatch for installing a safety inlet valve, and a drain device. The material used for the production of the main elements of the boiler is in accordance with the current regulatory documents.

The boiler must be equipped with a fence, external stairs with a platform that allow for maintenance, repair and control of tank wagon draining and filling operations, as well as internal stairs fixed to the manhole cover for inspection and repair inside the boiler.

The deviation of the internal diameter of the bottom of the tank wagon boiler from the nominal should be within the tolerance of  $\pm 6$  mm.

Bumps, scratches and other defects (pits, sinks, etc.) are not allowed on the surface of the boiler of a tank wagon, if their depth exceeds the minus limit deviations stipulated by the relevant standards or technical conditions for the supply of metal.

The deviation from the straightness of the generator boiler of the tank wagon should not exceed 2 mm per 1 m of length, but not more than 20 mm over the entire length of the joint, without taking into account the local deviation from straightness in the welds.

Local dents and bulges with a height of no more than 5 mm per 1 m of length are allowed on the body of the tank wagon boiler, but no more than 2 units on each side of the rail.

The displacement of the edges of the sheets in the butt joints, the accuracy of the docking of the ends of the skirting boards with the bottoms must be ensured within the tolerances for the displacement and removal of the edges provided by the current regulatory documents.

Welding of the boiler of a tank wagon and its elements, as well as welding of parts to the boiler, must be carried out by welders certified in accordance with current regulatory documents.

In the butt welds of the boiler of the tank wagon, a common removal of the edges (inside and outside) is allowed within 10% of the sheet thickness plus 3 mm, but not more than 5 mm, while the removal of the edges in the longitudinal seams is determined according to the template, the length of which

(along the chord) is equal to  $1/3$  of the radius of the circle. The clumsiness of ring seams is determined by a ruler 300 mm long.

The boiler of the tank wagon must be symmetrically located on the pivot beams. Permissible displacement of the longitudinal axis of the boiler relative to the longitudinal axes of the backbone beams in the horizontal plane is no more than 5 mm.

The boiler of the tank wagon must be equipped with a drain-filling and safety valve.

Draining and filling fittings must include: a draining device, which must ensure the draining and filling of the product at the draining-filling points, the preservation of the product during the transportation of the tank wagon and include three sequentially installed locking devices:

- internal (main) locking device to ensure complete merging of the cargo and sealing of the boiler of the tank wagon during movement;
- additional locking device - disk valve for sealing the boiler of a tank wagon in the event of a malfunction of the main locking device;
- external shut-off device for sealing the boiler of a tank wagon in the event of a malfunction of the internal (main) and additional shut-off devices.

The distance from the surface of the drain device to the level of the rail head must comply with the current regulatory documents.

The housing of the draining device before welding to the tank wagon boiler shell must be inserted inside flush with the internal surface of the boiler. Then, full welding of the joint along the entire thickness of the boiler shell of the tank wagon should be ensured.



Draining the product from the boiler of the tank wagon should be provided with a slope to the drain device with a height difference of 25...30 mm.

The cover of the hatch of the boiler of the tank wagon must ensure the density of the boiler (taking into account water hammer and vapor pressure) at a pressure of at least 0.25 MPa (2.5 kgf/cm<sup>2</sup>). A sealing ring must be installed on the cover.

There must be a device for installing a locking and sealing device on the cover of the tank wagon's boiler hatch.

The hatch cover of the tank wagon must be equipped with a device for detonating the cover in the event of its freezing or the presence of a vacuum in the boiler, as well as to ensure safe opening of the cover in the presence of excess pressure in the boiler.

Safety fittings must include a safety inlet valve.

The safety-inlet valve must be installed in the upper part of the boiler and serves to exclude a possible increase in pressure inside the boiler beyond the permissible level, as well as to prevent the formation of a vacuum. The safety-inlet valve cannot act to eliminate the vacuum after steaming operations.

The design of the safety inlet valve and its placement on the boiler should exclude the possibility of accidental release or theft of the product from the tank. The safety valve must be sealed after adjustment.

### **2.3 Adoption and use of moment theory of shells for mathematical calculation**

When calculating for all types of loads, except for the calculation of bottoms from internal pressure, the boiler of a tank wagon is considered as a closed cylindrical shell, freely supported at the ends on diaphragms that are absolutely rigid in their plane and absolutely flexible perpendicular to this plane. Such diaphragms are the bottoms of the tank wagon boiler. To calculate the bottom and the adjacent zone of the cylindrical part of the boiler, the actual shape and elasticity of the tank wagon may be taken into account.

Let's highlight an infinitesimally small element of the middle surface of the shell with two longitudinal and two transverse sections  $ABCD$  (Figure 2.2 a). This item has dimensions  $dx = R_1 d\alpha$  and  $ds = R_1 d\beta$ , where  $\alpha$  and  $\beta$  are the dimensionless coordinates of the cylindrical coordinate system  $\alpha = \frac{x}{R_1}$  i coincides with the original  $x$ , a  $\beta = \frac{s}{R}$  with a bow's cross section of the cylindrical part of the boiler.

Instead of the removed parts of the shell, we will apply it to the longitudinal and transverse sections of the element  $ABCD$  power factors (Figure 2.2 b): normal  $T_1(\alpha, \beta)$  and  $T_2(\alpha, \beta)$ . Transverse  $Q_1(\alpha, \beta)$  and  $Q_2(\alpha, \beta)$  and landslides  $S_1(\alpha, \beta)$  and  $S_2(\alpha, \beta)$  bending forces  $M_1(\alpha, \beta)$  and  $M_2(\alpha, \beta)$  and twisting  $M_{K1}(\alpha, \beta)$  and  $M_{K2}(\alpha, \beta)$  moments

All these force factors, which determine the stress state of the shell, are related to the length unit of the corresponding side of the analyzed element.

$$S_1(\alpha, \beta) = S_2(\alpha, \beta) = S(\alpha, \beta), \quad (2.1)$$



$$M_{K1}(\alpha, \beta) = M_{K2}(\alpha, \beta) = M_K(\alpha, \beta), \quad (2.2)$$

Let's take the positive reference direction of the coordinates as shown in Figure 2.2 a. Along these three mutually perpendicular directions, we will decompose the complete displacement of the point, marking its components: longitudinal (along the generating line) through  $u(\alpha, \beta)$ , tangential (tangential to the circle arc) –  $v(\alpha, \beta)$  and radial (according to the internal normal) –  $w(\alpha, \beta)$ .

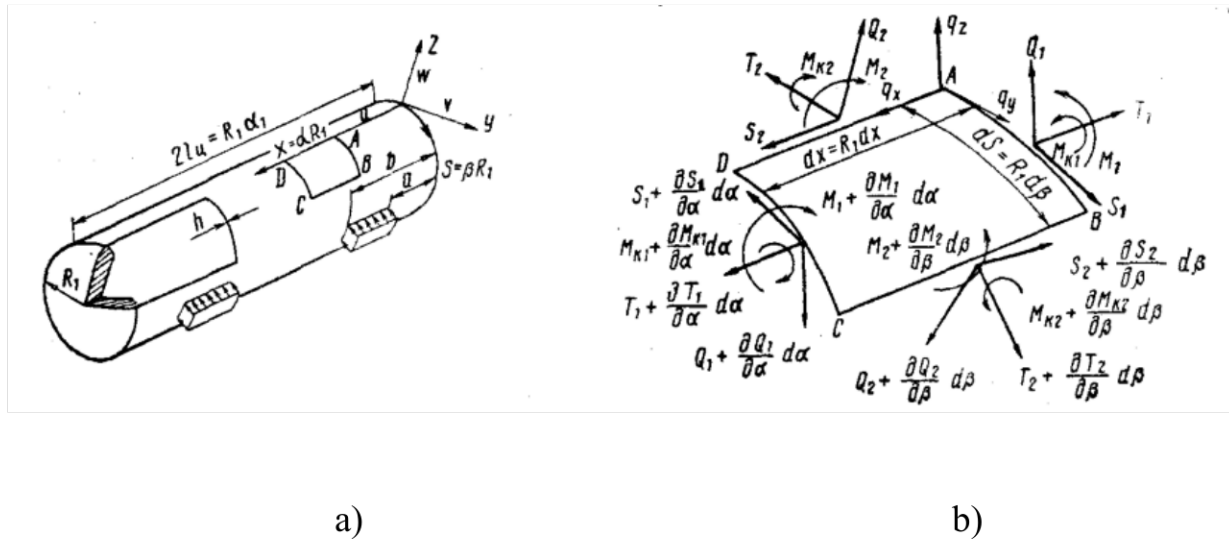


Figure 2 – Calculation scheme of the shell and its element

These movements of the middle surface determine the deformed state of the shell. In addition, the rotation angles of the longitudinal ones are considered  $\theta_2(\alpha, \beta)$  and transverse  $\theta_1(\alpha, \beta)$  cross-sectional planes.

The external load can also be distributed along these three directions. The components of the surface loading of the boiler shell have the following designations: longitudinal through  $q_x(\alpha, \beta)$ , tangential  $q_y(\alpha, \beta)$  and radial  $q_z(\alpha, \beta)$ . Brackets  $(\alpha, \beta)$  indicate that the considered parameters are, in the general case, functions of two variables  $\alpha$  and  $\beta$ , and in the future are omitted to

shorten the record. Equilibrium equations are formulated to determine the unknown force factors acting on an infinitesimal element of the shell. Since these equations are not sufficient to solve the statically indeterminate problem under consideration, the conditions of non-discontinuity of deformations are used, i.e. connections between components of movements and deformations (geometric relations) and connections of deformations with force factors (physical relations).

The complete system of equations, consisting of equilibrium equations and strain continuity equations, is equivalent to the following equation in partial derivatives of the eighth order:

$$\nabla^2 \nabla^2 \nabla^2 \nabla^2 \Phi + 4k^4 \frac{\partial^4 \Phi}{\partial \alpha^4} = 0, \quad (2.3)$$

where  $\nabla^2 = \frac{\partial^2}{\partial \alpha^2} + \frac{\partial^2}{\partial \beta^2}$  – differential Laplace operator;

$\Phi(\alpha, \beta)$  – enabling function.

Part of the expression of equation (1.3), which contains  $4k^4$  is calculated by the formula:

$$4k^4 = \frac{12(1 - \mu^2)R_1^2}{h_1^2}, \quad (2.4)$$

where  $\mu$  – Poisson's ratio;

$h_1$  is the thickness of the wall of the cylindrical part of the boiler.

Through the enabling function  $\Phi$  all power factors and displacements of the boiler shell can be determined. However, the calculation of the boiler based on the given equations of the moment theory of shells for all types of loading,

especially taking into account the different thicknesses of the sheets that make up the boiler, is a rather difficult and time-consuming task. Therefore, it is advisable to use electronic computing machines to solve it. The machine calculation algorithm in matrix form can be constructed as follows.

Equation (2.3) by substitution is reduced to the form:

$$\begin{aligned} \Phi = \sum_{m=1}^{\infty} f_m(\beta) \sin \lambda_m \alpha, \text{ тоді} \\ \sum_{m=1}^{\infty} \left[ \frac{d^8 f_m(\beta)}{d\beta^8} - 4\lambda_m^2 \frac{d^6 f_m(\beta)}{d\beta^6} + 6\lambda_m^4 \frac{d^4 f_m(\beta)}{d\beta^4} + \right. \\ \left. \lambda_m^4 (\lambda_m^4 + 4k^4) f_m(\beta) \right] \sin \lambda_m \alpha = 0 \end{aligned} \quad (2.5)$$

$$\text{where } \lambda_m = \frac{m\pi R_l}{2l_y};$$

$m$  – row member number;

$2l_y$  – length of the cylindrical part of the boiler;

$f_m(\beta)$  is the coefficient of the number  $m$  a number of functions  $\Phi$ ,

which depends on the coordinate  $\beta$ .

Condition (2.5) is fulfilled for any values  $\alpha$  only if for each number  $m$  the expression in square brackets is equal to zero.

Using this condition, we obtain a system of independent differential equations of the eighth order with respect to the coefficients  $f_m(\beta)$  a number of functions  $\Phi$ . Index later  $m$  is omitted, but it should be borne in mind that all calculation dependencies refer to the same number  $m$  member of the series

Given function expression  $\Phi$  has an important property: the forces and displacements calculated based on it satisfy the boundary conditions adopted

above, i.e. the resting of the ends of the boiler on the indicated diaphragms.

These conditions mean that at  $\alpha = 0$  and  $\alpha = \alpha_1 = \frac{2l_y}{R_1}$   $M_1 = T_1 = w = v = 0$ .

To solve ordinary differential equations (2.5), we will formulate a characteristic equation of the form:

$$(\gamma^2 + \lambda^2)^2 + 4k^4 \lambda^4 = 0, \quad (2.6)$$

The roots of equation (6) are of the complex form:

$$\gamma_j = \pm c_l \pm id_l, \quad (2.7)$$

where  $j = 1, 2, 3, \dots, 8$ ;  $l = 1, 2$ .

Valid parts  $c_l$  and  $d_l$  of complex roots are calculated using the formulas obtained from expression (2.6) after transferring its second term to the right-hand side, extracting the roots of the fourth and then the second degree from the right and left-hand sides, taking into account the rules used when performing these operations on complex numbers:

$$c_l^2 = \frac{\lambda}{2} \left\{ (\lambda \pm k) + \left[ (\lambda \pm k)^2 + k^2 \right]^{\frac{1}{2}} \right\}, \quad (2.8)$$

$$d_l = \frac{\lambda k}{2c_l}, \quad (2.9)$$

In formula (2.8), the plus sign corresponds to the index  $l = 1$ , and the minus sign  $l = 2$ .

The general integral of each of the homogeneous equations (2.5) has the form:

$$f(\beta) = C_1\varphi_1(\beta) + C_2\varphi_2(\beta) + C_3\varphi_3(\beta) + C_4\varphi_4(\beta) + C_5\varphi_5(\beta) + C_6\varphi_6(\beta) + C_7\varphi_7(\beta) + C_8\varphi_8(\beta), \quad (2.10)$$

where  $\varphi_j(\beta)$  are partial integrals of a homogeneous equation.

It is advisable to present them in the form of:

$$\left. \begin{aligned} \varphi_{1,5}(\beta) &= e^{c_{1,2}(\beta-\beta_0)} \cos d_{1,2}(\beta-\beta_0); \\ \varphi_{2,6}(\beta) &= e^{c_{1,2}(\beta-\beta_0)} \sin d_{1,2}(\beta-\beta_0); \\ \varphi_{3,7}(\beta) &= e^{-c_{1,2}(\beta+\beta_0)} \cos d_{1,2}(\beta+\beta_0); \\ \varphi_{4,8}(\beta) &= e^{-c_{1,2}(\beta+\beta_0)} \sin d_{1,2}(\beta+\beta_0). \end{aligned} \right\}, \quad (2.11)$$

In formula (2.11)  $\beta_0$  means half of the central angle corresponding to the arc of the panel from which the cylindrical part of the boiler can be assembled.

Representing power factors  $M_1, M_2, T_1, T_2, Q_2$  and displacement  $v, w, \theta_2$  in rows  $\sin \lambda \alpha$ , a  $S, M_k, Q_1$   $u$  and  $\theta_1$  in rows  $\cos \lambda \alpha$  using the formulas of V.Z. Vlasov [20] through known coefficients  $f(\beta)$  we will obtain the coefficients of the series of the listed force factors and displacements.

It is advisable to present the coefficient formulas in matrix form. Then, if we denote the vector of coefficients of force factors on the longitudinal edges  $-\beta_0$  and  $\beta_0$  panels through the expression:

$$\vec{S} = \| S(-\beta_0) \ T_2(-\beta_0) \ Q_2(-\beta_0) \ M_2(-\beta_0) \ S(\beta_0) \ T_2(\beta_0) \ Q_2(\beta_0) \ M_2(\beta_0) \| \quad (2.12)$$

and the vector of arbitrary integrations through  $\vec{C}_j$ , then you can write:

$$\vec{S} = \|A\| \vec{C}_j, \quad (2.13)$$

Similarly, if the vector of displacement coefficients of the longitudinal edges:

$$\vec{u} = \|u(-\beta_0) \ v(-\beta_0) \ w(-\beta_0) \ \theta_2(-\beta_0) \ u(\beta_0) \ v(\beta_0) \ w(\beta_0) \ \theta_2(\beta_0)\| \quad (2.14)$$

then it can be represented as

$$\vec{u} = \|B\| \vec{C}_j, \quad (2.15)$$

In formulas (2.13) and (2.15)  $\|A\|$  and  $\|B\|$  – matrices of transformation of the vector of arbitrary integrations into vectors of forces and displacements. With:

$$\left. \begin{aligned} \|A\| &= \|A_\delta\| \|A_\kappa\| \\ \|B\| &= \|B_\delta\| \|B_\kappa\| \end{aligned} \right\}, \quad (2.16)$$

where  $\|A_\delta\|$  and  $\|B_\delta\|$  – diagonal matrices of the eighth order;

$\|A_\kappa\|$  and  $\|B_\kappa\|$  are square matrices of the eighth order.

In diagonal matrices, the non-zero elements are, respectively:

$$\left. \begin{aligned} & \frac{Eh_1}{R_1} \lambda^3, \frac{Eh_1}{R_1} \lambda^4, -2 \frac{D}{R_1^3} \lambda^2 k^2, 2 \frac{D}{R_1^2} \lambda^2 k^2, \\ & \frac{Eh_1}{R_1} \lambda^3, \frac{Eh_1}{R_1} \lambda^4, -2 \frac{D}{R_1^3} \lambda^2 k^2, 2 \frac{D}{R_1^2} \lambda^2 k^2, \\ & \lambda, 1, 2 \lambda^2 k^2, 2 \frac{\lambda^2 k^2}{R_1}, 1, 2 \lambda^2 k^2, 2 \frac{\lambda^2 k^2}{R_1}. \end{aligned} \right\}, \quad (2.17)$$

where  $D = \frac{Eh_1^3}{12(1-\mu^2)}$  – cylindrical shell stiffness;

$E$  – modulus of elasticity of the boiler material;

$\mu, h_1$  and  $R_1$  have previous values.

