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DETERMINING PATTERNS IN THE LONGITUDINAL LOADING OF THE MODERNIZED CARRIER STRUCTURE OF AN OPEN WAGON FOR TRANSPORTING LONG CARGOES

Alyona Lovska
Corresponding author
Doctor of Technical Sciences, Professor
Department of Wagon Engineering and Product Quality
Ukrainian State University of Railway Transport
Feuerbakh sq., 7, Kharkiv, Ukraine, 61050
E-mail: alyonaLovskaya.vagons@gmail.com
ORCID: https://orcid.org/0000-0002-8604-1764

Nurlana Karimova
PhD, Associate Professor
Department of Engineering and Applied Sciences
Azerbaijan State University of Economics (UNEC)
Istiglaliyat str., 6, Baku, Azerbaijan, AZ1001
E-mail: nurlana_karimova@unec.edu.az
ORCID: https://orcid.org/0000-0001-5387-9782

This study investigates processes related to the occurrence, acceptance, and redistribution of loads in the modernized supporting structure of a railroad open wagon. The task addressed is to improve the efficiency of transporting long-length cargo by rail.

The work proposes that the bearing structure of an open wagon should be modernized by dismantling the end walls or doors. This makes it possible to reduce the sprung mass of the bearing structure of the open wagon by more than 1 t and, accordingly, to increase the load capacity by the same amount.

To substantiate the proposed modernization, the strength of the bearing structure of an open wagon moving in a train was calculated. The longitudinal loads acting on the bearing structure of the open wagon were determined by mathematical modeling. The calculated acceleration value was taken into account when studying the stress state of the bearing structure of the open wagon. It was established that its strength is maintained as the calculated stresses are 14.5% lower than the permissible ones. In addition, as part of the study, a modal analysis of the bearing structure of the open wagon was conducted. The calculation results showed that traffic safety from the point of view of modal analysis is observed.

A feature of the proposed modernization is that, if necessary, the bearing structure of the open wagon can be returned to the original version.

The scope of practical application of the reported results is the transportation industry, in particular railroad transport.

A condition for practical use of the results is symmetrical loading of the bearing structure of the open wagon with cargo.

This study could contribute to compiling recommendations for increasing the efficiency of transportation of long-length cargo by rail

Keywords: railroad transport, open wagon, structural modernization, stressed state of the structure, transportation of long-length cargo

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1. Introduction

The railroad industry has long been a leading sector not only of the transport system but also of the economy of European countries. The railroad industry accounts for a significant segment of freight and passenger transportation. Freight transportation enables the stable functioning of manufacturing enterprises; therefore, the timeliness of cargo delivery is an important factor in the operation of railroad transport.

One of the most common types of cargo transported by railroads is long-haul. Specialized platform wagons equipped with vertical superstructures to hold the cargo are used for their transportation. But the fleet of such platform wagons is limited; therefore, there is a shortage of them. This circumstance led to the adaptation of universal platform wagons for the transportation of long-haul cargo. At the same time, this did not completely solve the issue of providing the railroad industry with vehicles for the transportation of long-haul cargo. In this regard, it is advisable to engage other types of wagons, in particular open-type, for the transportation of long-haul cargo, for example, open wagons. But it causes a problem, which is associated with the lack of technical adaptation of open wagons to the transportation of such cargo.

There are known options for modernizing open wagons for such transportation but, to improve the efficiency of railroad transportation of long-length cargo, it is necessary to further search for alternative solutions for open wagon modernization. Therefore, the issues of improving open wagons for the possibility of their involvement in the transportation of long-length cargo are relevant and require further consideration.

2. Literature review and problem statement

The issues of adapting an open wagon to the transportation of long-length cargo are covered in [1]. The authors proposed the use of a special device that works on the principle of a sliding rod and is attached to the upper strapping of the wagon. The design features of this device are presented, as well as the calculation of the strength of the side wall of the body when interacting with it. However, it must be noted that the authors did not study the stressed state of the open wagon body as a whole. This does not allow us to assess the feasibility of using such a device.

In [2], the features of determining the strength of the floor of the open wagon body of an improved design are highlighted. The essence of the improvement is that the floor has a wave-like configuration. This contributes to improving its strength. The authors give the results of calculating the strength of such a floor, which proved that this implementation is effective. However, the issues of determining the strength of the body as a whole, including when transporting various types of cargo in it, were ignored.

