https://doi.org/10.33271/nvngu/2024-6/045

O. V. Fomin[*1],
orcid.org/0000-0003-2387-9946,
A. M. Fomina[2],
orcid.org/0000-0002-9810-8997,
A. O. Klymash[2],
orcid.org/0000-0002-4055-1195,
S. V. Kuzmenko[2],
orcid.org/0000-0003-0871-9864,
A. O. Vorokh[2],
orcid.org/0000-0001-7505-7616

1 – State University of Infrastructure and Technologies, Kyiv, Ukraine
2 – Volodymyr Dahl East Ukrainian National University, Kyiv, Ukraine
[*] Corresponding author e-mail: fomin1985@ukr.net

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

Purpose. Determination of the stress-deformation state and fatigue strength of the proposed concept of the composite module of the wagon body, designed for the transportation of hard coal and other bulk cargoes that do not require protection from the influence of the external environment (atmospheric precipitation, exposure to high and low temperatures, etc.).

Methodology. When conducting research, a systematic approach was used. In order to achieve the goal set in the research, the following tasks were solved: to determine the features and consider the impact of hard coal on the structural components of the body module of a coal wagon; to do node-by-node and element-by-element analysis of the engineering complex of documents for the synthesis of the geometric-spatial 3-D model of the open wagon under investigation; to develop a computer model with the help of a modern computing software complex; to adjust its adequacy on the basis of the obtained mathematical data by applying the semi-momentless theory of shells; to apply calculated loads that are characteristic of the defining case; by means of simulations, to determine graphical representations of stress-strain states; to check fatigue strength by computer simulation method.

Findings. A computer model was developed with the help of a modern computing software complex. The adequate finite-element model includes: the number of mesh elements 911,782, nodes – 1,551,011, while the maximum size of the mesh element is 40.0 mm, the minimum is 13.3 mm. The results of calculating the strength of the developed model of the composite module of the body of a coal-carrying wagon from the determination of loads proved that the obtained stresses do not exceed the permissible values. Also, the proposed structure was tested for fatigue strength by calculation method and computer simulations. The results of such analysis are positive.

Originality. For the first time, a conceptual implementation of the body module of an open wagon for the transportation of hard coal from a composite material has been proposed. With the help of calculations and computer simulations, the stress-strain state and fatigue strength of the proposed concept were analyzed.

Practical value. 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 loose cargoes that do not require protection from atmospheric precipitation. The obtained results will be 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. In the final case, the introduction of this or a similar technology will allow increasing the efficiency of the domestic fleet of freight wagons in the transportation of the specified bulk cargoes.

Keywords: *mechanical engineering, coal transportation, freight wagons, strength*

Introduction. 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 railwagon 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 article.

Literature review. 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 [1, 2], 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 articles [3, 4], 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 [5–7], 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 article [7], 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 [5] 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 [6], 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.

Articles [7–9] 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, the perspective of using composites is highlighted.

In the works [10, 11], the authors investigated the stress-deformed state and the strength of the universal wagon. At the same time, decisive aggregates of loads are taken into account. However, the possibility of manufacturing a composite structure was not considered.

The work [12] 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 [13], 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 [14, 15] 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 articles [16–18] 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 [19, 20] 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.

Unsolved aspects of the problem. Summing up the analysis of information sources on the issues under investigation, it can be argued that there is no sufficient attention paid to the issue of strength analysis of the composite module of the body of a freight wagon, which is created for the transportation of hard coal, and therefore the authors of this publication directed the scientific search to find solutions to this very scientific – applied task.

Purpose. The purpose of the article is to highlight the results of research on determining the stress-strain state and fatigue strength of the proposed concept of the composite module of the wagon body designed for the transportation of hard coal and other bulk cargoes that do not require protection from the influence of the external environment.

To achieve the set goal, the following scientific and applied tasks were defined and solved:

1. Analysis of existing scientific and technical developments on the issues of the issue under investigation.
2. Determination of the set of loads that act on the body module of a coal-carrying wagon, in the decisive calculation case.
3. Adoption of the shell theory for the mathematical determination of stresses in the control points of the design of the coal wagon body module.
4. Creation of a computer spatial geometric model of the proposed concept of the coal wagon body and its adequate finite element model.
5. Application of efforts and calculation of the developed finite-element model, analysis of the obtained pictures of the stress-strain state.
6. Computer simulation, in order to calculate the fatigue strength of the proposed composite body of a coal-carrying wagon, analysis of the obtained results.
7. Formation of general conclusions.