Let's denote by  $\beta = -\beta_0$  functions  $\varphi_j = p_j$ , and at  $\beta = \beta_0$  functions  $\varphi_j = \delta_j$ . Taking this into account, square matrices can be represented in the form:

$$\|A_\kappa\| = \left\| \begin{pmatrix} (\alpha_s p_1 - \beta_s p_2) & (\alpha_s p_2 + \beta_s p_1) & -(\alpha_s p_3 + \beta_s p_4) & -(\alpha_s p_4 - \beta_s p_3) & \dots \\ \vdots & \vdots & \vdots & \vdots & \dots \\ (\alpha_s \delta_1 - \beta_s \delta_2) & (\alpha_s \delta_2 + \beta_s \delta_1) & -(\alpha_s \delta_3 + \beta_s \delta_4) & -(\alpha_s \delta_4 - \beta_s \delta_3) & \dots \\ \vdots & \vdots & \vdots & \vdots & \dots \end{pmatrix} \right\|, \quad (2.18)$$

$$\|B_\kappa\| = \left\| \begin{pmatrix} (\alpha_u p_1 - \beta_u p_2) & (\alpha_u p_2 + \beta_u p_1) & -(\alpha_u p_3 + \beta_u p_4) & -(\alpha_u p_4 - \beta_u p_3) & \dots \\ \vdots & \vdots & \vdots & \vdots & \dots \\ (\alpha_u \delta_1 - \beta_u \delta_2) & (\alpha_u \delta_2 + \beta_u \delta_1) & -(\alpha_u \delta_3 + \beta_u \delta_4) & -(\alpha_u \delta_4 - \beta_u \delta_3) & \dots \\ \vdots & \vdots & \vdots & \vdots & \dots \end{pmatrix} \right\|, \quad (2.19)$$

In matrices (2.18) and (2.19) to shorten the record, only the first halves of the two terms corresponding to the effort are given  $S$  and movement  $u$  on the edges of the panel  $-\beta_0$  and  $\beta_0$ . The next four elements are the same as the first, but they have coefficients  $\alpha_s$  and  $\beta_s$  must be replaced by  $\alpha_{1s}$  and  $\beta_{1s}$ , and the coefficients  $\alpha_u$  and  $\beta_u$  on  $\alpha_{1u}$  and  $\beta_{1u}$ . In addition, functions  $p_{1,2,3,4}$  and  $\delta_{1,2,3,4}$  are replaced by  $p_{5,6,7,8}$  and  $\delta_{5,6,7,8}$  in accordance. The other six terms, marked in the matrices with dots, are written the same as the filled ones, if the coefficients are



replaced  $\alpha$  and  $\beta$  with indexes  $S$  on coefficients with indices  $T, Q$  and  $M$ , and coefficients with indices  $u$  – on coefficients with indices  $v, w$  and  $\theta$ .

The values of the coefficients are given in Table 2.2. In addition, in the matrices  $\|A_k\|$  and  $\|B_k\|$  the third, fourth, seventh and eighth elements of terms with coefficients having indices  $T, M, v$  and  $\theta$ , must have signs reversed to the signs of these elements in strings with indices  $S$  and  $u$ .

Table 2.2 The values of the coefficients

| Index    | Coefficients                                     |                                                 |                                                  |                                                  |
|----------|--------------------------------------------------|-------------------------------------------------|--------------------------------------------------|--------------------------------------------------|
|          | $\alpha$                                         | $\beta$                                         | $\alpha_1$                                       | $\beta_1$                                        |
| $S$      | $c_1$                                            | $d_1$                                           | $c_2$                                            | $d_2$                                            |
| $T$      | 1                                                | 0                                               | 1                                                | 0                                                |
| $Q$      | $(d_1^3 - 3c_1^2 d_1) + (2 - \mu)\lambda^2 d_1$  | $(c_1^3 - 3c_1 d_1^2) - (2 - \mu)\lambda^2 c_1$ | $-(d_2^3 - 3c_2 d_2^2) - (2 - \mu)\lambda^2 d_2$ | $-(c_2^3 - 3c_2 d_2^2) + (2 - \mu)\lambda^2 c_2$ |
| $M$      | $-2c_1 d_1$                                      | $(c_1^2 - d_1^2) - \mu\lambda^2$                | $2c_2 d_2$                                       | $-(c_2^2 - d_2^2) + \mu\lambda^2$                |
| $u$      | $(c_1^2 - d_1^2) + \mu\lambda^2$                 | $2c_1 d_1$                                      | $(c_2^2 - d_2^2) + \mu\lambda^2$                 | $2c_2 d_2$                                       |
| $v$      | $-(c_1^3 - 3c_1 d_1^2) + (2 + \mu)\lambda^2 c_1$ | $(d_1^3 - 3d_1 c_1^2) + (2 + \mu)\lambda^2 d_1$ | $-(c_2^3 - 3c_2 d_2^2) + (2 + \mu)\lambda^2 c_2$ | $(d_2^3 - 3d_2 c_2^2) + (2 + \mu)\lambda^2 d_2$  |
| $w$      | 0                                                | 1                                               | 0                                                | 1                                                |
| $\theta$ | $-d_1$                                           | $c_1$                                           | $d_2$                                            | $-c_2$                                           |

We will use the displacement method to calculate the tank wagon boiler. Let us present the cylindrical part of the boiler of the tank wagon divided into separate panels, which are the main elements of the calculation scheme. As the boundaries of these elements, it is expedient to take the lines of transition from one thickness of the sheet to another, intersections of sudden changes in load,



generating lines along which concentrated forces are applied. For the hydrostatic pressure of the liquid, which is variable along the arc of the section of the cylindrical part of the boiler of the tank wagon, it is advisable to choose the width of the panels in such a way that it is possible to accept the load on it as constant.

Apply to the longitudinal edges  $-\beta_0$  and  $\beta_0$  selected panels of connections, and then one by one we assign forced movements to these connections  $u, v, w$  and  $\theta_2$ , which change along the generating line according to the law  $\cos \lambda \alpha$  or  $\sin \lambda \alpha$  with unit amplitude. These movements will be single.

For each main element from equation (2.15) we find the vectors:

$$\vec{C}_j = \|B\|^{-1} \vec{u}, \quad (2.20)$$

where  $\|B\|^{-1}$  – matrix, inverse  $\|B\|$ .

In vector  $\vec{u}$  consecutively, one of the components is equal to one, and all others are equal to zero.

The vector of reactions of the longitudinal edges at all considered single displacements according to equations (2.13) and (2.20) is:

$$\vec{S} = \|A\| \|B\|^{-1} \vec{u}, \quad (2.21)$$

So, the reaction matrix of the main element can be presented in the form:

$$\|r\| = \|A\| \|B\|^{-1}, \quad (2.22)$$

Formulas (2.13) and (2.15) are valid for homogeneous equations. In the case of an inhomogeneous equation, when the right-hand side of equation (2.3) is not equal to zero, these formulas will have the form:

$$\left. \begin{aligned} \vec{S} &= \|A\| \vec{C}_j + \vec{S}_{\text{uacm}} \\ \vec{u} &= \|A\| \vec{C}_j + \vec{u}_{\text{uacm}} \end{aligned} \right\}, \quad (2.23)$$

where  $\vec{S}_{\text{uacm}}$  and  $\vec{u}_{\text{uacm}}$  – respectively, the vectors of the partial values of force factors and displacements determined by the right-hand side of the inhomogeneous equation, which depends on the nature of the surface external load.

So, if the power element of the boiler shell is loaded with surface radial forces, then in vectors  $\vec{S}_{\text{uacm}}$  and  $\vec{u}_{\text{uacm}}$  non-zero components:

$$\left. \begin{aligned} T_{2 \text{ част}} &= \frac{Eh_1}{\Delta R_1} Z \\ M_{2 \text{ част}} &= -\frac{D\mu\lambda^2}{\Delta R_1} Z \\ u_{\text{част}} &= \frac{\mu}{\lambda\Delta} Z \\ w_{\text{част}} &= \frac{1}{\Delta} Z \end{aligned} \right\}, \quad (2.24)$$

where  $Z$  is the expansion factor in a series of  $\sin \lambda \alpha$  radial load, which is transmitted to the main element of the shell of the tank wagon boiler:

$$\Delta = \frac{Eh_1 \left[ h_1^2 \lambda^4 + 12R_1^2 (1 - \mu^2) \right]}{12R_1^4 (1 - \mu^2)}, \quad (2.25)$$

If the main element is loaded with surface tangential loads, then the non-zero components will be:

$$S_{\text{част}} = - \left[ 1 + \frac{h_1^2}{12(1-\mu^2)R_1^2} \lambda^4 \right] \frac{Eh_1}{\Delta R_1 \lambda} Y, \quad (2.26)$$

$$v_{\text{част}} = 2 \left[ (1+\mu) + \frac{h_1^2}{12(1-\mu^2)R_1^2} \lambda^4 \right] \frac{1}{\Delta \lambda^2} Y, \quad (2.27)$$

where  $Y$  is the coefficient of expansion into a series of tangential load transmitted to the main element of the shell of the tank wagon boiler.

Components of vectors of private solutions for the main element loaded with surface longitudinal forces:

$$\left. \begin{aligned} N_{2 \text{ част}} &= - \frac{Eh_1^3 \mu \lambda^3}{12R_1^3 (1-\mu^2) \Delta} X \\ M_{2 \text{ част}} &= - \frac{Eh_1^3 \mu^2 \lambda}{12R_1^2 (1-\mu^2) \Delta} X \\ u_{\text{част}} &= \frac{1 + \frac{h_1^2}{12R_1^2} \lambda^4}{\Delta \lambda^2} X \\ w_{\text{част}} &= \frac{\mu}{\lambda \Delta} X \end{aligned} \right\}, \quad (2.28)$$

where  $X$  is the expansion factor in a series of  $\cos \lambda \alpha$ .

With the known law of load distribution along the coordinate lines  $\alpha$  calculation of decomposition coefficients  $Z$ ,  $Y$  and  $X$  is carried out according to Euler-Fourier formulas [83].

The tank boiler is a symmetrical structure with respect to the average cross-section, symmetrically loaded by external forces - support, hydrostatic and internal pressures, and for frameless tank wagons - longitudinal tensile and compressive forces. Therefore, members of the series with odd numbers are kept in the series, i.e  $m = 1, 3, 5 \dots$

For bearing radial and tangential loads, uniformly distributed over the sections of the boiler supports, the coefficients of the series are determined by the formulas:

$$\left. \begin{aligned} Z &= \frac{4q_{z1}}{m\pi} \\ Y &= \frac{4q_{y1}}{m\pi} \end{aligned} \right\}, \quad (2.29)$$

where  $q_{z1}$  and  $q_{y1}$  – intensities of radial and tangential loads uniformly distributed over the entire length of the main element, respectively.

For an inhomogeneous equation, the vector of arbitrary integrations is found from formula (2.23) taking into account the obtained values  $\vec{u}_{\text{факт}}$  that is, from the expression:

$$\vec{C}_j = \|B\|^{-1} \vec{u} - \|B\|^{-1} \vec{u}_{\text{факт}}, \quad (2.30)$$

Therefore, the reaction vector on the longitudinal edges of the main element subjected to external forces, according to the first formula (2.23) and equation (2.22), will be equal to:

$$\vec{S} = \|A\| \|B\|^{-1} \vec{u} - \|A\| \|B\|^{-1} \vec{u}_{\text{qact}} + \vec{S}_{\text{qact}} = \|r\| \vec{u} - \|r\| \vec{u}_{\text{qact}} + \vec{S}_{\text{qact}}, \quad (2.31)$$

The second and third components of formula (2.31) at a given load represent an eighth-order vector:

$$\vec{S}_{\Sigma \text{qact}} = -\|r\| \vec{u}_{\text{qact}} + \vec{S}_{\text{qact}}, \quad (2.32)$$

Formula (2.31) is convenient for machine calculations of boiler shells made of panels of the same length, but of different thicknesses.

A boiler composed of panels with different radii of curvature and made of different materials can be calculated in a similar way.

Consider the calculation sequence of a boiler with a symmetrical design and loading, the cylindrical part of which consists of six panels (Figure 2.3).

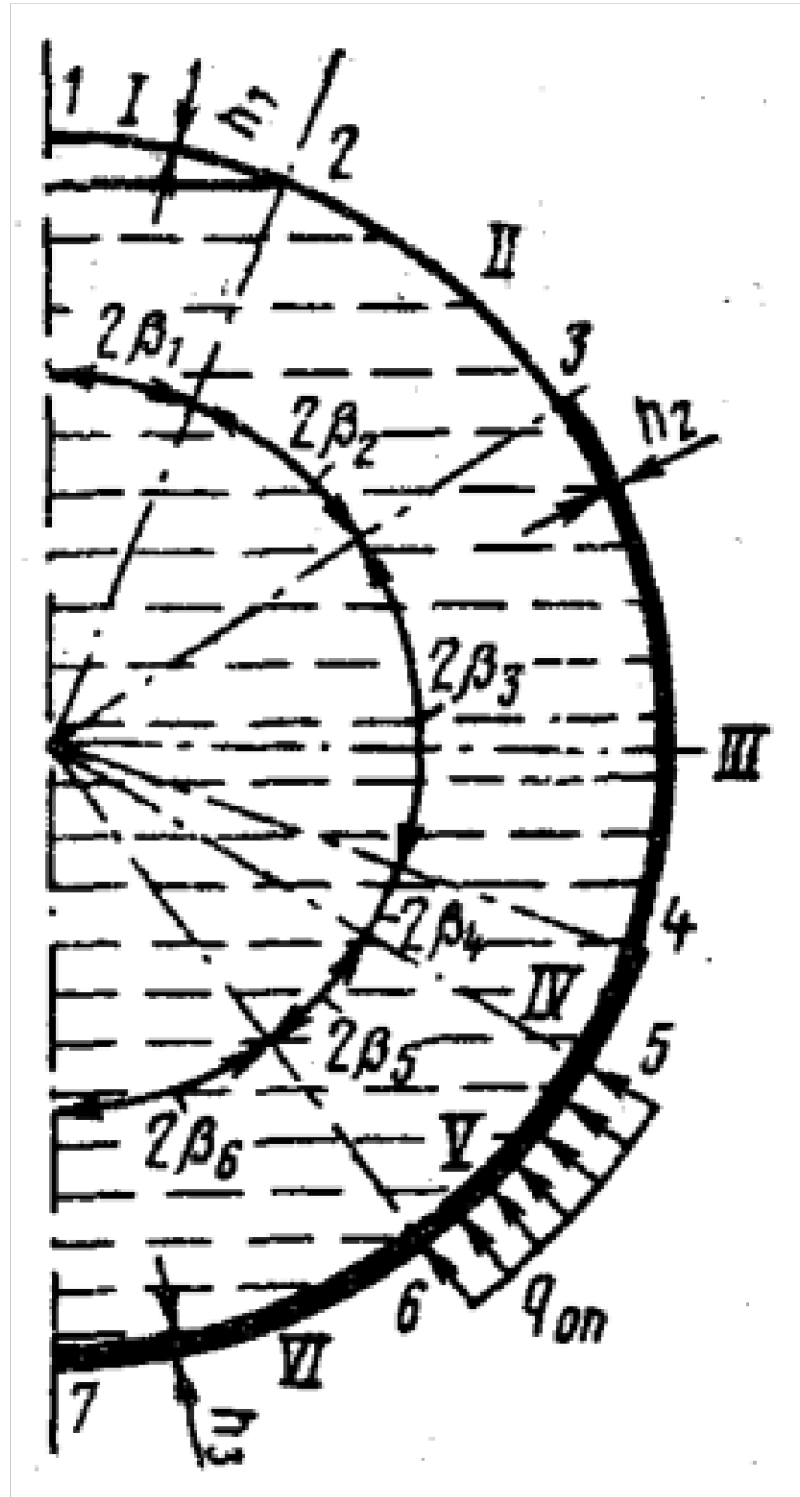


Figure 2.3 – Cross section of the boiler shell

In this figure, panel numbers are indicated by Roman numerals. Nodal intersections are indicated by Arabic numerals. The length of the arc of the  $i$ -th

panel is equal to  $2R\beta_i$ . Having built reaction matrices  $\|r\|$  and vectors  $\vec{S}_{\Sigma_{\text{факт}}}$  for each of the main elements, let's fulfill the conjugation condition of the panels that make up the shell. These conditions are expressed in the equality of forces along the panel joining lines. For this, the last four components of the vector are needed  $\vec{S}$ , i.e.  $S(\beta_0), T_2(\beta_0), Q_2(\beta_0)$  and  $M_2(\beta_0)$  equal to the first four components of the vector of the next panel, i.e.  $S(-\beta_0), T_2(-\beta_0), Q_2(-\beta_0)$  and  $M_2(-\beta_0)$ . As a result of such superimposition of vectors, we will get a canonical system of equations of the displacement method.

Such a canonical system must satisfy the boundary conditions at the initial edge of the first and the final edge of the last panel.

According to the conditions of symmetry on the generators of the boiler, which coincide with the upper and lower ends of the vertical diameter  $v = \theta_2 = Q_2 = S = 0$ . Therefore, in the canonical system of order  $n$  cross out the second, fourth,  $n-2$ , and  $n$ -th column, as well as the second, fourth,  $n-2$ , and  $n$ -th row. After solving such a system that has  $n-4$  we determine the order of the vectors  $\vec{v}$  of each panel of the calculation scheme, and according to them and formula (31) – force factor vectors  $\vec{S}$ . We multiply the resulting vectors of force factors and displacements by the diagonal matrix  $\|\alpha_i\|$  of the eighth order, the elements of which are  $\cos \lambda \alpha, \sin \lambda \alpha, \sin \lambda \alpha, \sin \lambda \alpha, \cos \lambda \alpha, \sin \lambda \alpha, \sin \lambda \alpha, \sin \lambda \alpha$ .

At certain values of the argument  $\alpha_i$  after adding up the number of retained members of the series  $m$  determine the force factors and displacements in the cross-sections of the shell of the tank wagon boiler:



$$\left. \begin{aligned} \vec{S}(\alpha_i) &= \sum_{m=1}^m \|\alpha_i\|_m \vec{S}_m \\ \vec{u}(\alpha_i) &= \sum_{m=1}^m \|\alpha_i\|_m \vec{u}_m \end{aligned} \right\}, \quad (2.33)$$

In formula (33)  $\vec{S}(\alpha_i)$  and  $\vec{u}(\alpha_i)$  – respectively, the vectors of force factors and displacements in the intersections  $\alpha_i$ , and indices  $m$  it is emphasized that the matrices and vectors in the right-hand side of the equalities depend on the number of the term of the series.