The study of the dependence of the asymmetry coefficient of the open wagon body on the stresses in the welded seam of the transverse beam is reported in [3]. This dependence is important because it makes it possible to predict cracks in the structural components of the open wagon body. The authors proposed a mathematical apparatus that allows it to be detected. The disadvantage of the work is that the case of loading the body with long cargo was not taken into account. The loading was considered from a conditional cargo taking into account the use of the full load capacity of the body.

In [4], the features of optimizing the geometric parameters of freight wagons were highlighted. The purpose of this optimization was to ensure full use of the usable volume of the wagon bodies when loading them. A new determining criterion was proposed – the tare loading coefficient, which depends on the type of cargo being transported. The calculations proved the feasibility of using such a coefficient. However, the authors did not study the features of using this coefficient when transporting long cargo in an open wagon.

The author of [5] proposed an open wagon design with increased load capacity. A feature of the wagon structure is that the floor is formed by a corrugated sheet. The results of the calculation of the strength of the open wagon floor are presented. The rationality of the proposed solution is proven. However, when performing the calculations, the author took into account that the floor is loaded with a conditional load in the form of a uniformly distributed load. At the same time, the case of loading the floor with a long cargo was not taken into account. Perhaps such a loading scheme is planned to be considered in further work in this area.

The design features of the open wagon with high body sides are highlighted in [6]. The wagon body is made of aluminum, which made it possible to reduce its packaging compared to the prototype. The study of the stressed state of the open wagon confirmed that the strength of its structure is maintained. The wagon certainly has certain advantages compared to many existing structures. However, the authors did not study its strength when transporting long cargo. This does not allow us to fully assess the strength properties of the wagon under operational load schemes. The reason for the lack of such studies may be that the wagon is not adapted to the transportation of long-length cargo.

In paper [7], in order to improve the strength of the wagon body, it is proposed to introduce sandwich panels into its design. This solution also contributes to a 35.5% reduction in the wagon's tare weight compared to the prototype. The features of calculating the panels for strength are highlighted. The calculation results showed that the stress in the panels does not exceed the permissible values. However, the authors did not pay attention to the issue of determining the strength of the panels when receiving loads from long-length cargo. This can probably be explained by the fact that the authors took into account the most common load schemes of the wagon body in operation.

A similar drawback is also found in [8], in which the authors proposed using magnesium alloys as the wagon body cladding. This solution also helps reduce the tare of the sprung mass of the wagon while ensuring the conditions of operational strength. However, when calculating the strength, the authors of the publication limited themselves to the most common body load schemes and did not take into account the possibility of transporting long-length cargo in it.

Having analyzed the literature [1–8], we can conclude that currently the study of the loading of the supporting structures of open wagons when transporting long-length cargo and their adaptation to such transportation has not been given due attention. Therefore, there is a need to conduct research in this area.

3. The aim and objectives of the study

The purpose of our study is to determine the features of the longitudinal loading of the modernized supporting structure of the open wagon for transporting long-length cargo. This will make it possible to improve the efficiency of long-length cargo transportation by rail.

The goal is accomplished by solving the following tasks:

– to conduct mathematical modeling of the longitudinal loading of the modernized supporting structure of an open wagon for transporting long-length cargo;

– to calculate the strength and perform modal analysis of the supporting structure of the open wagon.

4. Materials and methods

The object of our study is the processes of occurrence, acceptance, and redistribution of loads in the modernized supporting structure of an open wagon.

The principal hypothesis assumes that the dismantling of the end walls (doors) of the open wagon body could contribute to increasing the load-bearing capacity of the open wagon.

The basic assumption of our study is that there is no wear of the open wagon structural components. In this case, a simplification was adopted that the body is a monolithic structure. That is, welds between individual components were not taken into account.

To enable the use of open wagons for transporting long-length cargo, it is proposed to modernize their supporting structure. This modernization involves dismantling the end walls or doors of the open wagon, which makes it possible to reduce its sprung mass by more than 1 t, and, accordingly, increase the load-bearing capacity by the same amount. In order to substantiate such modernization, appropriate calculations were carried out. The open wagon model 12-757 was chosen as the prototype. This open wagon model has end double-leaf doors. Taking into account their dismantling, the spatial model of the supporting structure of the open wagon takes the form shown in Fig. 1.