Description of the methodology (structure, sequence) of the research. Determination and analysis of the results of the given solution of the scientific and applied task included the stages of research generally accepted in the expert environment in accordance with the goal. They include: a formalized presentation of the research problem and tasks (based on: the results of an information-analytical and international patent search, a complete and systematic critical analysis of global and industry developments in this direction, a collection of expert-experienced assessments and proposals, a comprehensive and systematized review of modern scientific and technical departments on the profile of issues); node-by-node and element-by-element analysis of the engineering complex of documents for the synthesis of the geometric-spatial 3-D model of the open wagon under investigation; development of a computer model with the help of a modern computing software complex; adjusting its adequacy on the basis of the obtained mathematical data by applying the semi-momentless theory of shells; application of calculated loads that are characteristic of the defining case; by means of simulations, determination of graphical representations of stress-strain states; fatigue strength check by computer simulation method. At the same time, normative data were used from: interstate standards, DSTU, instructions, calculation methods, regulations and projects that correspond to the problems of the study, and when creating a computer calculation model, modern computing and software products were investigated.

Results. The semi-momentless shell theory 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 φ, 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 ε_x and ε_t, angular deformation or shear deformation γ_{xt}, curvature deformations xx and xt and torsion xxt 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

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

In the semi-momentless theory, it is assumed that Poisson's ratio $m = 0$, and $\varepsilon_t = l_{xt} = 0$, 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

$$\left.\begin{aligned}
T_x &= E\delta\varepsilon_x\\
M_t &= \frac{E\delta^3}{12}\chi_t
\end{aligned}\right\}, \tag{2}$$

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 us 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 $Rd\varphi$. After dividing these equations by dx and $d\varphi$, we get

$$\left.\begin{aligned}
&\frac{\partial Q_t}{\partial\varphi} + T_t - P_1 R = 0\\
&\frac{\partial T_x}{\partial x}R + \frac{\partial S}{\partial\varphi} + P_2 R = 0\\
&\frac{\partial T_t}{\partial\varphi} + \frac{\partial S}{\partial x}R - Q_t + P_2 R = 0\\
&\frac{\partial M_t}{\partial\varphi} - Q_t R = 0
\end{aligned}\right\}. \tag{3}$$

Geometric equations (1), physical relations (2) and static equations (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 us 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 (3) and eliminating the forces from the remaining equilibrium equations

$$Q_t = \frac{\partial M_t}{R\partial\varphi}, \tag{4}$$

we will get

$$\left.\begin{aligned}
&\frac{\partial^2 M_t}{R\partial\varphi^2} + T_t - P_1 R = 0\\
&\frac{\partial T_x}{\partial x}R + \frac{\partial S}{\partial\varphi} + P_2 R = 0\\
&\frac{\partial T_t}{\partial\varphi} + \frac{\partial S}{\partial x}R - \frac{\partial M_t}{R\partial\varphi} + P_3 R = 0
\end{aligned}\right\}. \tag{5}$$

Since there are no elasticity ratios for the forces T_t and S, they can only be found from the equilibrium equations (5). Let's transform these equations, eliminating the forces T_x and M_t, using the relation (2) and the hypotheses $e_t = 0$ and $\gamma_{xt} = 0$.