In addition to the forces that are the components of the vector  $\vec{S}$ , normal forces are important for assessing the stress state of the boiler  $T_1(\alpha_i)$  and bending moments  $M_1(\alpha_i)$  on the transverse platforms of intersections. The coefficients of the series of these power factors are determined from the elasticity ratios using the formulas:

$$\left. \begin{aligned} T_1 &= \mu T_2 - \frac{Eh_1}{R_1} \lambda u \\ M_1 &= \mu M_2 + \lambda^2 \frac{D}{R_1^2} (1 - \mu^2) w \end{aligned} \right\}, \quad (2.34)$$

Then:

$$\left. \begin{aligned} T_1(\alpha_i) &= \sum_{m=1}^m T_{1m} \sin \lambda \alpha_i \\ M_1(\alpha_i) &= \sum_{m=1}^m M_{1m} \sin \lambda \alpha_i \end{aligned} \right\}, \quad (2.35)$$

Normal stresses on transverse  $\sigma_1$  and longitudinal  $\sigma_2$  The intersection points of the cylindrical part of the boiler are determined by the formulas:

$$\left. \begin{aligned} \sigma_1 &= \frac{T_1}{h_1} \pm \frac{6M_1}{h_1^2} \\ \sigma_2 &= \frac{T_2}{h_1} \pm \frac{6M_2}{h_1^2} \end{aligned} \right\}, \quad (2.36)$$

The specified mathematical approach to the determination of stresses in the control locations of the boiler of the tank wagon was implemented with the help of the modern computer software complex Mathcad. Solving the relevant equations made it possible to obtain stress values, which became the basis for adjusting the adequacy of the developed calculated finite-element model.

## **2.4 Analysis of the temperature effect on the stress-strain state of the composite tank wagon boiler during steaming**

Modeling/simulation of the temperature effect of hot steam at a temperature of 160° C on a tank wagon boiler. Such a temperature effect is standard during a typical washing-steaming process of tank wagon boilers. At the same time, the time of performing the washing and steaming technological operation is from 15 minutes to 1 hour, depending on the external temperature and the initial temperature of the boiler of the tank wagon with cargo residues.

In the case under investigation, the following input data are taken into account: steaming time is 20 minutes; the temperature of the supplied steam is 160 °C; the external temperature is 20 °C; the temperature of the boiler of the tank wagon with cargo residues is 20 °C.

At the first stage, a calculation model of a tank wagon boiler was created in a modern software computing environment, in natural size (Figure 2.4).

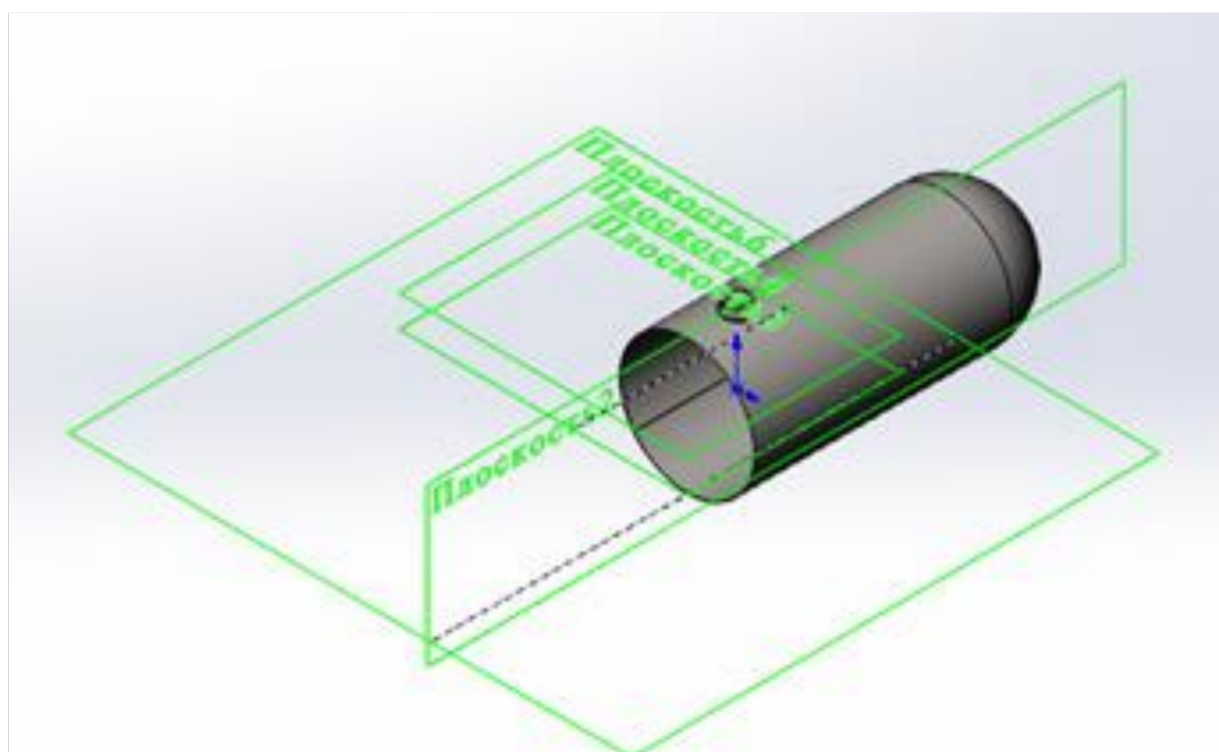
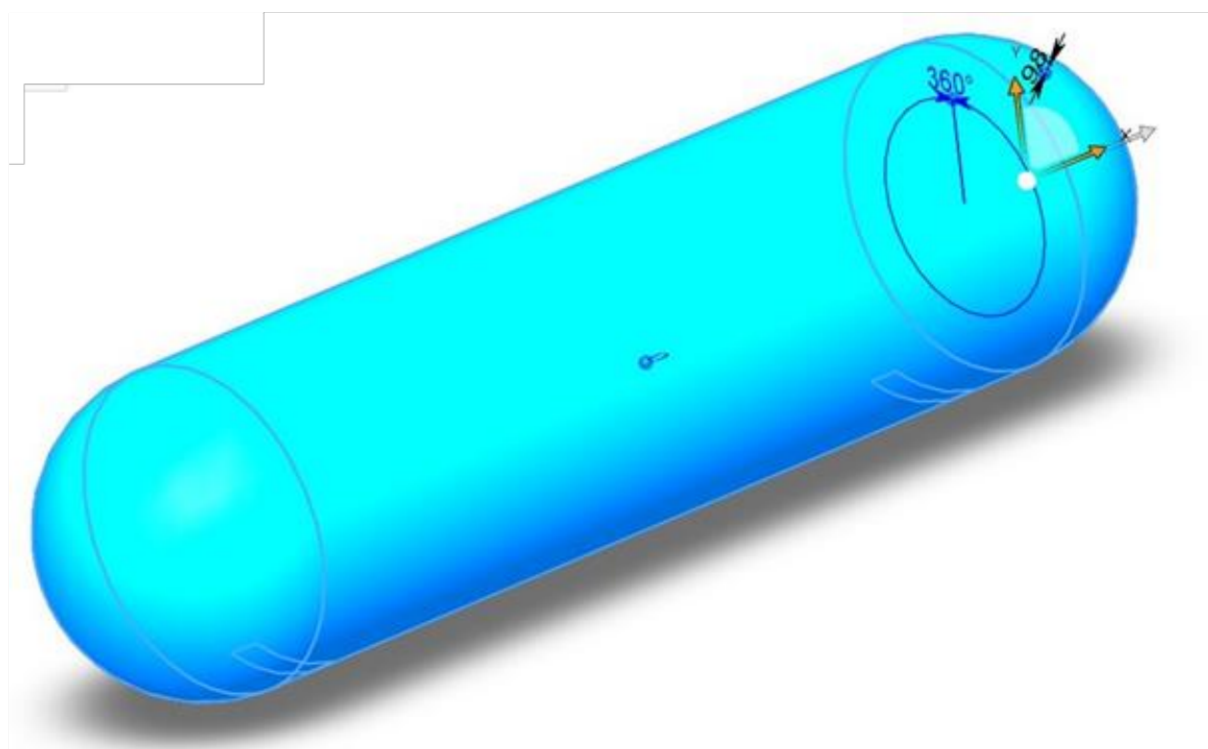


Figure 2.4 – Calculated computer model of a tank wagon boiler

At the same time, the above technical characteristics and requirements for its design are taken into account. Composites material. Taking into account the peculiarities of the given task, the loading hatch was not taken into account in the model of the tank wagon boiler. Fixation of the calculation model is carried out by zonal abutments on the stud nodes, which are given below.

At the second stage, the adequacy of the developed calculation model was adjusted by comparing theoretically (mathematically, based on the method of moment theory of shells) obtained stress values at the control points of the tank wagon boiler with those determined by computer modeling. Namely, the values were taken in the control locations of the bottoms and the bottoms. On the basis of the performed tuning, it was found that an adequate calculation model will have the optimal parameters of the finite element mesh presented below. The number of mesh elements was 25684178, nodes – 4569496. The maximum size of the mesh element is 10,3 mm, the minimum is 0.52 mm, the maximum aspect ratio of the elements is 37.326, the percentage of elements with an aspect ratio less than three is 98.7, more than ten is 0.0329.

The finite element model of the tank wagon boiler is shown in Figure 2.5.

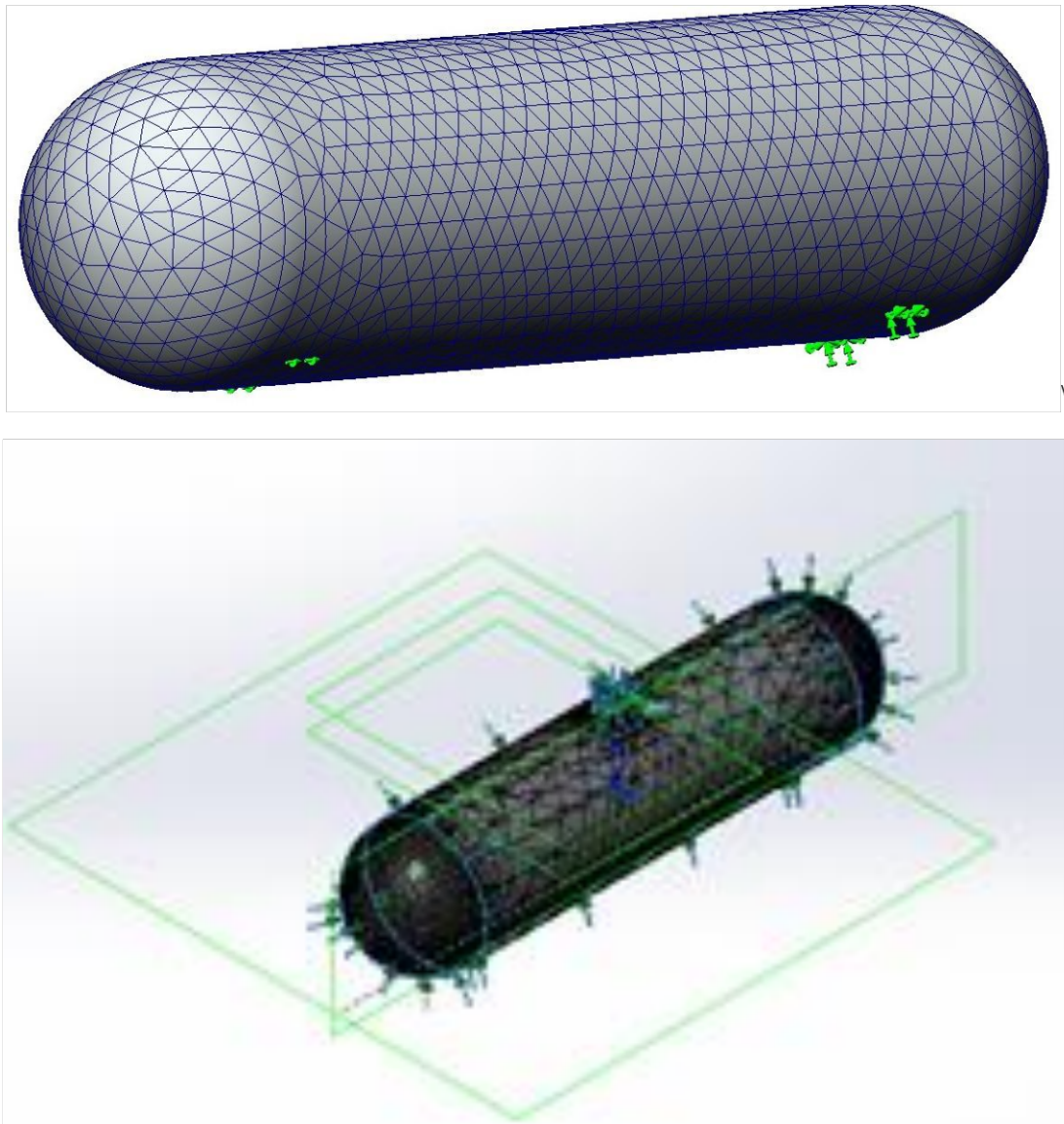


Figure 2.5 – Computational finite-element model of a tank wagon boiler

At the next (third) stage of research, temperature analysis was carried out. Temperature loads were applied to all internal faces of the tank wagon boiler. At the same time, the temperature effect was equal to 160 °C, and the convection coefficient was selected from Table 2.3.



Table 2.3 Temperature analysis

| No.<br>z/p | Average value                             | Convection coefficient<br>(W/m <sup>2</sup> *k) |
|------------|-------------------------------------------|-------------------------------------------------|
| 1.         | Air (natural convection)                  | 5-25                                            |
| 2.         | Air/superheated steam (forced convection) | 20-300                                          |
| 3.         | Steam (condensing)                        | 4000-20000                                      |

The calculated model with applied temperature loads is shown in Figure 2.6.

At the fourth stage, the application of loads from the external temperature, which is equal to 20° C, to the external faces of the calculation model was simulated. At the same time, the convection coefficient was also chosen from Table 2.3. The model with applied external temperature loads is shown in Figure 2.7.

Later, the characteristics of the transient process of temperature analysis were specified. Namely, the process time is 20 minutes, and the process step is 1 minute.

At the fifth stage of the research, the initial temperature of the boiler of the tank wagon with cargo remains was set at 20°C.

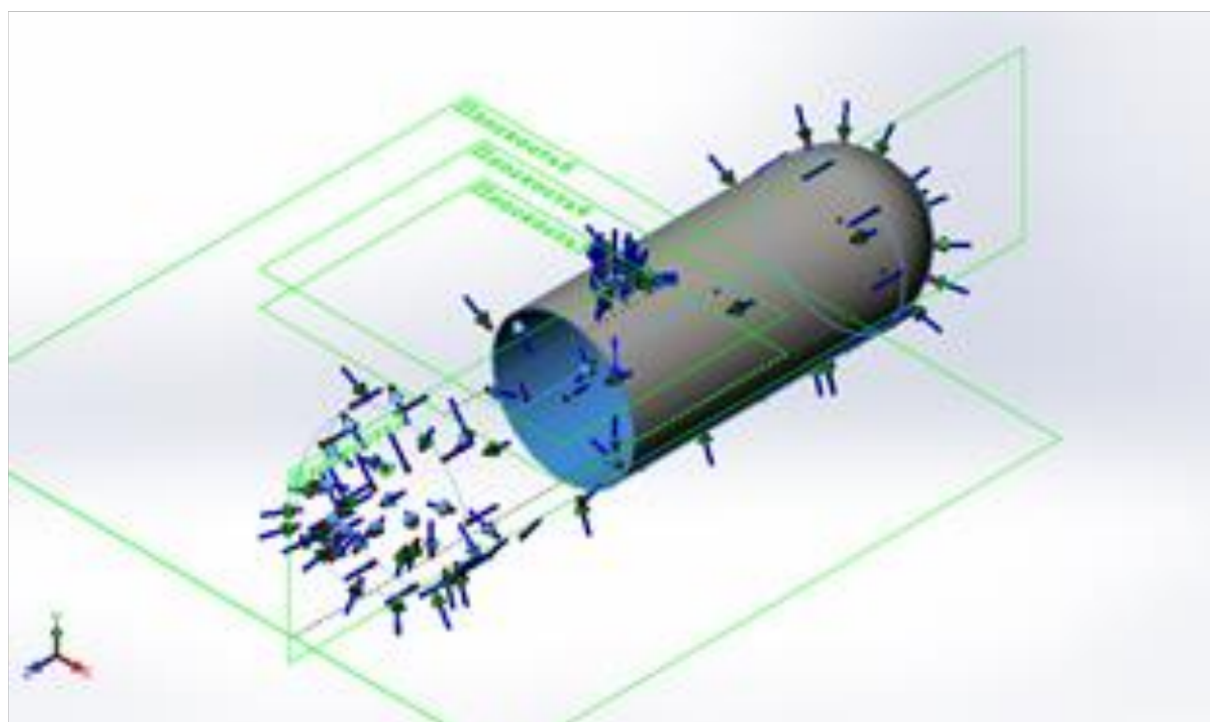
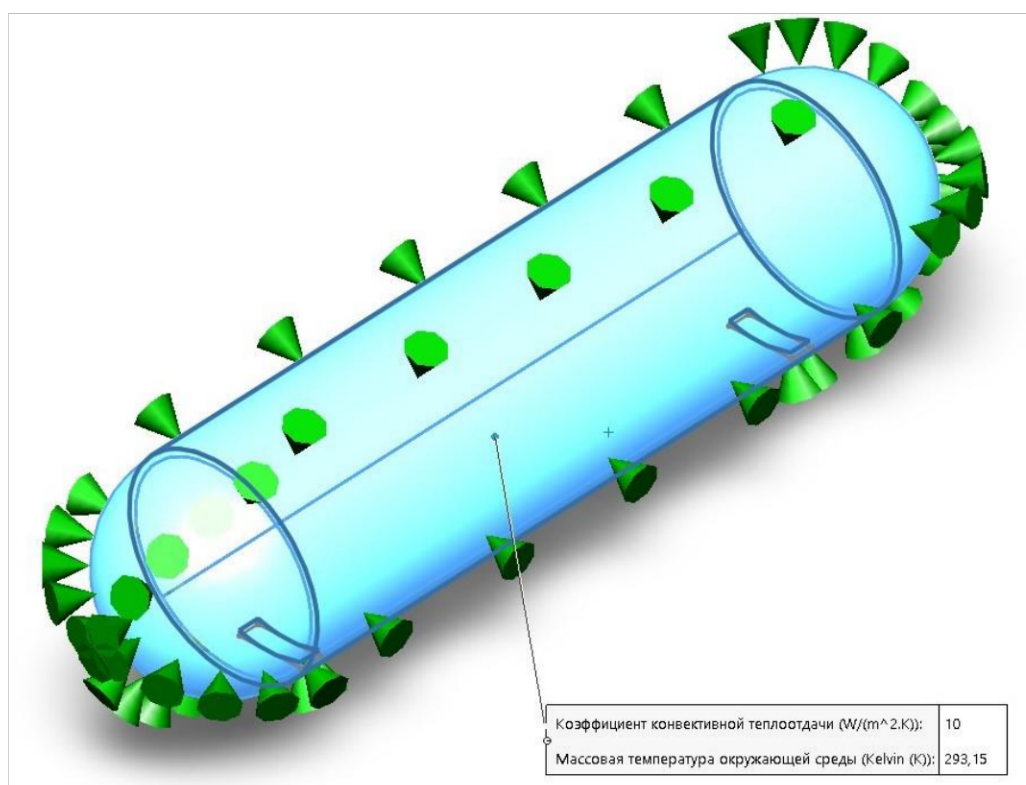