The spatial model of the modernized supporting structure of the open wagon was constructed in SolidWorks (France). When building the model, elements that rigidly interact with each other were taken into account, and since the hatch covers are hinged to the body, they are absent in the model.

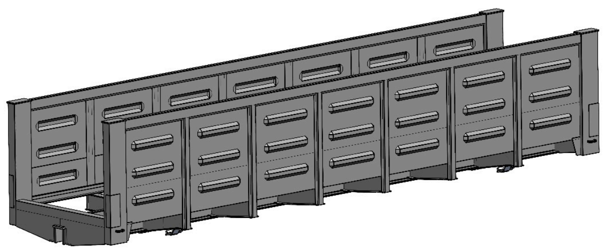

Fig. 1. Spatial model of the modernized supporting structure of the open wagon

The calculation of the strength of the modernized supporting structure of the open wagon was carried out in the SolidWorks Simulation software package (France). This software package implements the finite element method, which is currently the most progressive calculation method in mechanical engineering. The Mises criterion was chosen as the calculation criterion [9, 10]. This choice is based on the fact that the material of the open wagon structure is the low-alloy steel 09G2S, which has linear isotropic properties.

In this case, the longitudinal loading of the wagon was studied. The main calculated longitudinal loads include compression and tension forces during the interaction of wagons with the locomotive and among themselves in the train. These forces are caused by the action of traction and braking forces, as well as aerodynamic drag forces. They arise during transient and steady train motion modes, in their transportation modes and in special situations (DSTU 7598:2014. Freight wagons. General requirements for calculations and design of new and modernized 1520 mm gauge wagons (non-self-propelled)). The international analog of this document is the EN 12663-2 standard. Railroad applications – structural requirements of railroad vehicle bodies – Part 2: Freight wagons.

The tensile or compressive forces are applied, respectively, to the front or rear stops of both ends of the wagon at the level of the axis of the autocoupling equipment.

The calculation scheme of the modernized supporting structure of the open wagon is shown in Fig. 2. It takes into account the action of the following loads: vertical P_v, which is due to the self-weight of the structure and the weight of the transported cargo (marked in blue). A lateral load P_l from the cargo (marked in red) was applied to the vertical racks. A longitudinal force P_{lg} (marked in pink), taken equal to 1.0 MN, was applied to the rear stops of the autocoupling on one side of the wagon. On the opposite side of the wagon, it was balanced by reaction P_r. The model also takes into account the friction forces P_{fr} (marked in purple), which occur between the cargo on the body. Reactions P_{st} to the action of dynamic loading were applied to the vertical pillars of the body from top to bottom (marked in green). In these zones, wooden pillars are attached to hold the transported cargo.

The determination of reactions in the vertical pillars of the open wagon body to the action of dynamic loading was carried out by mathematical modeling. For this purpose, a mathematical model was built, which takes into account that the wagon has three degrees of freedom: translational movements relative to the longitudinal axis, angular, and translational movements relative to the vertical axis. The mathematical model was solved in the Mathcad software package (USA) [11, 12].

The lateral load along the height of the rack L_r was determined from the following formula [13]

$$P_l = \frac{n \cdot P' - F_{fr}^n}{L_r}, \qquad (1)$$

n – coefficient, which is set at the stage of designing the wagon; P' – load, which takes into account the inertial, centrifugal, and wind components; F_{fr}^n – friction force, which acts in the transverse direction.

Rigid connections were installed on the horizontal surfaces of the thrust bearings, which simulated the support of the body on the running gear [14, 15].

When constructing a finite element model, tetrahedral elements were used (Fig. 3). Their number was determined graphically [16–18].

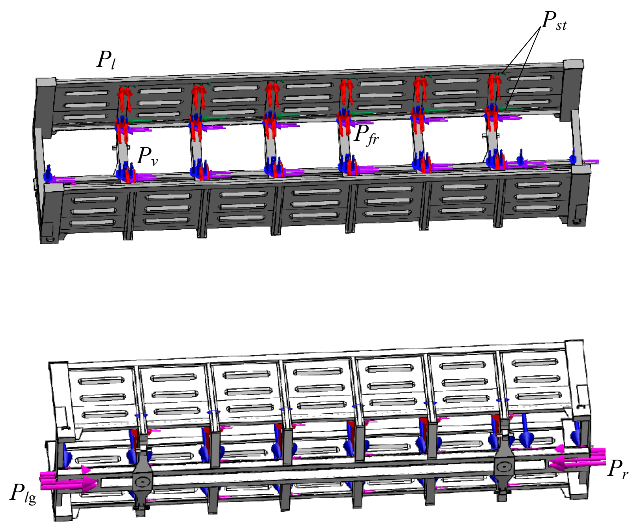

Fig. 2. Calculation diagram of the modernized supporting structure of the open wagon: *a* – type 1; *b* – type 2