Based on the hypotheses, we get

$$\left.\begin{aligned}
w &= -\frac{\partial v}{\partial\varphi}\\
\frac{\partial u}{\partial\varphi} &= -\frac{R\partial v}{\partial x}
\end{aligned}\right\}. \tag{6}$$

Using the first and last ratio (1), we obtain formulas (2) and (3).

$$\left.\begin{aligned}
T_x &= -E\delta\int_{\varphi}\frac{\partial^2 v}{\partial x^2}Rd\varphi\\
M_t &= -\frac{E\delta^3}{12R^2}\left(\frac{\partial^3 v}{\partial\varphi^3} + \frac{\partial v}{\partial\varphi}\right)
\end{aligned}\right\}. \tag{7}$$

Substituting T_x and M_t expressed by formula (6) into the system of equations (4), we get

$$\left.\begin{aligned}
&-\frac{E\delta^3}{12R^3}\left(\frac{\partial^5 v}{\partial\varphi^5} + \frac{\partial^3 v}{\partial\varphi^3}\right) + T_t - P_1 R = 0\\
&E\delta\int_{\varphi}\frac{\partial^3 v}{\partial x^3}R^2 d\varphi - \frac{\partial S}{\partial\varphi} - P_2 R = 0\\
&\frac{\partial T_t}{\partial\varphi} + \frac{\partial S}{\partial x}R + \frac{E\delta^3}{12R^3}\left(\frac{\partial^4 v}{\partial\varphi^4} + \frac{\partial^2 v}{\partial\varphi^2}\right) + P_3 R = 0
\end{aligned}\right\}. \tag{8}$$

The system of integral differential equations (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 the Fourier formulas

$$\left.\begin{aligned} P_1 &= \sum_{m=1}^{\infty}\sum_{n=2}^{\infty} P_{1mn}\cos n\varphi \sin\lambda x \\ P_2 &= \sum_{m=1}^{\infty}\sum_{n=2}^{\infty} P_{2mn}\cos n\varphi \cos\lambda x \\ P_3 &= \sum_{m=1}^{\infty}\sum_{n=2}^{\infty} P_{3mn}\sin n\varphi \sin\lambda x \end{aligned}\right\}, \tag{9}$$

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

$$\lambda = \frac{m\pi}{2L}. \tag{10}$$

The selected combination of trigonometric functions in formula (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

$$v = \sum\sum v_{mn}\sin n\varphi \sin\lambda x, \tag{11}$$

and effort

$$\left.\begin{aligned} S &= \sum\sum S_{mn}\sin n\varphi \cos\lambda x \\ T_t &= \sum\sum T_{tmn}\cos n\varphi \sin\lambda x \end{aligned}\right\}. \tag{12}$$

Coefficients v_{nm}, S_{mn}, T_{tmn} are unknown. Let us 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

$$\left.\begin{aligned} w &= 1\cdot\cos n\varphi \sin\lambda x \\ v &= 1\cdot\sin n\varphi \sin\lambda x \\ u &= 1\cdot\cos n\varphi \cos\lambda x \end{aligned}\right\}. \tag{13}$$

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

Substitute series (11–13) into the equilibrium equation (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 us calculate the work of these force projections on the corresponding possible displacements (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 $x = 2L_c$ and from $\varphi = 0$ to $\varphi = 2\pi$, expressions of the form

$$\left.\begin{aligned} &\int_0^{2L_c}\int_0^{2\pi}\left(\cos n\varphi \sin\frac{m\pi x}{2L_c}\right)\left(\cos k\varphi \sin\frac{i\pi x}{2L_c}\right)dx d\varphi \\ &\int_0^{2L_c}\int_0^{2\pi}\left(\sin n\varphi \sin\frac{m\pi x}{2L_c}\right)\left(\sin k\varphi \sin\frac{i\pi x}{2L_c}\right)dx d\varphi \\ &\int_0^{2L_c}\int_0^{2\pi}\left(\cos n\varphi \cos\frac{m\pi x}{2L_c}\right)\left(\cos k\varphi \cos\frac{i\pi x}{2L_c}\right)dx d\varphi \end{aligned}\right\}. \tag{14}$$

Taking into account the orthogonality of the trigonometric functions, when $n = k$ and $m = i$, these integrals are equal to $Lc\pi$, 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 (14) will be reduced to systems of algebraic equations with respect to the coefficients of the series v_{mn}, S_{mn}, T_{tmn}

$$\begin{vmatrix} -\dfrac{E\delta^3}{12R^3}n^3(n^2-1) & 0 & 1 \\ \dfrac{E\delta R^2\lambda^3}{n} & -n & 0 \\ \dfrac{E\delta^3}{12R^3}n^2(n^2-1) & \lambda R & n \end{vmatrix} \times \begin{vmatrix} v_{mn} \\ S_{mn} \\ T_{tmn} \end{vmatrix} = \begin{vmatrix} P_{1mn}R \\ P_{2mn}R \\ P_{3mn}R \end{vmatrix}. \tag{15}$$

From equation (15) we find the coefficients v_{mn}, S_{mn}, T_{tmn}, and from formula (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 φ of these points.