Figure 2.6 – Section of the calculation model of the tank wagon boiler with applied loads from the action of hot steam



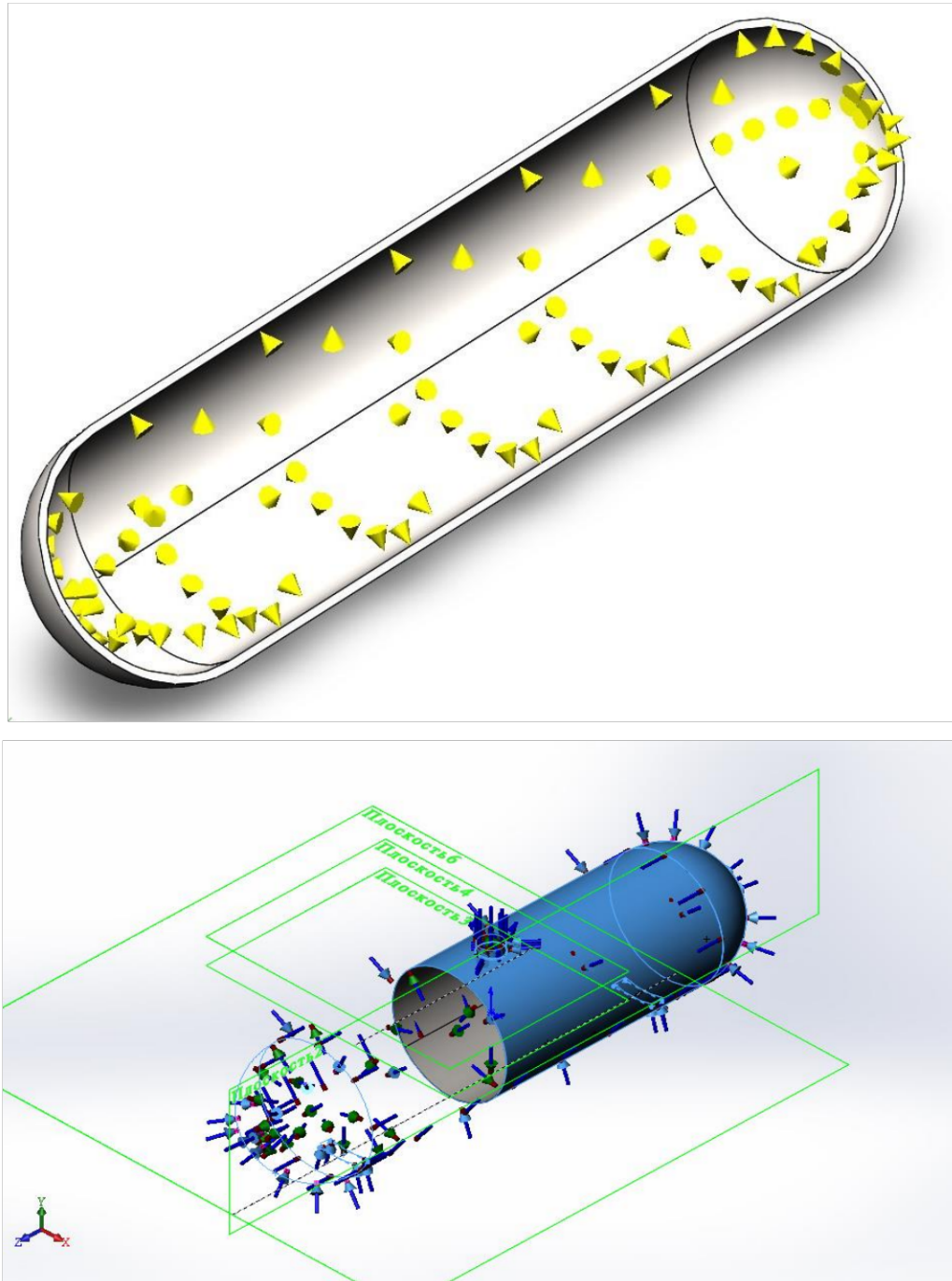


Figure 2.7 – Calculation model of a tank wagon boiler with applied temperature loads from the external temperature

The obtained temperature load modeling data made it possible to determine temperature analysis patterns at all 20 calculation steps. At the same time, it was found out that the construction undergoes the greatest temperature influence in the fifth step (Figure 2.8).

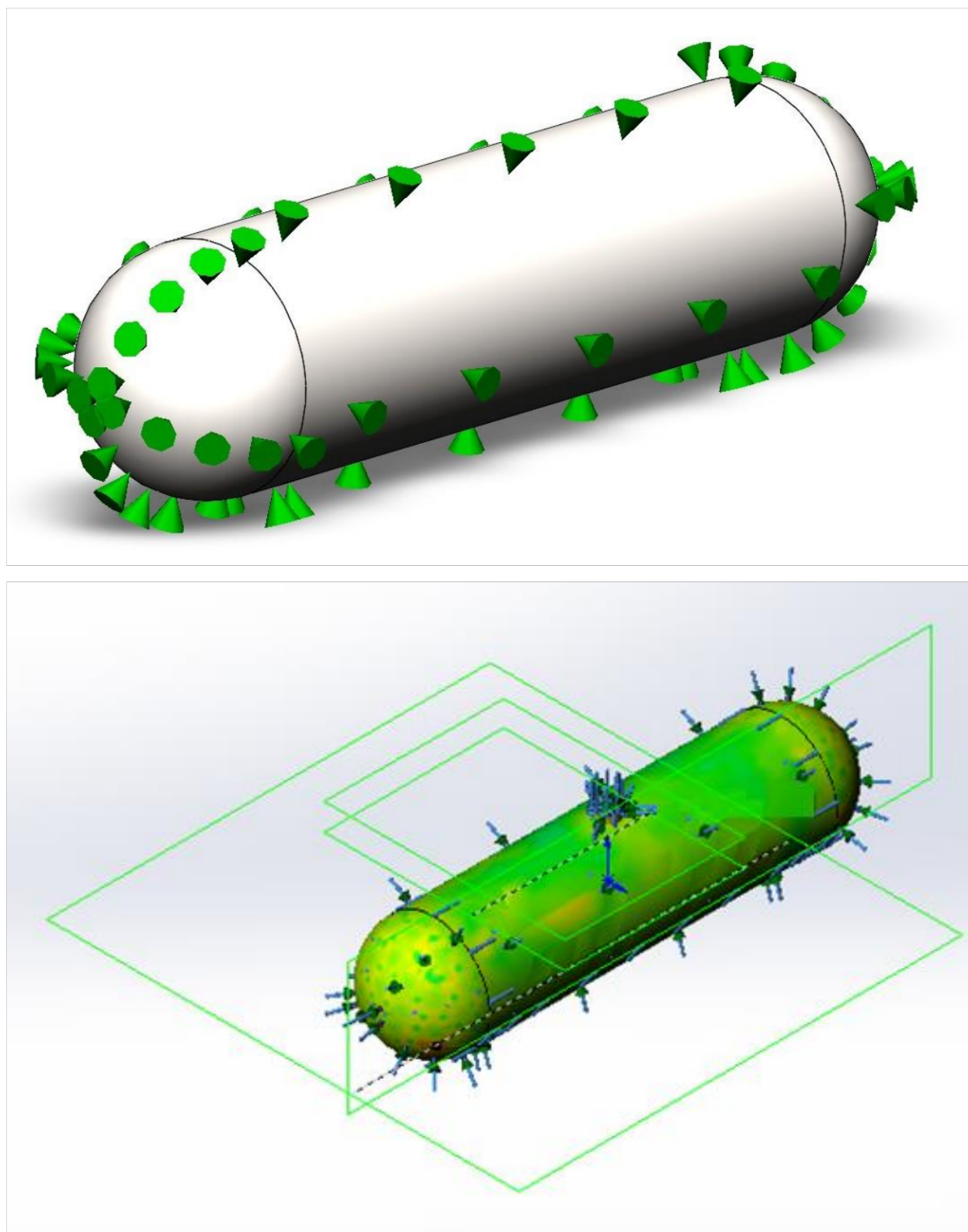


Figure 2.8 – Chart of temperature loads of a tank wagon boiler

At the sixth stage of research, in order to find out the stress-deformed state of the boiler of the tank wagon due to temperature effects, a new study was performed. This is how the calculation model was first attached (Figure 2.9).

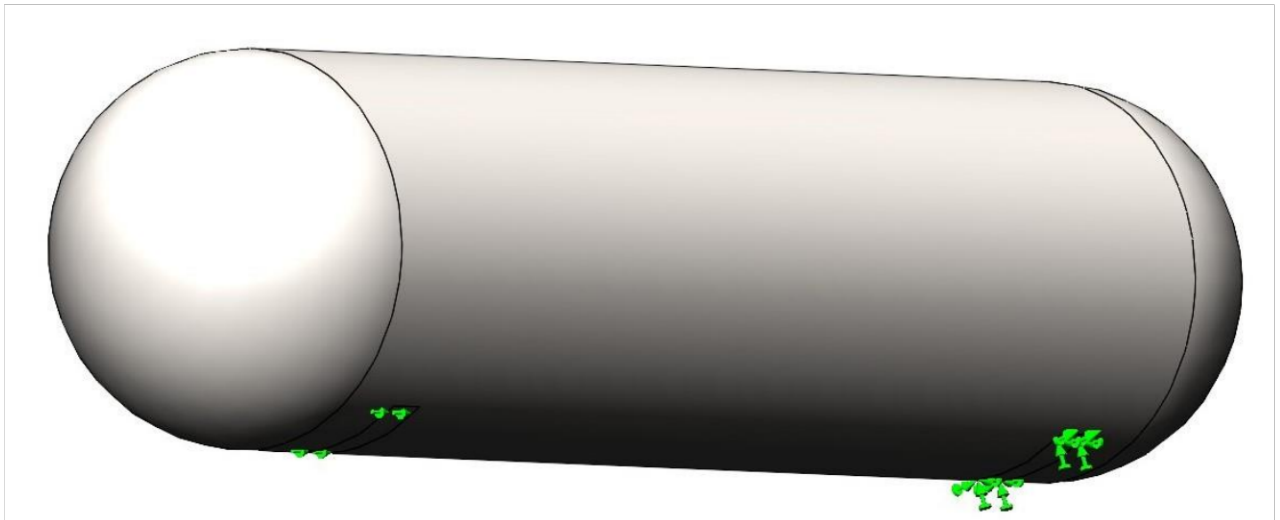


Figure 2.9 – Fixation of the calculation model for determining the stress-strain state of the tank wagon boiler

After that, the previously obtained temperature loads were transferred to be taken into account in static studies. Temperature loads corresponding to the fifth calculation step were chosen as the calculation case. As a result of the calculations, the picture of the stress state due to the action of temperature loads is presented in Figure 2.10.

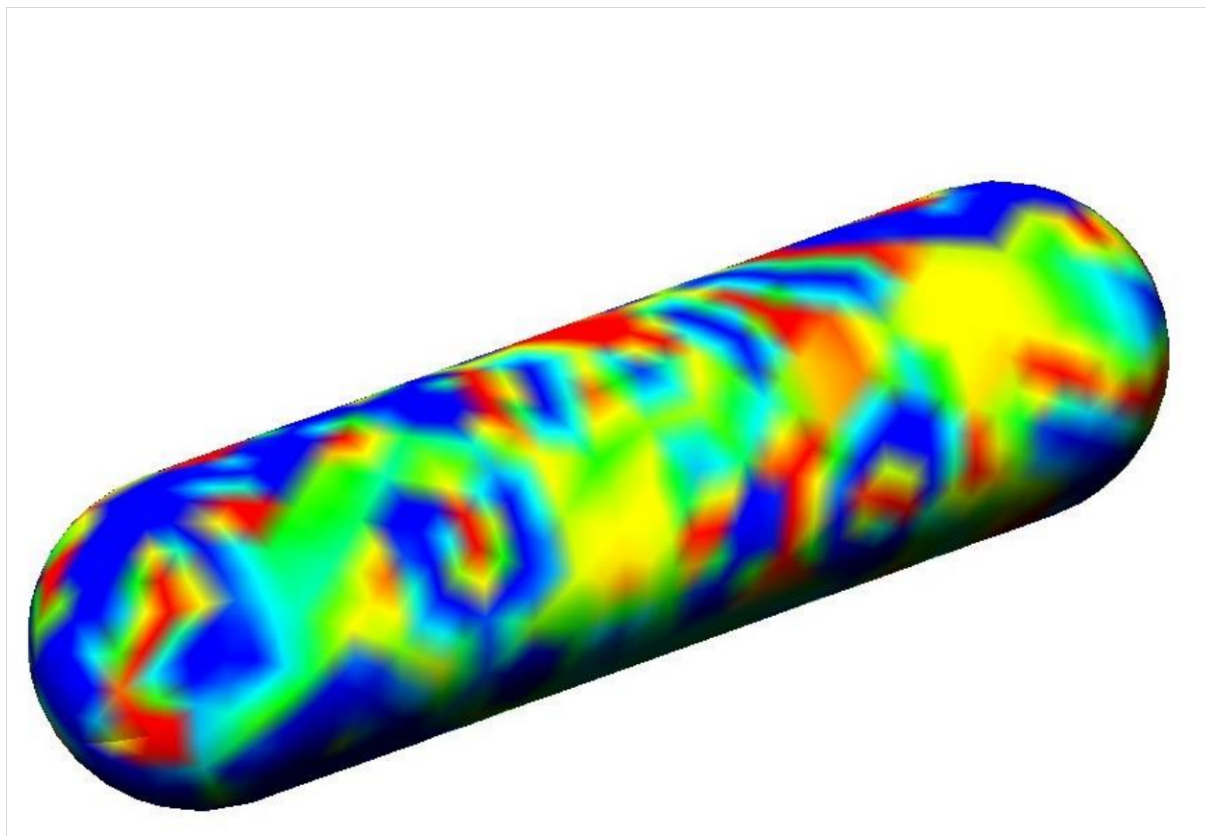


Figure 2.10 – Picture of the stress state of the calculation model of the boiler of a tank wagon under the influence of temperature loads

It was found that the maximum stress value is 157 MPa and does not exceed the permissible values.

### **SECTION 3**

#### **CREATION OF CONCEPTUAL SOLUTIONS FOR THE MANUFACTURE OF COMPONENT FREIGHT WAGONS FROM COMPOSITES**

The section presents patented [123-150] concepts for freight wagons made of composites.

The main advantages of composite materials are high strength values and lower, compared to similar materials, density values, high controllability of the corresponding physical and mechanical characteristics. Such advantages can be purposefully used and purposefully improved when creating various types of composites. At the same time, depending on the expected characteristics, it is possible to manage the availability of reinforcement and fastening means. And accordingly, such advantages and technological development of modern production increasingly lead to the use of composites in comparison with traditional structural materials.

It should be noted that the characteristics of composites directly depend on the quality and properties of the included component components. Namely matrices and reinforcement. At the same time, the composite connection of the included elements allows you to obtain their complementary properties. What cannot be achieved in traditional designs, where the included elements work in separate functional sectors.

The range of useful properties of composite materials is very significant. So, in particular, it is possible to distinguish: times less mass, significantly increased service life, and others. Such advantages make composites undisputed leaders in fully ensuring the expected structural and functional properties in constructions of various purposes. Constructions of various types of mechanical engineering are characterized by: exceptional perfection, controlled anisotropy



of physical and mechanical properties, life cycle increased many times, resistance to aggressive environmental influences.

It can be argued that with the help of technologies for the production of composite materials, it is possible to create their samples for each individual structure. That is, to manufacture component structural elements that will fully satisfy functional needs.

In order to determine service life of the bearing structure of a freight wagon, we used the methodology given in the works of Afanasyev A. V.

In accordance with the methodology, the probability of failures  $P_i$  of the elements of the bearing structure of the wagon in operation is determined by the formula

$$P_i = \frac{\sum_{k=1}^k \frac{R_H}{R}}{k}, \quad (3.1)$$

where

$k$  – the number of railcars examined;

$R_H$  – number of defective elements of the same type in the wagon;

$R$  – the total number of elements of the same type.

The estimated design life was determined by the formula

$$T_k = \frac{\left( \frac{\sigma_{a_i N}}{[n]} \right)^m \cdot N_0}{N_{cI} \cdot \sum_j \left( \sigma_{a_j}^I \right)^m \cdot P_j^I + N_{cII} \cdot \sum_k \left( \sigma_{a_k}^{II} \right)^m \cdot P_k^{II}}, \quad (3.2)$$

where

$\sigma_{aiN}$  – average value of the endurance limit;

$[n]$  – permissible safety factor;  $N_0$  – base of examinations;

$N_{cI}, N_{cII}$  – number of defective structural elements of the wagon under examination;  $m$  – the indicator of the degree of fatigue curve;

$\sigma_{aj}^I, \sigma_{ak}^{II}$  – tensile strength of the studied structure material;

$P_j^I, P_k^{II}$  – probability of failure of a structural element.

The research was conducted on the bearing structure of the load-bearing structure of the model 12-4745 freight wagon (Figure 3.1). At the same time, computer models were built based on its existing (Figure 3.1) and prospective (Figure 3.2) structural schemes from composite materials.

The geometric parameters of the main bearing elements of the frame were determined during field studies and reported in the work [86].

The results obtained allowed us to conclude that the design service life of the bearing structure of the freight wagon is at least 50 years.

To study the dynamic load of a freight wagon a calculation was performed. The mathematical model formed by Professor Bogomaz H. I. was used, taking into account its adaptation to determine the dynamic.