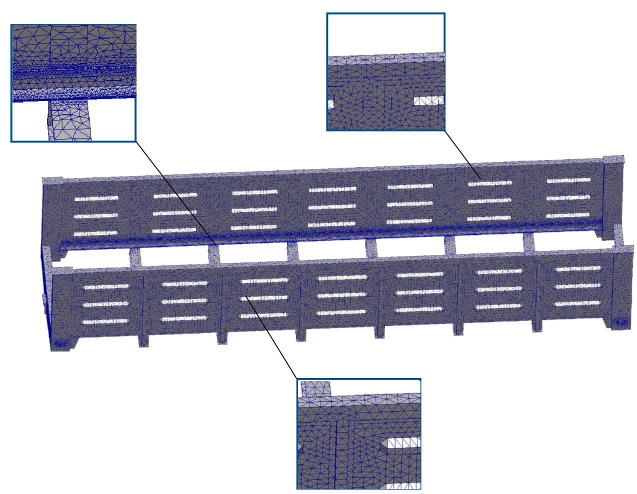

Fig. 3. Finite element model of the modernized supporting structure of an open wagon

In this case, the option of constructing a high-quality mesh with the number of Jacobian points of 16 was used. The model has 570,560 elements with a number of nodes of 1,112,063. The maximum element size was 80 mm with a minimum of 16 mm.

In addition, as part of the study, a modal analysis of the modernized supporting structure of the open wagon was carried out.

The purpose of this calculation is to determine the natural frequencies and vibration forms of the open wagon [19]. The safety of the open wagon movement in the train was assessed using the first natural frequency of oscillation. The calculation was carried out using options in the SolidWorks Simulation software package.

5. Results of determining the features of the longitudinal loading of the modernized supporting structure of the open wagon for transporting long-length cargo

5. 1. Results of mathematical modeling of the longitudinal loading of the modernized supporting structure of the open wagon

To determine the reactions in the vertical struts of the open wagon body to the action of dynamic loading, mathematical modeling of longitudinal dynamics when moving in a train was carried out. The calculation model is shown in Fig. 4. It was taken into account that the longitudinal force P_{lg} acts on the rear stop of the autocoupler. The wagon body is supported by bogies of model 18-100 with the corresponding stiffness characteristics $k_{1,\,2}$ and friction forces F_{fr} in spring sets.

The mathematical model takes the form:

$$\begin{cases} M_W^{tot}\cdot x_W'' + M_W\cdot h\cdot\varphi_W'' = P_{\lg}, \\ I_W\cdot\varphi_W'' + M_W\cdot h\cdot x_W'' - g\cdot\varphi_W\cdot M_W\cdot h = \\ = l\cdot F_{fr}\left(\operatorname{sign}\left(z_W - l\cdot\varphi_W\right)' - \operatorname{sign}\left(z_W + l\cdot\varphi_W\right)'\right) + \\ + l\left(k_1\cdot\left(z_W - l\cdot\varphi_W\right) - k_2\cdot\left(z_W + l\cdot\varphi_W\right)\right), \\ M_W\cdot z_W'' = \left(k_1\cdot\left(z_W - l\cdot\varphi_W\right) - k_2\cdot\left(z_W + l\cdot\varphi_W\right)\right) - \\ - F_{fr}\left(\operatorname{sign}\left(z_W - l\cdot\varphi_W\right)' - \operatorname{sign}\left(z_W + l\cdot\varphi_W\right)'\right), \end{cases} \quad (2)$$

where M_W^{tot} – total mass of the wagon with cargo; M_W – mass of the supporting structure of the wagon with cargo; I_W – moment of inertia of the wagon with cargo relative to the longitudinal axis; l – half of the wagon base; x_W, φ_W, z_W – coordinates of the wagon movements in the longitudinal, angular relative to the vertical axis, and vertical directions.