Dependencies (13) with known coefficients v_{mn} make it possible to determine the coefficients of the normal force T_x and the moment M_t

$$\left.\begin{aligned} T_{xmn} &= -\frac{E\delta R\lambda^2}{n}v_{mn} \\ M_{tmn} &= \frac{E\delta^3}{12R^2}n(n^2-1)v_{mn} \end{aligned}\right\}. \tag{16}$$

With these coefficients, we will have

$$\left.\begin{aligned} T_x &= \sum\sum T_{xmn}\cos n\varphi \sin\lambda x \\ M_t &= \sum\sum M_{tmn}\cos n\varphi \sin\lambda x \end{aligned}\right\}. \tag{17}$$

Tension

$$\left.\begin{aligned} \sigma_x &= \sigma + \frac{T_x}{\delta} \\ \sigma_t &= \frac{T_t}{\delta} \pm \frac{6M_t}{\delta^2} \\ \tau_{xt} &= \frac{S}{\delta} \end{aligned}\right\}, \tag{16}$$

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

$$\sigma_e = \sqrt{\sigma_x^2 - \sigma_x\sigma_t + \sigma_t^2 + 3\tau_{xt}^2}. \tag{19}$$

To ensure the required strength, the condition must be met

$$\sigma_e \leq [\sigma]. \tag{20}$$

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

$$q_1 = \gamma R(\cos\varphi - \cos\beta_0), \tag{21}$$

where γ is specific weight of cargo; β_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 β_2–β_1, which is 4°, 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

$$P_{1mn} = \frac{4}{\pi^2 mn}q(\cos\lambda a - \cos\lambda b)(\sin n\beta_2 - \sin n\beta_1). \tag{22}$$

For longitudinal load

$$P_{2mn} = \frac{4}{\pi^2 mn}r(\sin\lambda d - \sin\lambda c)(\sin n\beta_4 - \sin n\beta_3), \tag{23}$$

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 (Fig. 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 1,100–1,300 MPa, in the transverse direction – 650 MPa.

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.

An advanced software-and-computing complex was used to carry out strength calculation studies of the bearing system of a conceptually new version of the coal car body module made of composites which is based on the classical finite element method in its software. The spatial grid was generated on a solid body with all curvature elements reflected and taken into account. At the same time, the applied tetrahedra of isoparametric form were used, the optimal characteristics of such a mesh were determined: 911,782 simple elements, 1,551,011 nodal elements. The defined maximum size of a simple mesh element is 40.0 mm, the minimum defined size is 13.3 mm, the minimum defined aspect ratio is 10.33, the aspect ratio of less than three is 100, and, accordingly, more than ten is 0.00087. The minimum defined number of simple elements in a circle is 12, the increase in the size of simple elements is 1.8.

Fastening (Fig. 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.

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 275 MPa. At the same time, the stress in the shell of the hopper wagon is about 190 MPa, which is 15 % 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 180 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 Fig. 6.

When performing calculation studies, it was established that the determined value of the first natural frequency is 10.6 Hz, and is not lower than the standard permissible value – 8 Hz. And that is why it can be said that the safe mode of movement of the wagon is guaranteed.

At the next stage of the scientific and practical work, the fatigue resistance [20] 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

$$m = \frac{\lambda_{-1D}}{\lambda_{a,e}} \geq [m], \tag{24}$$

where $\lambda_{a,e}$ 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; $[m]$ – 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

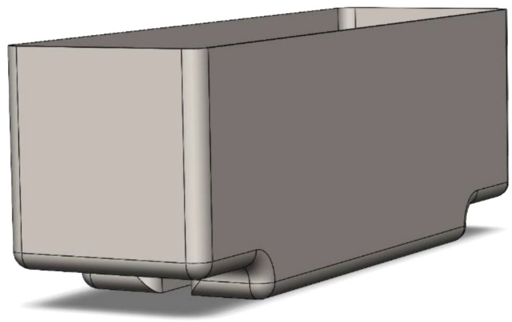


Fig. 1. Computer spatial geometric model of the conceptually new version of the coal wagon body module made of composites