Figure 3.1. End wall of freight wagon model 12-4745. Existing design scheme



Figure 3.2. End wall of freight wagon model 12-4745. Prospective design scheme

At the initial stage of research, the longitudinal load of the bearing structure of the freight wagon under shunting collision was taken into account.

$$M'_B \cdot \ddot{x}_B + M' \cdot \ddot{\varphi}_B = P_l, \quad (3.3)$$

$$I_B \cdot \ddot{\varphi}_B + M' \cdot \ddot{x}_B - g \cdot \varphi_B \cdot M' = \\ = l \cdot F_{TP}(\text{sign} \dot{\Delta}_1 - \text{sign} \dot{\Delta}_2) + l(C_1 - C_2), \quad (3.4)$$

$$M_B \cdot \ddot{z}_B = C_1 + C_2 - F_{TP}(\text{sign}\dot{\Delta}_1 - \text{sign}\dot{\Delta}_2), \quad (3.5)$$

where

$$M'_B = M_B + 2 \cdot m_T + \frac{n \cdot I_{kp}}{r^2}; \quad M' = M_B \cdot h;$$

$$C_1 = k_1 \cdot \Delta_1; \quad C_2 = k_2 \cdot \Delta_2;$$

$$\Delta_1 = z_B - l \cdot \varphi_B; \quad \Delta_2 = z_B + l \cdot \varphi_B,$$

$M_B$  – mass characteristics of the load-bearing structural component of the freight wagon;

$I_B$  – the moment of inertia of the flat wagon relative to the longitudinal axis;

$P_l$  – the value of the shock load in the auto coupling along the axis;

$m_T$  – wagon weight;

$I_{kp}$  – the moment of inertia of the wheel pair;

$r$  – the radius of the average worn wheel;

$n$  – presence of the crew;

$l$  – half base of the freight wagon;

$F_{TP}$  – absolute value of the dry friction force in the spring set;

$k_1, k_2$  – spring stiffness of the spring suspension of the freight wagon wagons;

$x_B, \varphi_B, z_B$  – corresponding coordinates.

It is taken into account that the freight wagon is loaded with a conditional cargo, taking into account the use of the full load capacity. The flat wagon is assumed to be supported by 18-100 wagons. The impact on the coupler is considered to be absolutely rigid.

Differential equations (3 - 5) were solved in the MathCad software package [88, 90]. The initial displacements and velocities were set to zero [87-90]. The longitudinal shock load acting on the vertical surface of the rear stop of the auto coupling is set at zero level 3.5 MN [96-112].

As a result of the calculations, it was found that the acceleration acting on the load-bearing structural system of the freight wagon is equal to  $37.7 \text{ m/s}^2$ .

The vertical load of the bearing structure of the flat wagon was also investigated. The study used a mathematical dependence developed by Dr. tech., prof. Yuriy Demin. It was established that the main indicators of the flat wagon dynamics do not exceed the permissible ones. At the same time, the acceleration of the bearing structure of the freight wagon in the center of mass was  $5.5 \text{ m/s}^2$ . The calculated accelerations do not exceed the standard values [91-94].

The force of bulk load spacer on the side walls and end doors of the freight wagon body, determined according to the methodology given in [95-98]. According to this methodology [96-112], it is assumed that the load of the bulk cargo spacer on the side walls of the wagon body is distributed according to the law of a triangle with a maximum at its base, and on the end wall - according to the law of a trapezoid. The maximum loads near the bases of the side wall racks are determined:

$$q_1 = 0,5 \cdot p_a \cdot l_1, \quad (3.6)$$

$$q_2 = 0,5 \cdot p_a \cdot (l_1 + l_2), \quad (3.7)$$

$$\dots\dots\dots q_3 = 0,5 \cdot p_a \cdot (l_2 + l_3), \quad (3.8)$$

$$q_4 = 0,5 \cdot p_a \cdot (l_3 + l_4), \quad (3.9)$$

де  $p_a$  – active (static) pressure of bulk load spacer, which occurs per unit surface area of the vertical wall at floor level, kPa;

$l_1$  – the distance from the end beam of the frame to the geometric axis of the wagon hee, m;

$l_2$  – the distance from the geometric axis of the wagon heel to the second body rack, m;

$l_3$  – the distance from the second pillar of the body to the third, m;

$l_4$  – the distance from the third pillar of the body to the vertical geometric axis of the wagon body, m.

The active pressure of the spacer of the bulk cargo is determined by the formula:

$$p_a = \gamma \cdot g \cdot H \cdot \operatorname{tg}^2 \left( \frac{\pi}{4} - \frac{\varphi}{2} \right), \quad (3.10)$$

where  $\gamma$  – density of bulk cargo, t/m<sup>3</sup>;

$H$  – height of the side wall, m;

$\varphi$  – the angle of the natural slope of the load, rad;

$g$  – acceleration of gravity, m/s<sup>2</sup>.

Taking into account the characteristics of hard coal, the active pressure of the bulk cargo on the side wall of the wagon body was (kN/m<sup>2</sup>):

$$P_a^I = 0,9 \cdot 9,81 \cdot 2,315 \cdot \operatorname{tg}^2 \left( \frac{\pi}{4} - \frac{0,52}{2} \right) = 6,86$$

$$P_a^{III} = 0,9 \cdot 9,81 \cdot (1 + 0,12) \cdot 2,315 \cdot \operatorname{tg}^2 \left( \frac{\pi}{4} \right) = 22,86$$



The calculated values of the forces of bulk cargo spacer on the side walls of the freight wagon body are given in the table 3.1.

Table 3.1 The numerical value of the pressure of the spacer of the bulk cargo on the elements of the side wall of the body of the freight wagon

| Side wall vertical stay                                                   | Flowable freight pressure, kPa |
|---------------------------------------------------------------------------|--------------------------------|
| side:<br>I r. c.                                                          | 6,104                          |
| III r. c.                                                                 | 22,5                           |
| the first vertical stay from<br>the side of the stub end:<br>I r. c.      | 12,45                          |
| III r. c..                                                                | 42,37                          |
| the second vertical stay<br>from the side of the stub<br>end::<br>I r. c. | 10,987                         |
| III r. c.                                                                 | 38,75                          |
| the third vertical stay from<br>the side of the stub end:<br>I r. c.      | 7,63                           |
| III r. c.                                                                 | 28,68                          |

The pressure of an unevenly distributed load, which is applied to the end door leaf, is determined by the formula:

$$p = p_a + p_n, \quad (3.11)$$

where  $p_n$  – passive pressure of bulk cargo, in which the square of the tangent of the difference of two angles is replaced by the square of the tangent of their sum and taking into account the coefficient of vertical dynamics, as well as the angle of natural slope (kN/m<sup>2</sup>):

$$P_n^I = 0,9 \cdot 9,81 \cdot 2,315 \cdot \operatorname{tg}^2 \left( \frac{\pi}{4} + \frac{0,52}{2} \right) = 60,7$$

$$P_n^{III} = 0,9 \cdot 9,81 \cdot 2,315 \cdot \operatorname{tg}^2 \left( \frac{\pi}{4} \right) = 24,9$$

The intensity of the trapezoidal load falling on the corner post is determined:

$$q_{T1}^H = 0,5(p_a + p_n) \cdot b_1; \quad (3.12)$$

$$q_{T1}^6 = 0,5 \cdot p_n \cdot b_1; \quad (3.13)$$

on the intermediate rack:

$$q_{T2}^H = 0,5(p_a + p_n) \cdot (b_1 + b_2); \quad (3.14)$$

$$q_{T2}^6 = 0,5 \cdot p_n \cdot (b_1 + b_2); \quad (3.15)$$

on the middle rack:



$$q_{T3}^H = 0,5(p_a + p_n) \cdot b_2; \quad (3.16)$$

$$q_{T3}^6 = 0,5 \cdot p_n \cdot b_2 \quad (3.17)$$

The calculated values of the forces of bulk cargo spacer on the end wall of the freight wagon body are given in the table 3.2.

Table 3.2 The numerical value of the pressure of the spacer of the bulk cargo on the elements of the end wall of the body of the freight wagon

| Gangway door element        | Flowable freight pressure, kPa |
|-----------------------------|--------------------------------|
| corner vertical stay        | 49,73                          |
| I r. c.                     | 43,55                          |
| III r. c.                   | 34,81                          |
|                             | 17,36                          |
| intermediate vertical stay: | 99,78                          |
| I r. c.                     | 88,76                          |
| III r. c.                   | 69,88                          |
|                             | 35,76                          |
| middle vertical stay:       | 49,37                          |
| I r. c.                     | 43,88                          |
| III r. c.                   | 34,53                          |
|                             | 17,47                          |

In addition, the model takes into account the reactions in the hinge nodes caused by the action on the supporting structure of lateral and longitudinal forces.

The accelerations obtained during the modeling of dynamic loading were used to determine the strength characteristics of the load-bearing structural system of the freight wagon. This was done by applying the finite element method on the software and computer base of the engineering software packages SolidWorks Simulation and CosmosWorks [89, 90].

The graph-analytical method was used to determine the number of finite elements [91-95]. Tetrahedra with isoparameters were used as finite elements [96-98]. Quantitatively, the mesh includes: 922345 elements, 301567 nodes. The size of the maximum element was 90 mm, the minimum – 15 mm, the sides have a maximum ratio of 5042.7, the percentage of elements with sides less than 3 is 37.4, and more than 10 - 10.2. The model was fixed in areas that rely on running modules (wagons). The structural material used was composites.

To determine the profile of the vertical posts, a calculation was performed using the method of sections [61]. The results of the calculations allowed us to determine a possible profile of the racks  $\Omega$  - a similar profile with a value of  $W_x = 118.2 \text{ cm}^3$  and  $W_y = 119.3 \text{ cm}^3$ . The geometric parameters of the body cladding were assumed to be identical to the prototype wagon.

The following loads were taken into account when drawing up the design scheme of the bearing structure of the freight wagon: vertical  $P_v$  and longitudinal  $N$ . It was also taken into account that the full carrying capacity of the freight wagon loaded with a conditional load was used. The calculation was performed for the main design modes.

The maximum values of equivalent stresses were recorded at the points of interaction between the girder beam and the pivot beam and amounted to 333.4

MPa, and, accordingly, did not exceed the maximum permissible values, which are equal to the yield strength of the material.

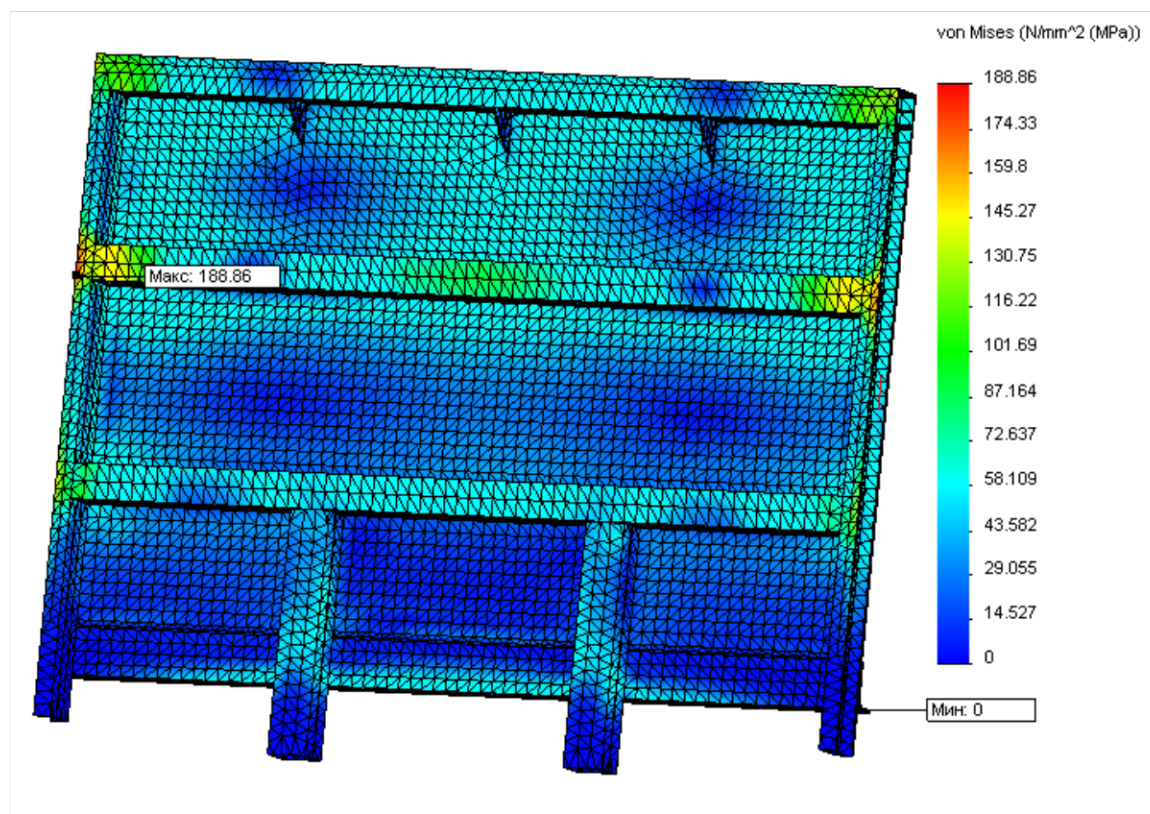


Figure 3.3 A fragment (end wall) of the strength calculation results. Existing design scheme



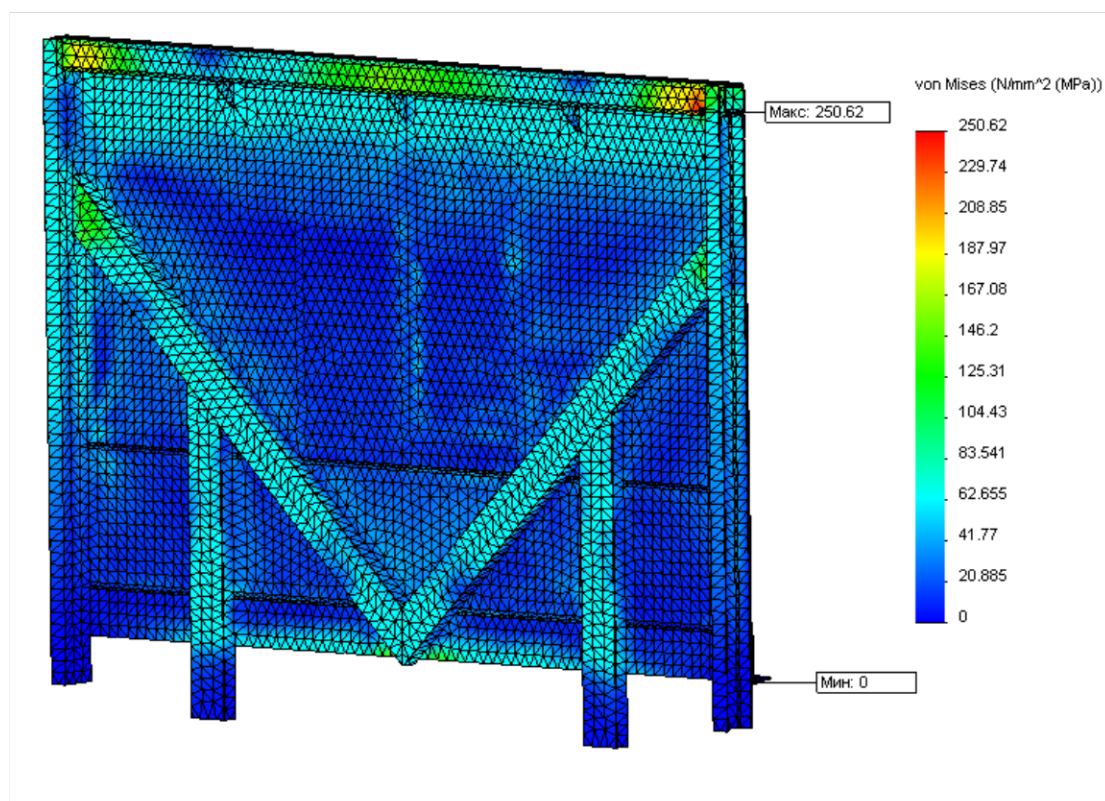


Figure 3.4 A fragment (end wall) of the strength calculation results. Prospective design scheme

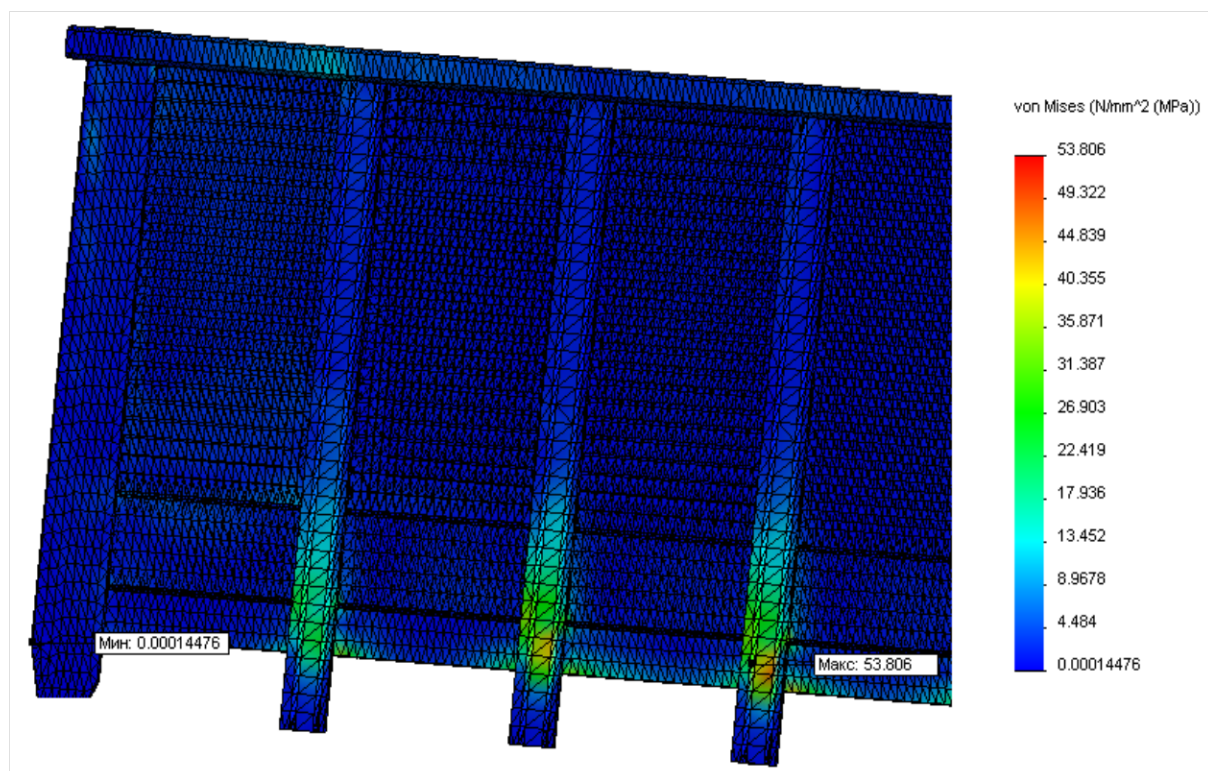


Figure 3.5 A fragment (side wall) of the strength calculation results. Existing design scheme

With other loading schemes, the strength of the flat wagon's supporting structure is also ensured.