To solve the model, it was reduced to the form:

$$y_2' = \frac{P_W - M_W\cdot h\cdot y_4'}{M_W^{tot}},$$

$$y_4' = \frac{l\cdot F_{fr}\left(\operatorname{sign}\left(z_W - l\cdot y_3\right)' - \operatorname{sign}\left(z_W + l\cdot y_3\right)'\right)}{I_W} + \frac{l\left(k_1\cdot\left(y_5 - l\cdot y_3\right) - k_2\cdot\left(y_5 + l\cdot y_3\right)\right) - M_W\cdot h\cdot y_2' + g\cdot y_3\cdot M_W\cdot h}{I_W},$$

$$y_6' = \frac{\left(k_1\cdot\left(y_5 - l\cdot y_3\right) - k_2\cdot\left(y_5 + l\cdot y_3\right)\right) - F_{fr}\left(\operatorname{sign}\left(y_5 - l\cdot y_3\right)' - \operatorname{sign}\left(y_5 + l\cdot y_3\right)'\right)}{M_W}, \quad (3)$$

here $x_W'' = y_1;\ y_2 = y_1';\ \varphi_W'' = y_3;\ y_4 = y_3';\ z_W'' = y_5;\ y_6 = y_5'$.

Next, the Runge-Kutta stepwise iteration method was used:

$$Q(t, y) = \begin{bmatrix} y_2 \\ y_4 \\ y_6 \\ \dfrac{P_{\lg} - M_W\cdot h\cdot y_4'}{M_W^{tot}} \\ \dfrac{l\cdot F_{fr}\left(\operatorname{sign}\left(z_W - l\cdot y_3\right)' - \operatorname{sign}\left(z_W + l\cdot y_3\right)'\right)}{I_W} + \\ + \dfrac{l\left(k_1\cdot\left(y_5 - l\cdot y_3\right) - k_2\cdot\left(y_5 + l\cdot y_3\right)\right) - M_W\cdot h\cdot y_2' + g\cdot y_3\cdot M_W\cdot h}{I_W} \\ \dfrac{\left(k_1\cdot\left(y_5 - l\cdot y_3\right) - k_2\cdot\left(y_5 + l\cdot y_3\right)\right) - F_{fr}\left(\operatorname{sign}\left(y_5 - l\cdot y_3\right)' - \operatorname{sign}\left(y_5 + l\cdot y_3\right)'\right)}{M_W} \end{bmatrix}, \quad (4)$$

$$Y = rkfixed\left(J, tn, tk, n, Q\right).$$

Generalized accelerations were calculated in an array $ddy_{j,i}$:

$$ddy_{j,1} = \frac{P_{\lg} - M_W\cdot h\cdot y_4'}{M_W^{tot}}, \quad (5)$$

$$ddy_{j,2} = \frac{l\cdot F_{fr}\left(sign\left(z_W - l\cdot y_3\right)' - \operatorname{sign}\left(z_W + l\cdot y_3\right)'\right)}{I_W} + \frac{\left(k_1\cdot\left(y_5 - l\cdot y_3\right) - k_2\cdot\left(y_5 + l\cdot y_3\right)\right) - M_W\cdot h\cdot y_2' + g\cdot y_3\cdot M_W\cdot h}{I_W}, \quad (6)$$

$$ddy_{j,3} = \frac{\left(k_1\cdot\left(y_5 - l\cdot y_3\right) - k_2\cdot\left(y_5 + l\cdot y_3\right)\right)}{M_W} - \frac{F_{fr}\left(\operatorname{sign}\left(y_5 - l\cdot y_3\right)' + \operatorname{sign}\left(y_5 + l\cdot y_3\right)'\right)}{M_W}. \quad (7)$$

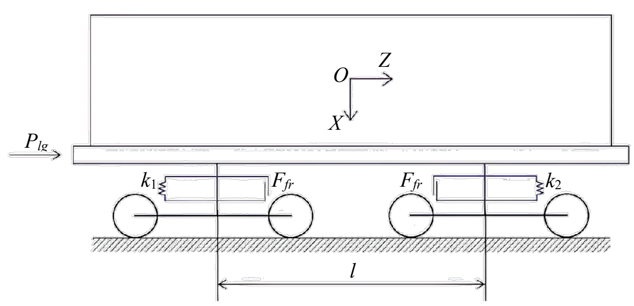

Fig. 4. Calculation scheme of an open wagon

The initial conditions are set to zero [20–23]. It has been established that the acceleration acting on the body of an open wagon is about 20 m/s[2].