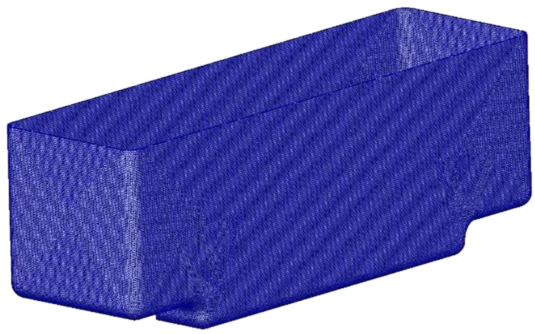


Fig. 2. Finite element model of the conceptually new version of the coal wagon body module made of composites

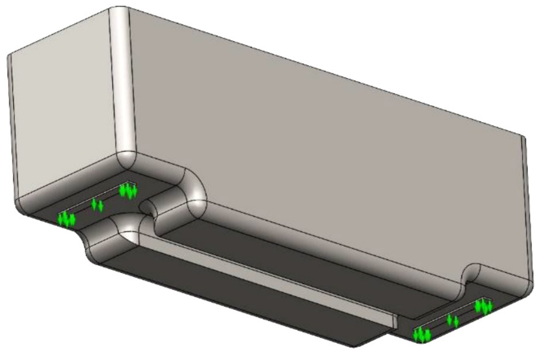


Fig. 3. Fixing the model of the conceptually new version of the coal wagon body module made of composites

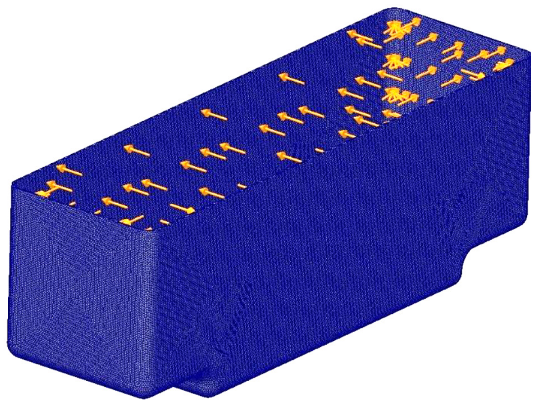


Fig. 4. Application of loads of the conceptually new version of the coal wagon body module made of composites

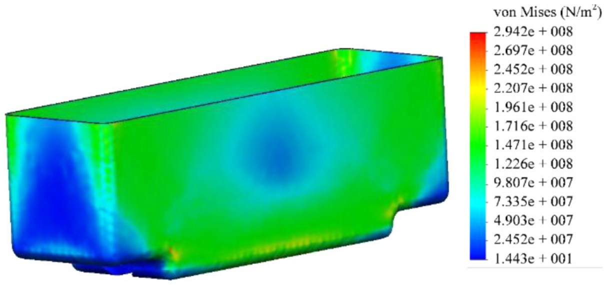


Fig. 5. The stressed state of the model of the conceptually new version of the coal wagon body module made of composites

$$\lambda_{a,e} = \sqrt[m]{\frac{N_c}{N_0}\sum_{i=1}^{k} P_{vi} f_b \sum_{i=1}^{k} \lambda_{ai}^{m} P_i}, \qquad (25)$$

where N_c is the total number of dynamic stress cycles determined for the calculated life cycle; P_{vi} and P_i are the probabilities of the appearance of stresses with the level of σ_i in a given speed interval and the proportion of time that is determined during the operation of the wagon structure at the speed vi; λ_{ai} – level (degree) of stress amplitude, MPa; k_{ai} and k_{vi} – 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 σ_i, which is 0.95 values $\lambda_{a,e}$ = 47.7 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.