Taking into account the capabilities of transportation of steel in coils on the flat wagon model 13-401, it is proposed to install cradles on its supporting structure for fastening steel coils (Figure 3-5).

The results of the calculations showed that the strength of the improved bearing structures of freight wagons is ensured. At the same time, the maximum stresses were recorded in the zones of interaction between the girder beam and the pivot beams, but these stresses do not exceed the permissible ones.

It is important to note that the proposed improvement is also other possible by using composite components in the bearing structures of wagons. Preliminary calculations conducted by the authors showed that this solution is effective. In this case, a composite with a titanium matrix is used, which is reinforced with boron, borsic, silicon carbide, beryllium, and molybdenum fibers. Such a composite has high heat resistance and significant tensile strength: in the fiber direction it is 1100-1300 MPa, in the transverse direction - 650 MPa. However, the widespread introduction of such an improvement is constrained by the cost of the material.

## **SECTION 4**

### **ANALYSIS OF THE STRENGTH OF THE COMPOSITE MODULE OF THE BODY WAGON-COAL TRUCK**

The section presents patented [123-140]. concepts for freight wagons made of composites.

Smooth and efficient operation of railways is an important factor in the existence and development of the country's economy. At the same time, a significant amount of cargo transportation carried out by rail transport is bulk cargo that does not require protection from atmospheric precipitation. Among such cargoes, in terms of the largest volumes of transportation, it is possible to single out hard coal. Traditionally, universal and deep-bottom semi-wagons are used to transport hard coal by rail. And accordingly, the efficiency of such transportation largely depends on the level of their technical, economic and operational indicators. However, it should be noted that the structures of the modern domestic fleet of semi-trailers were designed in the last century, and accordingly based on the technologies and achievements in materials science of those times. In addition, the vast majority of the semi-wagon fleet has already reached the end of its intended service life and is therefore awaiting renewal. From the above, it can be concluded that the creation and implementation of

innovative component structures of semi-trailers is an important and urgent problem.

Among the main modules (crew part module, coupling and braking equipment modules) of semi-wagons, the body module is characterized by the largest material capacity. Therefore, its improvement to reduce its own weight and correspondingly increase the wagon's carrying capacity has development potential. In addition, an important problem is to increase the term of its operation with a corresponding reduction in costs. Therefore, the improvement of the freight wagon body module can rightly be considered one of the main tasks faced by scientists and designers, the activity is related to technical development in railcar construction.

The results of expert evaluations confidently point to the prospects of creating composite wagon modules for the transportation of hard coal as the main cargo, and the possibility of transporting other bulk cargoes that do not require protection from atmospheric precipitation. At the same time, before the design stage of the creation of a composite concept of the body of a coal-carrying wagon, a number of issues of a scientific nature must be resolved. And accordingly, such questions were posed and resolved as the goal and tasks of scientific and applied research, the results of which are presented in the scientific research.



The purpose of the analysis of the latest research and publications was to consider the existing developments, which highlight the results of the work on the creation of mathematical and computer models for the study of the strength of transport structures. As well as works devoted to the study of the strength of composite materials.

In works [124-128], the results of the study of the composite material proposed by the authors for use in vehicles are given. At the same time, the mathematical model, on the basis of which various properties of the material were considered in a variational manner, was not adopted for the possibility of research and use on rolling stock of railways.

In scientific researchs [129-135], a new computer model is proposed for analyzing the possibilities of the composite performance of the carrier module of the vehicle. At the same time, the possibility of using such a model for the perception of significant (over 3 MN) loads was not considered.

In works [136-145] the problem of transportation of bulk goods by sea transport is considered. It was determined that a promising way to increase the efficiency of vehicles in the transportation of bulk cargo (including hard coal) is to reduce the tare weight of vehicles through the use of composites. At the same time, in the scientific research [146], the authors continued their research on the search for modern solutions to improve the efficiency of transportation. At the same time, the main attention is paid to the issue of optimizing the interaction of

different types of transport. However, attention was not paid to the problems of individual vehicle modules.

The authors of the paper [147-153] investigated the prospects of using new power solutions in the load-bearing systems of machine-building facilities. However, the developed approach did not take into account the possibility of proposed solutions for other transport structures.

In a scientific study [154-161], a solution was found for mathematical modeling of the stress-strain state of a combined reinforced structure. Features of perception and redistribution of efforts by frame elements are also defined. However, the possibility of manufacturing a solid composite body, and accordingly the features of its functioning in terms of load perception, were not investigated.

Scientific researches [162-167] are devoted to the study of the strength of the freight wagon body at a separate stage of its life cycle. At the same time, it was found that the further development of wagon structures using the latest materials and technologies of their application. the perspective of the use of composites is highlighted.

The work [168] is devoted to the study of the stress-strain state of traction rolling stock. However, the issue of applying the developed models and methods for freight wagons was not considered.

In the paper [45], the authors studied the force processes in the components of the rolling stock. But the influence of external forces on the frame elements of the carrier system was not investigated.

Publications [46-48] are devoted to the problems of rolling stock. The features of the force interaction of body components and individual units are separately highlighted. Appropriate mathematical descriptions and computer models have been developed. However, their use for freight wagons was not considered.

The authors of the scientific researches [49-52] paid attention to the scientific search for solutions regarding the load on the elements of the wagon. However, the possibility of using composites for these purposes was not considered.

Scientific publications [53, 82] are devoted to highlighting the results of improving the designs of freight wagons. The main focus is on reducing dynamic forces from the undercarriage module.

The semi-momentless shell theory [96-112] is used for the mathematical calculation of the proposed body module. In the general case, there are five internal forces on the cross-sectional and longitudinal sections: normal forces  $T_x$  and  $T_t$  (the subscripts  $x$ ,  $t$  denote the transverse and longitudinal cross-sectional planes, respectively), shear forces  $S$ , which are the same on both sites due to the parity of the tangential stresses, bending moments  $M_x$  and  $M_t$ , transverse forces

$Q_x$  and  $Q_t$ , torques  $M_{xt} = M_{tx}$  - assumed to be equal in parity of tangential stresses. In the semi-momentless theory, the values  $M_x$ ,  $Q_x$ ,  $M_{xt}$ ,  $M_{tx}$  are assumed to be zero for small values.

Efforts and displacements determine the stressed-deformed state of the object under consideration.

All quantities are functions of two coordinates  $x$  and  $\varphi$ , and forces have the dimension of intensity. Therefore, by multiplying these forces by  $dx$  or  $Rd\varphi$ , their equivalent forces are determined. With an increase in coordinates by  $dx$  or  $Rd\varphi$ , these equivalent forces, like the displacements, get an increase.

In the theory of shells, in the general case, linear deformations  $\varepsilon_x$  and  $\varepsilon_t$ , angular deformation or shear deformation  $\gamma_{xt}$ , curvature deformations  $\chi_x$  and  $\chi_t$  and torsion  $\chi_{xt}$  are established. They are expressed through displacements  $w$ ,  $v$ ,  $u$ . We will write down those of them that will be needed when deriving the permissive equations that represent the complete system of the semi-momentless theory

$$\left. \begin{aligned} \varepsilon_x &= \frac{\partial u}{\partial x} \\ \varepsilon_t &= \frac{\partial v}{R \partial \varphi} + \frac{w}{R} \\ \gamma_{xt} &= \frac{\partial v}{\partial x} + \frac{\partial u}{R \partial \varphi} \\ \chi_t &= \frac{1}{R^2} \left( \frac{\partial^2 w}{\partial \varphi^2} + w \right) \end{aligned} \right\} \quad (4.1)$$

In the semi-momentless theory, it is assumed that Poisson's ratio  $\mu=0$ , and  $\epsilon_t=l_{xt}=0$ , i.e., the elasticity ratio for forces  $T_t$  and  $S$  cannot be expressed through deformations. Such relations in the selected version of the shell theory make sense for the force  $T_x$  and  $M_t$

$$\left. \begin{aligned} T_x &= E\delta\epsilon_x \\ M_t &= \frac{E\delta^3}{12}\chi_t \end{aligned} \right\} \quad (4.2)$$

where  $E$  is the modulus of elasticity of the shell material;

$i = \frac{\delta^3}{12}$  is the moment of inertia of the cross-section of an elementary ring

of unit width separated from the cylindrical part by cross-sections.

Let's write the equilibrium equation of an infinitesimal element. This will be the sum of the projections of all the forces acting on the normal, the  $x$ -axis and the tangent  $y$  to the circle of the cross-section, as well as the moment about the  $x$ -axis. At the same time, we will keep in mind that the loads  $P_1, P_2, P_3$  are distributed over the surface on the platforms  $dx$  and  $Rd\phi$ . After dividing these equations by  $dx$  and  $d\phi$ , we get

$$\left. \begin{aligned} \frac{\partial Q_t}{\partial \varphi} + T_t - P_1 R &= 0 \\ \frac{\partial T_x}{\partial x} R + \frac{\partial S}{\partial \varphi} + P_2 R &= 0 \\ \frac{\partial T_t}{\partial \varphi} + \frac{\partial S}{\partial x} R - Q_t + P_2 R &= 0 \\ \frac{\partial M_t}{\partial \varphi} - Q_t R &= 0 \end{aligned} \right\} \quad (4.3)$$

Geometric equations (4.1), physical relations (4.2) and static equations (4.3), taking into account the hypotheses of the semi-momentless theory, allow us to obtain a solution to the problem of determining additional internal forces at the control points of the composite module of the coal wagon body, caused by the deformations of the contour of its cross sections. Let's transform these equations into a form convenient for solving, abandoning the traditional approach adopted in the theory of semi-momentless shells, in which, when transforming the load,  $P_1$ ,  $P_2$ ,  $P_3$  are differentiated by any variable. Load distribution functions have a discontinuous nature (support pressure and other intermittent loads), and therefore their differentiation operations must be treated carefully.

Using the last equation of system (4.3) and eliminating the forces from the remaining equilibrium equations

$$Q_t = \frac{\partial M_t}{R \partial \varphi} \quad (4.4)$$

we will get

$$\left. \begin{aligned} \frac{\partial^2 M_t}{R \partial \varphi^2} + T_t - P_1 R &= 0 \\ \frac{\partial T_x}{\partial x} R + \frac{\partial S}{\partial \varphi} + P_2 R &= 0 \\ \frac{\partial T_t}{\partial \varphi} + \frac{\partial S}{\partial x} R - \frac{\partial M_t}{R \partial \varphi} + P_3 R &= 0 \end{aligned} \right\} \quad (4.5)$$

Since there are no elasticity ratios for the forces  $T_t$  and  $S$ , they can only be found from the equilibrium equations (4.5). Let's transform these equations, eliminating the forces  $T_x$  and  $M_t$ , using the relation (4.2) and the hypotheses  $e_t=0$  and  $\gamma_{xt}=0$ .

Based on the hypotheses, we get

$$\left. \begin{aligned} w &= -\frac{\partial v}{\partial \varphi} \\ \frac{\partial u}{\partial \varphi} &= -\frac{R \partial v}{\partial x} \end{aligned} \right\} \quad (4.6)$$



Using the first and last ratio (4.1), we obtain formulas (4.2) and (4.3).

$$\left. \begin{aligned} T_x &= -E\delta \int_{\varphi} \frac{\partial^2 v}{\partial x^2} R d\varphi \\ M_t &= -\frac{E\delta^3}{12R^2} \left( \frac{\partial^3 v}{\partial \varphi^3} + \frac{\partial v}{\partial \varphi} \right) \end{aligned} \right\} \quad (4.7)$$

Substituting  $T_x$  and  $M_t$  expressed by formula (4.6) into the system of equations (4.4)

$$\left. \begin{aligned} -\frac{E\delta^3}{12R^3} \left( \frac{\partial^5 v}{\partial \varphi^5} + \frac{\partial^3 v}{\partial \varphi^3} \right) + T_t - P_1 R &= 0 \\ E\delta \int_{\varphi} \frac{\partial^3 v}{\partial x^3} R^2 d\varphi - \frac{\partial S}{\partial \varphi} - P_2 R &= 0 \\ \frac{\partial T_t}{\partial \varphi} + \frac{\partial S}{\partial x} R + \frac{E\delta^3}{12R^3} \left( \frac{\partial^4 v}{\partial \varphi^4} + \frac{\partial^2 v}{\partial \varphi^2} \right) + P_3 R &= 0 \end{aligned} \right\} \quad (4.8)$$

The system of integral differential equations (4.8) reflecting the equilibrium conditions of an infinitesimally small element of the shell is obtained taking into account geometric and physical relationships, i.e. it is equivalent to all three groups of equations of the shell theory taking into account the hypotheses of the semi-momentless theory. The system of equations is complete - three equations with three unknowns.

The laws of distribution of loads falling on the central part are such that they can be represented by double trigonometric series with coefficients  $P_{1mn}$ ,  $P_{2mn}$ ,  $P_{3mn}$  determined by Fourier formulas

$$\left. \begin{aligned} P_1 &= \sum_{m=1}^{\infty} \sum_{n=2}^{\infty} P_{1mn} \cos n\varphi \sin \lambda x \\ P_2 &= \sum_{m=1}^{\infty} \sum_{n=2}^{\infty} P_{2mn} \cos n\varphi \cos \lambda x \\ P_3 &= \sum_{m=1}^{\infty} \sum_{n=2}^{\infty} P_{3mn} \sin n\varphi \sin \lambda x \end{aligned} \right\} \quad (4.9)$$

where  $m$  and  $n$  are the numbers of members of the series ( $m$  - from one to infinity;  $n$  - from two to infinity);

$$\lambda = \frac{m\pi}{2L_y} \quad (4.10)$$

The selected combination of trigonometric functions in formula (4.9) reflects the nature of the distribution of movements caused by the corresponding load.

So, for the adopted calculation scheme, at  $x=0$  and  $x=2L$ , there should be no displacements of  $w$  and  $v$  (the contour of the cylinder at the end diaphragms is not deformed), and the shell can slide along the diaphragm along the generating cylinder, i.e.  $u \neq 0$ . When the load is symmetrical about the longitudinal vertical

plane of symmetry, the displacements  $w$  and  $u$  are symmetrical, and  $v$  is obliquely symmetrical.

The nature of the distribution and self-equilibrium of additional forces during deformations of the contour is reflected by counting  $n$ .

Thus, the displacement  $v$  can be represented (we omit the summation limits to simplify the notation) by an expression

$$v = \sum \sum v_{mn} \sin n\varphi \sin \lambda x, \quad (4.11)$$

and effort

$$\left. \begin{aligned} S &= \sum \sum S_{mn} \sin n\varphi \cos \lambda x \\ T_t &= \sum \sum T_{tmn} \cos n\varphi \sin \lambda x \end{aligned} \right\}, \quad (4.12)$$

Coefficients  $v_{mn}$ ,  $S_{mn}$ ,  $T_{tmn}$  are unknown. Let's imagine that the values of load factors  $P_{1mn}$ ,  $P_{2mn}$ ,  $P_{3mn}$  are obtained. Then we will use the principle of possible movements, taking the latter as

$$\left. \begin{aligned} w &= 1 \cdot \cos n\varphi \sin \lambda x \\ v &= 1 \cdot \sin n\varphi \sin \lambda x \\ u &= 1 \cdot \cos n\varphi \cos \lambda x \end{aligned} \right\}, \quad (4.13)$$

These expressions are continuous within the surface of the shell and correspond to the given boundary conditions at the finite sections.

Substitute series (4.11), (4.12) and (4.13) into the equilibrium equation (4.9), the first of which is equivalent to the projection of internal and external forces on the direction of movement  $w$ , the second - the projection on the movement  $u$ , and the third - the projection on the movement  $v$ . Let's calculate the work of these force projections on the corresponding possible displacements (4.13), and, as you know, this work must be zero. The work is calculated by integrating on the surface of the cylindrical part, i.e. within the range from  $x=0$  to  $x=2L_{ts}$  and from  $\varphi=0$  to  $\varphi=2\pi$ , expressions of the form

$$\left. \begin{aligned} & \int_0^{2L_u} \int_0^{2\pi} \left( \cos n\varphi \sin \frac{m\pi x}{2L_u} \right) \left( \cos k\varphi \sin \frac{i\pi x}{2L_u} \right) dx d\varphi \\ & \int_0^{2L_u} \int_0^{2\pi} \left( \sin n\varphi \sin \frac{m\pi x}{2L_u} \right) \left( \sin k\varphi \sin \frac{i\pi x}{2L_u} \right) dx d\varphi \\ & \int_0^{2L_u} \int_0^{2\pi} \left( \cos n\varphi \cos \frac{m\pi x}{2L_u} \right) \left( \cos k\varphi \cos \frac{i\pi x}{2L_u} \right) dx d\varphi \end{aligned} \right\} \quad (4.14)$$

Taking into account the orthogonality of the trigonometric functions, when  $n=k$  and  $m=i$ , these integrals are equal to  $L_u\pi$ , and when  $n \neq k$  and  $m \neq i$ , they are equal to zero.

As a result of the work calculation, the system of integral-differential equations (4.14) will be reduced to systems of algebraic equations with respect to the coefficients of the series  $v_{mn}$ ,  $S_{mn}$ ,  $T_{tmn}$

$$\begin{vmatrix} -\frac{E\delta^3}{12R^3}n^3(n^2-1) & 0 & 1 \\ \frac{E\delta R^2\lambda^3}{n} & -n & 0 \\ \frac{E\delta^3}{12R^3}n^2(n^2-1) & \lambda R & n \end{vmatrix} \times \begin{vmatrix} v_{mn} \\ S_{mn} \\ T_{tmn} \end{vmatrix} = \begin{vmatrix} P_{1mn}R \\ P_{2mn}R \\ P_{3mn}R \end{vmatrix} \quad (4.15)$$

From equation (4.15) we find the coefficients  $v_{mn}$ ,  $S_{mn}$ ,  $T_{tmn}$ , and from formula (4.13) the self-equilibrated forces  $T_t$  and  $S$  associated with deformations of the cross-section contour. The forces at the desired points are the summation of the series at the given coordinates  $x$  and  $\varphi$  of these points.