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

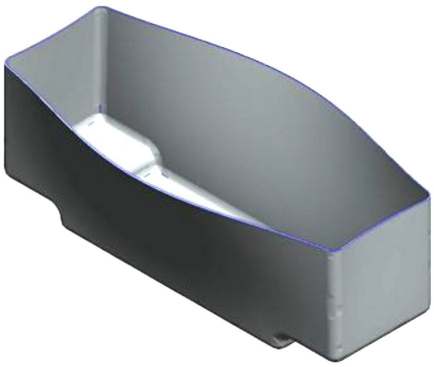
The applied tetrahedra of isoparametric form were used, the optimal characteristics of such a mesh were determined: 911,782 simple elements, 1,551,011 nodal elements. The defined maximum size of a simple mesh element is 40.0 mm, the minimum defined size is 13.3 mm.

As a result of the analysis of the stress-strain state of the proposed structure of the composite module of the coal wagon body, it was found that the maximum stresses in the decisive design mode are 190 MPa and do not exceed the permissible values. Which testifies to the efficiency of the proposed innovative concept.

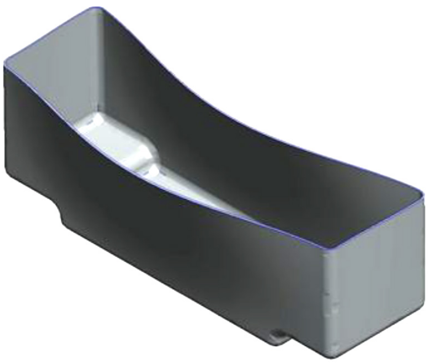
The results of the analysis of the fatigue strength of the composite module of the body of a coal-carrying wagon proved its operability and effective perception of the corresponding loads for a satisfactory period of operation. The proposed innovation is possible for implementation, both during the manufacture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

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.

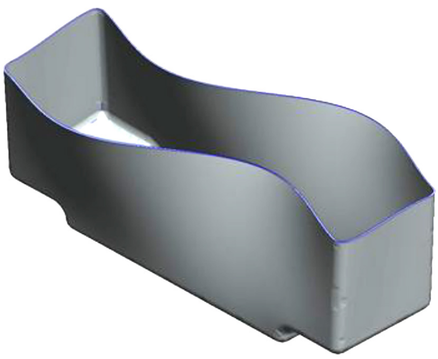
The obtained results will become the basis for further research and development work on the development and implementation of the composite module of the body of a coal-carrying wagon. Further stages of conducting research on the deployment of works in this direction require the mandatory conduct of 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.



a



b



c

Fig. 6. Some forms of oscillations of 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

References.

1. Kondratiev, A., & Slivinsky, M. (2018). Method for determining the thickness of a binder layer at its non-uniform mass transfer inside the channel of a honeycomb filler made from polymeric paper. *Eastern-European Journal of Enterprise Technologies*, *6*(5(96)), 42-48. https://doi.org/10.15587/1729-4061.2018.150387.

2. Patrascu, A., Hadar, A., & Pastrama, S. (2019). Structural Analysis of a Freight Wagon with Composite Walls. *Materiale Plastice*, *57*(2), 140-151. https://doi.org/10.37358/MP.20.2.5360.

3. Kondratiev, A. (2019). Improving the mass efficiency of a composite launch vehicle head fairing with a sandwich structure. *Eastern-European Journal of Enterprise Technologies*, *6*(7(102)), 6-18. https://doi.org/10.15587/1729-4061.2019.184551.

4. Yakovlieva, A., & Boichenko, S. (2020). Energy Efficient Renewable Feedstock for Alternative Motor Fuels Production: Solutions for Ukraine. *Studies in Systems, Decision and Control*, *298*, 247-259. https://doi.org/10.1007/978-3-030-48583-2_16.