Dependencies (4.13) with known coefficients  $v_{mn}$  make it possible to determine the coefficients of the normal force  $T_x$  and the moment  $M_t$ :

$$\left. \begin{aligned} T_{xmn} &= -\frac{E\delta R\lambda^2}{n}v_{mn} \\ M_{tmn} &= \frac{E\delta^3}{12R^2}n(n^2-1)v_{mn} \end{aligned} \right\} \quad (4.16)$$

With these coefficients we will have

$$\left. \begin{aligned} T_x &= \sum \sum T_{xmn} \cos n\varphi \sin \lambda x \\ M_t &= \sum \sum M_{tmn} \cos n\varphi \sin \lambda x \end{aligned} \right\} \quad (4.17)$$

Tension

$$\left. \begin{aligned} \sigma_x &= \sigma + \frac{T_x}{\delta} \\ \sigma_t &= \frac{T_t}{\delta} \pm \frac{6M_t}{\delta^2} \\ \tau_{xt} &= \frac{S}{\delta} \end{aligned} \right\} \quad (4.16)$$

where  $\delta^2/6$  is the moment of resistance of an elementary shell strip of unit width.

Equivalent stresses calculated according to the deformation criterion

$$\sigma_e = \sqrt{\sigma_x^2 - \sigma_x \sigma_t + \sigma_t^2 + 3\tau_{xt}^2}, \quad (4.17)$$

To ensure the required strength, the condition must be met

$$\sigma_e \leq [\sigma], \quad (4.18)$$

Tangential loads are not taken into account in the calculation, while  $P_3=0$ . The pressure is distributed according to the law

$$q_1 = \gamma R (\cos \varphi - \cos \beta_0), \quad (4.19)$$

where  $\gamma$  – specific weight of cargo;  $\beta_0$  – the angle that determines the position of the free surface of the load.

This pressure exerts a rather weak influence on the internal forces in the shell (with the accepted dimensions of the thickness of its walls). To simplify the calculation, they are limited to taking into account the action of support loads. At the same time, it is advisable to choose the angular width of the planes  $\beta_2$ - $\beta_1$ , which is  $4^\circ$ , that is, the support is carried out on four planes of width  $R(\beta_2-\beta_1)$  and length (ba). The load  $q$  is oriented along the radius.

Then, according to the Fourier formulas, we will have

$$P_{1mn} = \frac{4}{\pi^2 mn} q (\cos \lambda a - \cos \lambda b) (\sin n\beta_2 - \sin n\beta_1), \quad (4.20)$$

For longitudinal load

$$P_{2mn} = \frac{4}{\pi^2 mn} r (\sin \lambda d - \sin \lambda c) (\sin n\beta_4 - \sin n\beta_3), \quad (4.21)$$

where  $r$  is the intensity of surface distributed longitudinal load.

With the help of the above methodology, the stresses at the control points were determined mathematically, on the basis of which the adequacy of the developed computer model was adjusted.



In order to improve the technical, economic and operational indicators of the design of the coal wagon, it is proposed to improve it by making a body module made of composite material (Figure 4.1). For example, a composite with a titanium matrix, which is reinforced with fibers of boron, badger, silicon carbide, beryllium, and molybdenum. Such a composite has high heat resistance and a significant strength limit: in the direction of the fibers it is 1100-1300 MPa, in the transverse direction - 650 MPa.

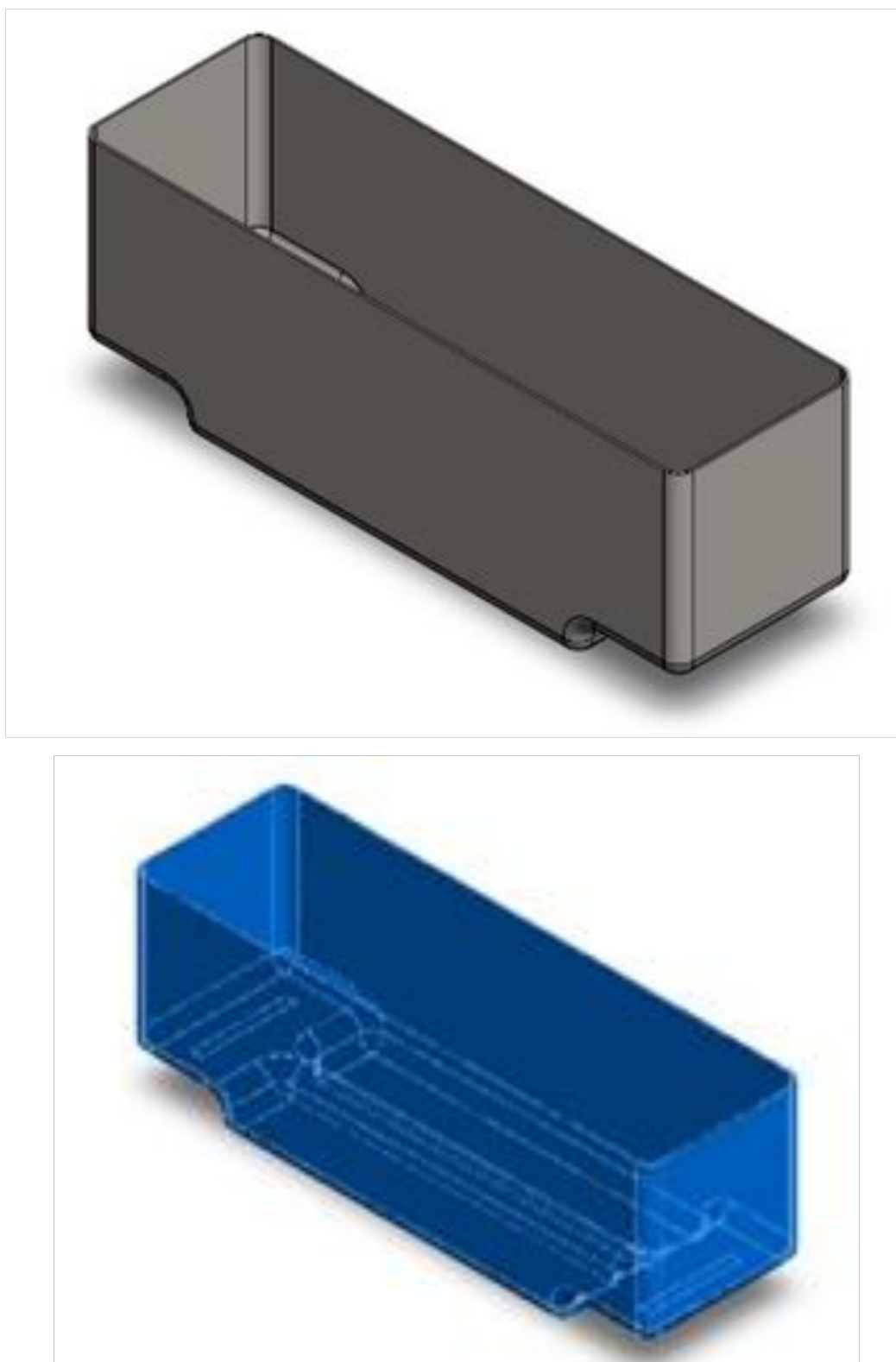


Figure 4.1. Computer spatial geometric model of the proposed concept of the composite module of the coal wagon body

It should be noted that the proposed innovation is possible for implementation, both during the manufacture of new wagon designs, as well as their modernization in the conditions of wagon repair enterprises.

To carry out calculations on the strength of the load-bearing structure of the proposed concept of the composite module of the body of a coal-carriage wagon, the calculation was carried out in a modern computing software complex. At the same time, the finite element method was applied. The mesh was created on a solid body taking into account the curvature. During calculations, isoparametric tetrahedra were used, the optimal characteristics of which are: the number of grid elements was 911782, nodes - 1551011. The maximum size of the grid element is 40.0 mm, the minimum is 13.3 mm, the maximum aspect ratio is 10.33, the percentage of elements with aspect ratio less than three – 100, more than ten – 0.00087. The minimum number of elements in a circle is 12, the ratio of increasing the size of an element is 1.8.

Fastening (Figure 4.3) of the model was carried out for the horizontal parts of the frills, that is, in the areas of abutment on the running parts. The construction material is composite.

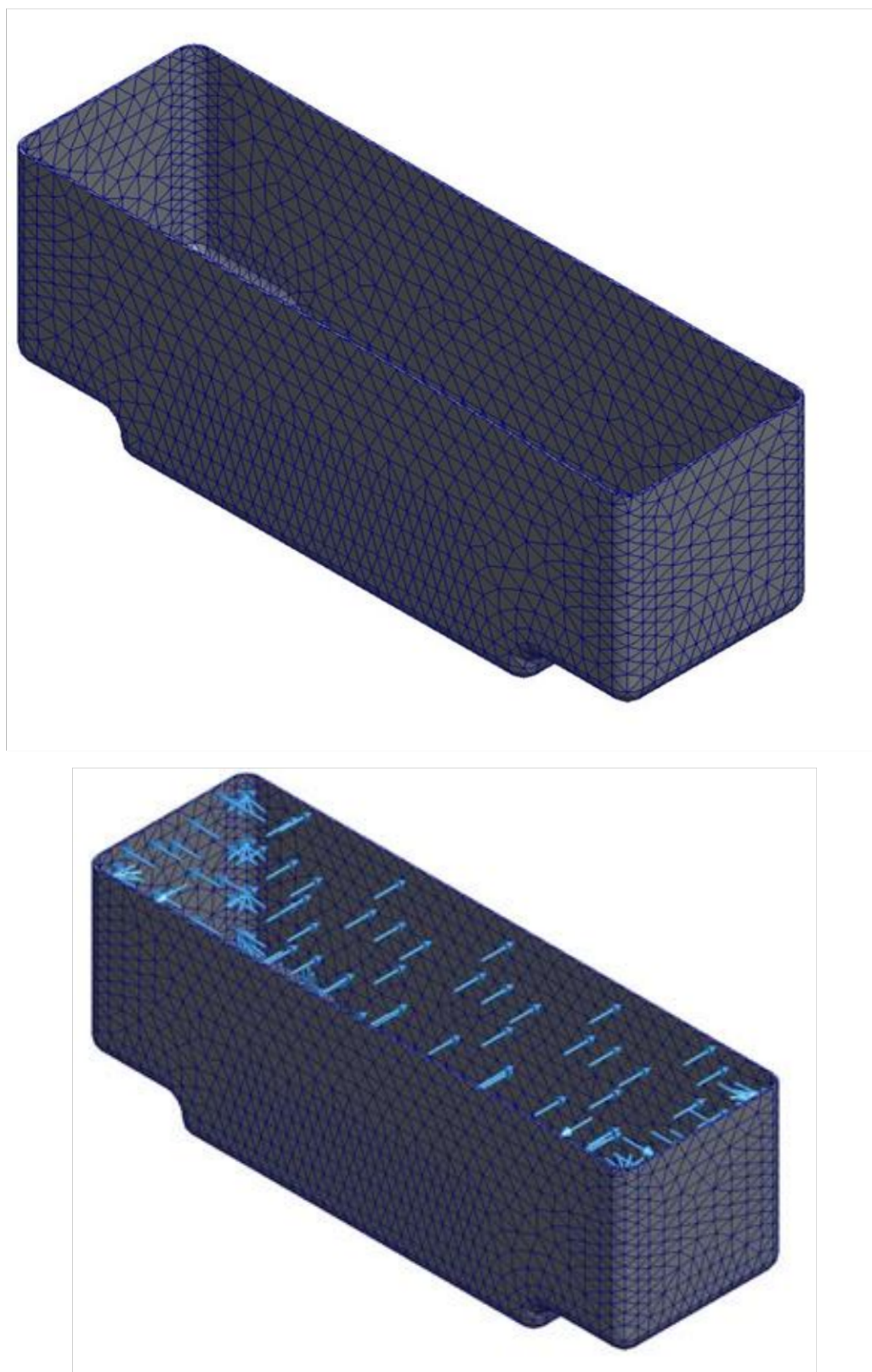


Figure 4.2. Finite element model of the proposed concept of the composite module of the body of a coal wagon

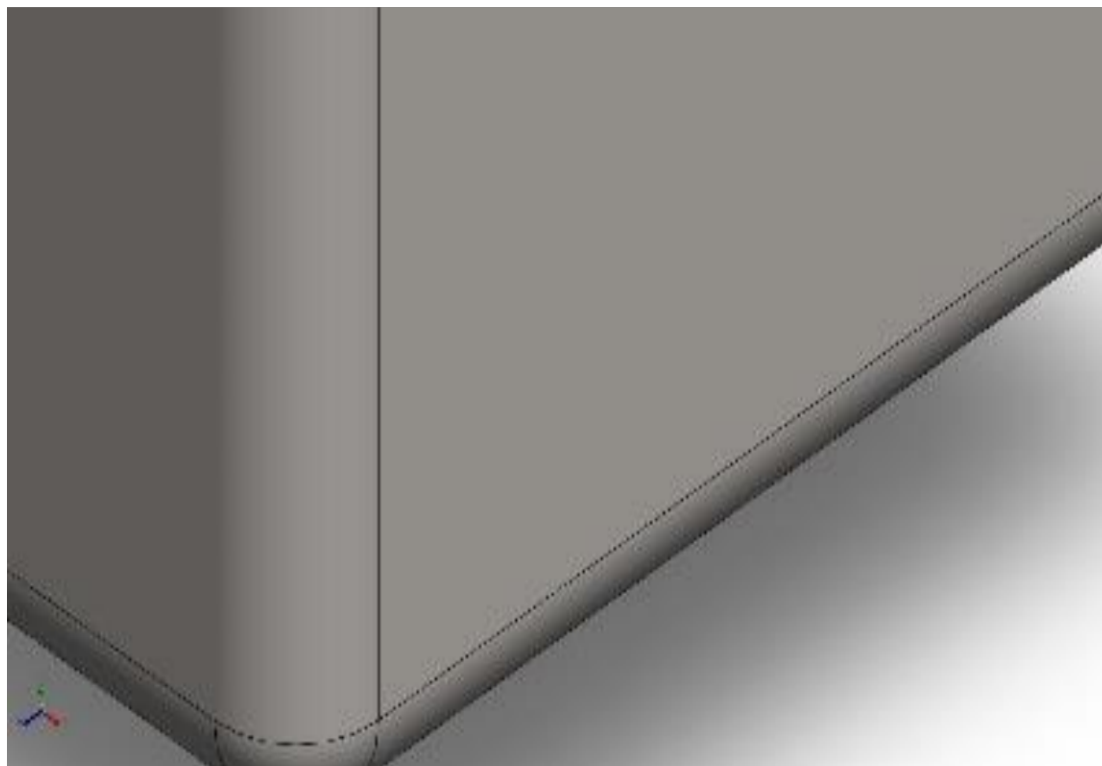


Figure 4.3. Fixing the model of the proposed concept of the composite module of the body of a coal-carrying wagon

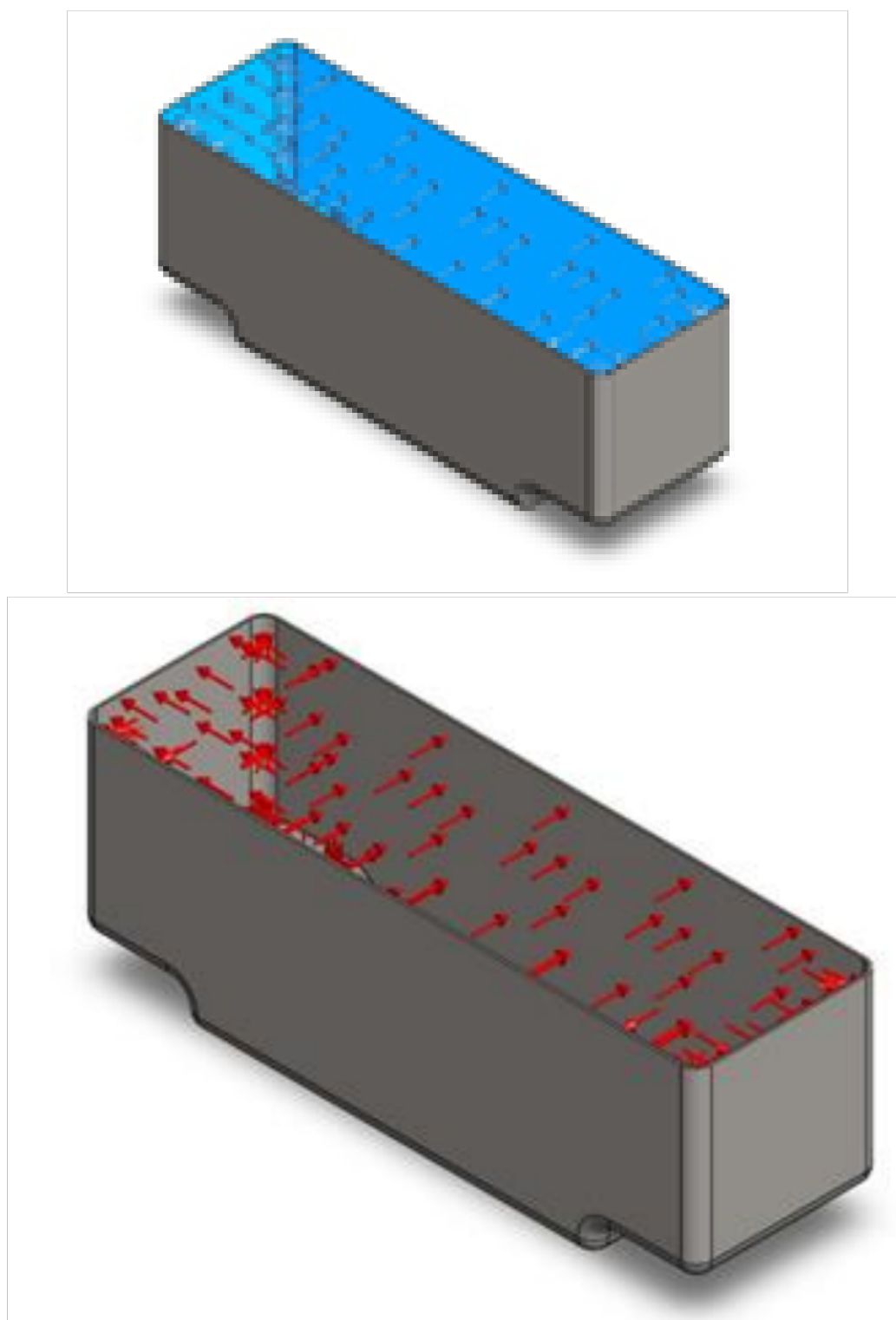


Figure 4.4. Application of loads to the model of the proposed concept of the composite module of the body of a coal-carrying wagon



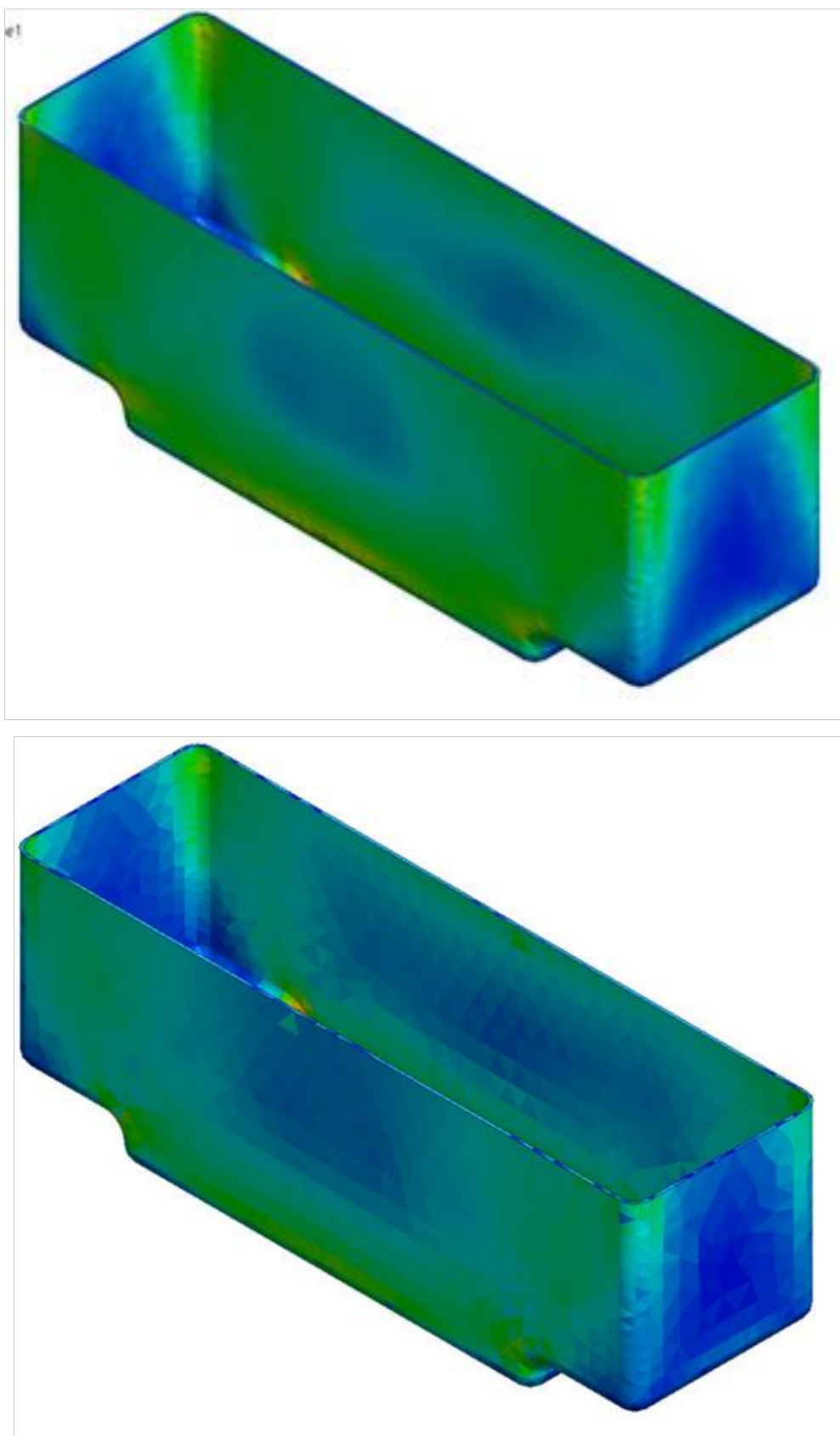


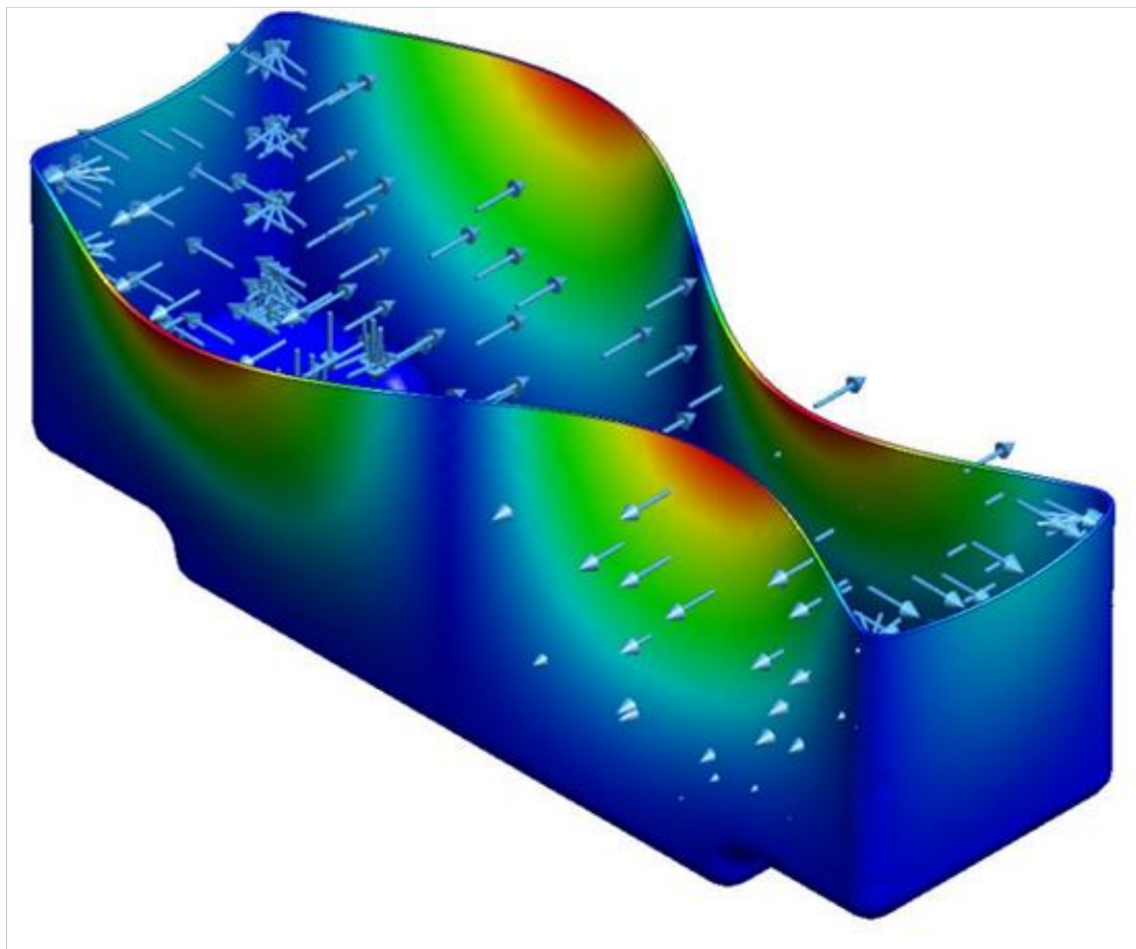
Figure 4.5. The stressed state of the model of the proposed concept of the composite module of the body of a coal-carrying wagon



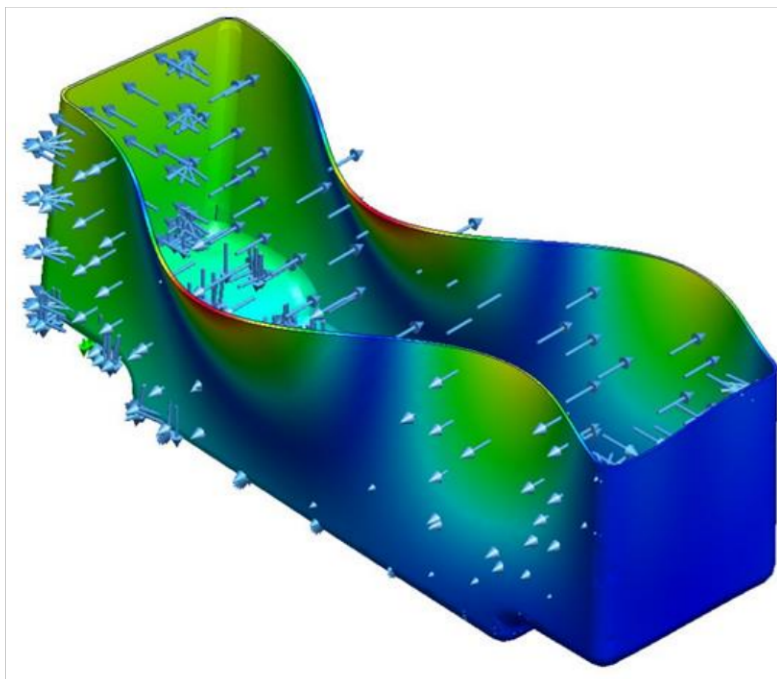
It was established that the maximum stress equivalents occur in the area of interaction between the body module and the crew module and are about 268 MPa. At the same time, the stress in the shell of the hopper wagon is about 177 MPa, which is 18% lower than in a typical design. So, the results of the study testify. that the maximum stresses occur in the cantilever parts of the body module. In the middle part, they sent about 176 MPa.

A modal analysis was conducted to determine the frequencies and forms of natural oscillations of the proposed concept of the composite module of the coal wagon body.

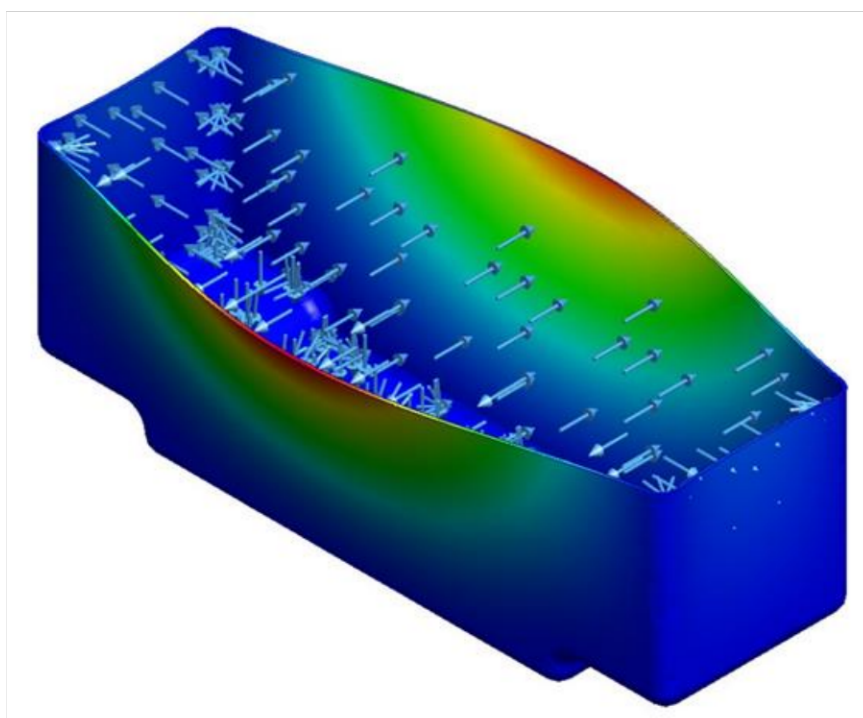
Some of the inherent forms of oscillations of the supporting structure of the hopper wagon are shown in Figure 4.6.



a)



*b)*



*c)*

Figure 4.6. Some forms of oscillationsof the proposed concept of the composite module of the coal wagon body(deformation scale 20:1): first mode – a; the second fashion - b; the third fashion - c

The calculation results established that the first natural frequency has a value of 9.7 Hz, i.e. not lower than the permissible value of 7.2 Hz. Therefore, the safety of the carriage is ensured.

At the next stage of the scientific and practical work, the fatigue resistance [96-112] of the proposed concept of the composite module of the body of a coal-carrying wagon was determined. Such studies were carried out with the determination and analysis of the coefficient of fatigue resistance reserve  $n$ , which is determined by the formula:

$$n = \frac{\sigma_{-1D}}{\sigma_{a,e}} \geq [n], \quad (4.22)$$

$\sigma_{and, is}$  – the calculated numerical value of the amplitude of the dynamic stress of the conventional symmetrical cycle, which will be added to the basic  $N_0$ , which is equivalent in terms of destruction to the value of the amplitudes taking into account the empirically determined stresses during the life cycle, MPa;

$[n]$  – the maximum allowable value of the fatigue resistance reserve factor.

When calculating fatigue  $\sigma_{a,e}$ , the determination of the equivalent summed amplitude of dynamic stresses in the case of an intermittent function of the distribution of stress amplitudes is carried out according to the formula:

$$\sigma_{a,e} = \sqrt[m]{\frac{N_c}{N_0} \sum_{i=1}^k P_{vi} f_{\epsilon} \sum_{i=1}^k \sigma_{ai}^m P_i} \quad (4.23)$$

where  $N_c$  is the total number of dynamic stress cycles determined for the calculated life cycle;

$p_{\sigma_i}$  and  $p_{v_i}$  are the probabilities of the appearance of stresses with the level of  $\sigma_{\sigma_i}$  in a given speed interval and the proportion of time that is determined during the operation of the wagon structure at the speed  $v_i$ ;

$\sigma_{AI}$ — level (degree) of stress amplitude, MPa;

$k_{\sigma_i}$  and  $k_{v_i}$  is the number of discretization stages, taking into account stress amplitudes and the range of movement speeds.

The results determined during the calculations proved that with the probability of the appearance of stresses with a level of  $\sigma_{\sigma_i}$ , which is 0.95 values  $\sigma_{\sigma_i} = 51.4$  MPa. And accordingly, the coefficient of the reserve of fatigue resistance is 4.5. Taking into account the absence of experimentally determined indicators, it can be assumed that the permissible value of the coefficient of the fatigue resistance reserve is equal to 2.2. Based on the above, it can be stated that the specified condition is fulfilled, and the fatigue strength of the composite module of the wagon body of the coal wagon is ensured.

## **GENERAL CONCLUSIONS**

1. The deformation of the space-reinforced fibrous material was studied. Such a material is considered as a multi-component material with a random arrangement of fibers. Determination of effective thermoelastic properties and stress-strain state of the material is based on stochastic differential equations of the theory of elasticity. The method of conditional moments is used to solve the problem. For the case of fibers located in a plane  $x_1x_2$  along the sides of the square and its diagonal the effective thermoelastic properties of the material are determined and the laws of the relationship between macrostresses and macrodeformations in the material and the dependence of the average deformations and stresses in the matrix of the material on macrodeformations or macrostresses, as well as the dependence of the material characteristics on the concentration of fibers, are established. An algorithm was built to determine the strength of the composite, based on the known strength of the matrix. The thermoelastic characteristics of the material and its strength were studied.
2. The scientific research presents the results of a scientific and applied research on the determination of the temperature effect on the stressed-deformed state of the boiler of a tank wagon during washing and steaming operations.
3. The moment theory of shells used and adapted to the given tasks is presented. On the basis of this mathematical theory, the values of the loads at the control points of the boiler of the tank wagon were determined. Based on these results, the calculation model built in a modern computer computing and software complex was adjusted. Which was calculated using the finite element method and brought to an adequate level.
4. The obtained results of simulations of temperature loads and the stress-strain states corresponding to them will be useful in conducting further research



and development works on the selected topic. In addition, the obtained results and achievements can be used in educational activities in the preparation of students of various levels of education.

5. The dynamic load of the bearing structure of a freight wagon. The longitudinal and vertical loadings of the bearing structure of the freight wagon were considered. The results of determining the longitudinal load of the bearing structure of a freight wagon. The obtained acceleration values do not exceed the permissible ones.

6. Measures are proposed to improve the structures of freight wagons by making them from composite materials. The maximum stresses are recorded in the areas of interaction between the girder beam and the pivot beams, but these stresses do not exceed the permissible ones.

7. The development of conceptual solutions for the manufacture of components of freight wagons load-bearing systems made of composites (microstructures based on composite materials, in particular: carbon fiber, fiberglass, metal shell (hollow and layered), etc.) will allow domestic freight wagon designs to achieve technical and economic indicators of the new generation level and thereby significantly improve the profitability and competitiveness of rail freight transportation, reduce resource consumption and improve traffic safety. This, in turn, will significantly improve the economic efficiency of cargo transportation by domestic railways both in the domestic market and in interstate transit. It will also allow numerous domestic railcar engineers to compete in the relevant global market.

8. The research will help to increase the efficiency of rail transport, the transportation process through international transport corridors, as well as create developments in the design of multifunctional railcar structures.

9. The scientific research presents the results of solving the scientific and applied task of creating in a computer environment and researching the model of the proposed composite module of the body of a coal-carrying wagon.

10. The results of the analysis of the fatigue strength of the composite module of the body of a coal-carrying wagon proved its operability and effective perception of the corresponding loads for a satisfactory period of operation. The proposed innovation is possible for implementation, both during the manufacture of new designs of wagons, as well as their modernization in the conditions of wagon repair enterprises.

11. The created concept of the coal wagon body can be used as a basis for the creation of composite body modules and other wagons, which will be oriented to the transportation of bulk and bulk cargoes that do not require protection from atmospheric precipitation.

12. The obtained results will become the basis for further research and development work on the development and implementation of the composite module of the body of a coal-carrying wagon. Further stages of conducting research on the deployment of works in this direction require the mandatory conduct of experimental research. At the same time, initial studies can be carried out on reduced models. Obtaining the final results from the determination of the influence of external loads on the proposed design of the coal wagon body module is directly related to field tests.



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CONCEPTUAL SOLUTIONS FOR THE MANUFACTURE OF CARGO WAGON  
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To date, the traditional approach to creating a structure of freight wagons from steel has almost completely exhausted the potential for improving their technical, economic and operational indicators. At the same time, the experience of the development of composite materials and technologies for their creation in other branches of light and heavy engineering and instrument building indicates the prospect of deploying relevant research and development works on the use of such materials in railcar construction.

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The book can be used as a study guide for the preparation of bachelors, masters, doctors of philosophy and doctors of sciences in various specialties of transport mechanics. Including from specialties: railway transport, transport technologies, mechanical engineering, materials science and others.

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**Published (PDF): 28.08.2024.**

Conventionally printed sheets 8,71.

**Publisher** <sup>[ISBN]</sup>: Primedia E-launch LLC.

KS 5518, United States, Kansas, Shawnee, Flint St.

E-mail: [info@primediaelaunch.com](mailto:info@primediaelaunch.com) | URL: [www.primediaelaunch.com](http://www.primediaelaunch.com)