5. Melnyk, O., Onyshchenko, S., Onishchenko, O., Lohinov, O., & Ocheretna, V. (2023). Integral Approach to Vulnerability Assessment of Ship's Critical Equipment and Systems. *Transactions on Maritime Science*, *12*(1). https://doi.org/10.7225/toms.v12.n01.002.
6. Melnyk, O., Onyshchenko, S., Onishchenko, O., Shumylo, O., Voloshyn, A., Koskina, Y., & Volianska, Y. (2022). Review of Ship Information Security Risks and Safety of Maritime Transportation Issues. *TransNav*, *16*(4), 717-722. https://doi.org/10.12716/1001.16.04.13.
7. Sagin, S., Kuropyatnyk, O., Sagin, A., Tkachenko, I., Píštěk, V., & Kučera, P. (2022). Ensuring the Environmental Friendliness of Drillships during Their Operation in Special Ecological Regions of Northern Europe. *Journal of Marine Science and Engineering, 10*, 1331. https://doi.org/10.3390/jmse10091331.
8. Sokolov, V., Porkuian, O., Krol, O., & Stepanova, O. (2021). Design Calculation of Automatic Rotary Motion Electrohydraulic Drive for Technological Equipment. In: Advances in Design, Simulation and Manufacturing IV. DSMIE 2021. *Lecture Notes in Mechanical Engineering*, *1*, 133-142. Springer, Cham. https://doi.org/10.1007/978-3-030-77719-7_14.
9. Krol, O., & Sokolov, V. (2020). Modeling of Spindle Node Dynamics Using the Spectral Analysis Method. In: Advances in Design, Simulation and Manufacturing III. DSMIE 2020. *Lecture Notes in Mechanical Engineering, 1*, 35-44. Springer, Cham. https://doi.org/10.1007/978-3-030-50794-7_4.
10. Koshel, O., Sapronova, S., & Kara, S. (2023). Revealing patterns in the stressed-strained state of load-bearing structures in special rolling stock to further improve them. *Eastern-European Journal of Enterprise Technologies*, *4*(7(124)), 30-42. https://doi.org/10.15587/1729-4061.2023.285894.
11. Sapronova, S., Tkachenko, V., Gatchenko, V., & Maliuk, S. (2017). Research on the safety factor against derailment of railway vehicles. *Eastern-European journal of enterprise technologies*, *6*(7(90)), 19-25. https://doi.org/10.15587/1729-4061.2017.116194.
12. Gorobchenko, O., Fomin, O., Gritsuk, I., Saravas, V., Grytsuk, Y., Bulgakov, M., Volodarets, M., & Zinchenko, D. (2018). Intelligent Locomotive Decision Support System Structure Development and Operation Quality Assessment. *IEEE 3rd International Conference on Intelligent Energy and Power Systems (IEPS)*, Kharkiv, Ukraine, 2018, (pp. 239-243). https://doi.org/10.1109/IEPS.2018.8559487.
13. Gubarevych, O., Goolak, S., Melkonova, I., & Yurchenko, M. (2022). Structural diagram of the built-in diagnostic system for electric drives of vehicles. *Diagnostyka*, *23*(4), 2022406. https://doi.org/10.29354/diag/156382.
14. Fomin, O., Sulym, A., Kulbovsky, I., Khozia, P., & Ishchenko, V. (2018). Determining rational parameters of the capacitive energy storage system for the underground railway rolling stock. *Eastern-European journal of enterprise technologies, 2/1*(92), 63-71. https://doi.org/10.15587/1729-4061.2018.126080.
15. Sulim, A. O., Fomin, O. V., Khozya, P. O., & Mastepan, A. (2018). Theoretical and practical determination of parameters of on-board capacitive energy storage of the underground rolling stock. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (5), 79-87. https://doi.org/10.29202/nvngu/2018-5/8.
16. Muradian, L., Shvets, A., & Shvets, A. (2024). Influence of wagon body flexural deformation on the indicators of interaction with the railroad track. *Archive of Applied Mechanics.* https://doi.org/10.1007/s00419-024-02633-2.
17. Li, X., Fang, J., Zhang, Q., Zhao, S., & Guan, X. (2020). Study on Key Technology of Railway Freight Car Body Fatigue Test. *Journal of Failure Analysis and Prevention*, *20*(1), 261-269. https://doi.org/10.1007/s11668-020-00828-7.
18. Poveda-Reyes, S., Rizzetto, L., Triti, C., Shi, D., García-Jiménez, E., Molero, G. D., & Santarremigia, F. E. (2021). Risk evaluation of failures of the running gear with effects on rail infrastructure. *Engineering Failure Analysis*, *128*, 105613. https://doi.org/10.1016/j.engfailanal.2021.105613.
19. Milenković, M., Bojović, N., & Abramin, D. (2023). Railway freight wagon fleet size optimization: A real-world application. *Journal of Rail Transport Planning & Management, 26*, June 2023, 100373. https://doi.org/10.1016/j.jrtpm.2023.100373.
20. Rakshit, U., Malakar, B., & Roy, B. K. (2018). Study on Longitudinal Forces of a Freight Train for Different Types of Wagon Connectors. *IFAC-PapersOnLine*, *51*(1), 283-288. https://doi.org/10.1016/j.ifacol.2018.05.074.
21. Fomin, O., Lovska, A., Píštěk, V., & Kučera, P. (2019). Dynamic load effect on the transportation safety of tank containers as part of combined trains on railway ferries. *Vibroengineering Procedia*, *29*, 124-129. https://doi.org/10.21595/vp.2019.21138.

Аналіз міцності композитного модуля кузова вагона-вуглевоза

О. В. Фомін[*1], *А. М. Фоміна*[2], *А. О. Климаш*[2], *С. В. Кузьменко*[2], *А. О. Ворох*[2]

1 – Державний університет інфраструктури та технологій, м. Київ, Україна
2 – Східноукраїнський національний університет імені В. Даля, м. Київ, Україна
[*] Автор-кореспондент e-mail: fomin1985@ukr.net

Мета. Визначення напружено-деформованого стану та втомної міцності запропонованого концепту композитного модуля кузова вагона, розробленого для перевезення кам'яного вугілля та інших насипних вантажів, що не потребують захисту від впливу зовнішнього середовища (атмосферних опадів, впливу високих і низьких температур та інше).

Методика. При проведенні досліджень застосований системний підхід. Для досягнення поставленої в дослідженні мети були вирішенні наступні задачі: визначення особливостей і розгляд впливу кам'яного вугілля на конструктивні складові модуля кузова вагона-вуглевоза; повузловий і поелементний аналіз інженерного комплексу документів для синтезу геометрично-просторової 3-D моделі відкритого вагону, що досліджується; розроблення, за допомогою сучасного обчислювального програмного комплексу, комп'ютерної моделі; настроювання її адекватності на основі отриманих математичних даних шляхом застосування напівбезмоментної теорії оболонок; прикладання розрахункових навантажень, що характерні для визначального випадку; за допомогою симуляцій визначення графічних відображень напружено-деформованих станів; методом комп'ютерної симуляції перевірка втомної міцності.

Результати. Була розроблена, за допомогою сучасного обчислювального програмного комплексу, комп'ютерна модель. Адекватна скінчено-елементна модель включає: кількість елементів сітки 911782, вузлів – 1551011, при цьому максимальний розмір елементу сітки дорівнює 40,0 мм, мінімальний – 13,3 мм. Результати розрахунку міцності розробленої моделі композитного модуля кузова вагона-вуглевоза з визначенням навантажень засвідчили, що отримані напруження не перевищують допустимих значень. Також запропонований конструктив був перевірений, розрахунковим методом і шляхом компьютерних симуляцій, на втомну міцність. Результати такого аналізу є позитивними.

Наукова новизна. Уперше запропоноване концептуальне виконання модуля кузова відкритого вагона для перевезення кам'яного вугілля із композитного матріалу. За допомогою розрахунків і компьютерних симуляцій проаналізовано напружено-деформований стан і втомну міцність запропонованого концепту.

Практична значимість. Створений концепт кузова вагона-вуглевоза може бути використаний як основа для створення композитних модулів кузова та інших вагонів, що будуть орієнтовані на перевезення насипних і навалочних вантажів, які не потребують захисту від атмосферних опадів. Отримані результати стануть основою для подальших науково-дослідних і дослідно-конструкторських робіт із розробки та впровадження композитного модуля кузова вагона-вуглевоза. У кінцевому випадку впровадження такої чи аналогічної технології дозволить підвищити ефективність функціонування вітчизняного парку вантажних вагонів при перевезеннях вказаних насипних вантажів.

Ключові слова: *механічна інженерія, перевезення вугілля, вантажні вагони, міцність*

The manuscript was submitted 31.06.24.