5. 2. Results of calculating the strength and a modal analysis of the supporting structure of the open wagon

The acceleration value determined in the previous subchapter, as a component of the dynamic load, was taken into account when calculating the strength of the open wagon body. The calculations showed that the maximum stresses in the open wagon structure arise in the zones of interaction of the girdle beam with pivots (Fig. 5). These zones are highlighted in blue.

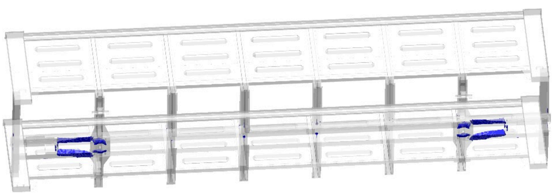

Fig. 5. Areas of greatest load of the modernized supporting structure of the open wagon

The highest stresses in these zones were 179.4 MPa (Fig. 6). In the middle part of the girdle beam there is also a slight concentration of stresses, which are equal to 157.3 MPa (Fig. 7). These stresses are less than the permissible ones by 14.5%. In this case, the permissible stresses are equal to 210 MPa.

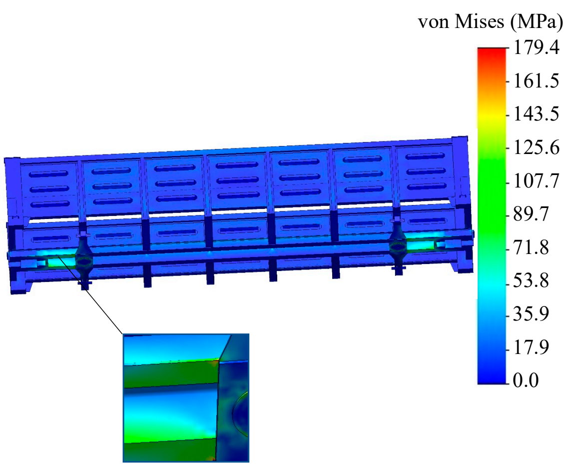

Fig. 6. Stressed state of the modernized supporting structure of the open wagon

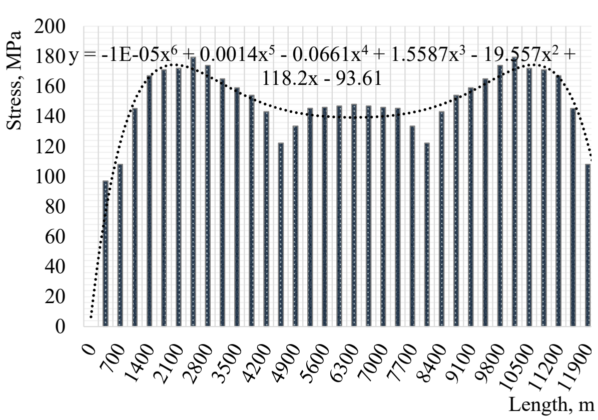

Fig. 7. Stress distribution along the length of the girdle beam of an open wagon

The largest displacements occur in the middle part of the girdle beam and are equal to 3.7 mm (Fig. 8).

In the upper strapping of the side wall, the maximum displacements were 3.6 mm.

According to the calculation scheme shown in Fig. 2, a modal analysis of the modernized supporting structure of the open wagon was also performed. The results of this analysis are shown in Fig. 9.

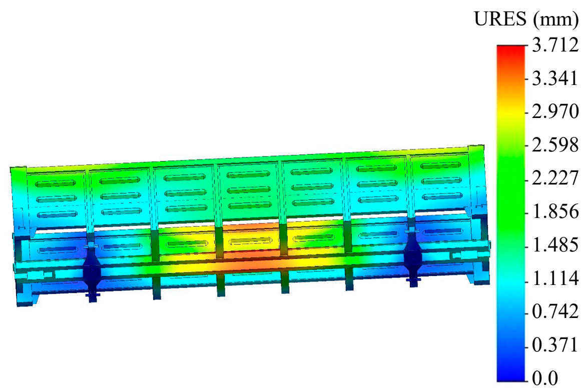

Fig. 8. Movement in the nodes of the modernized supporting structure of the open wagon

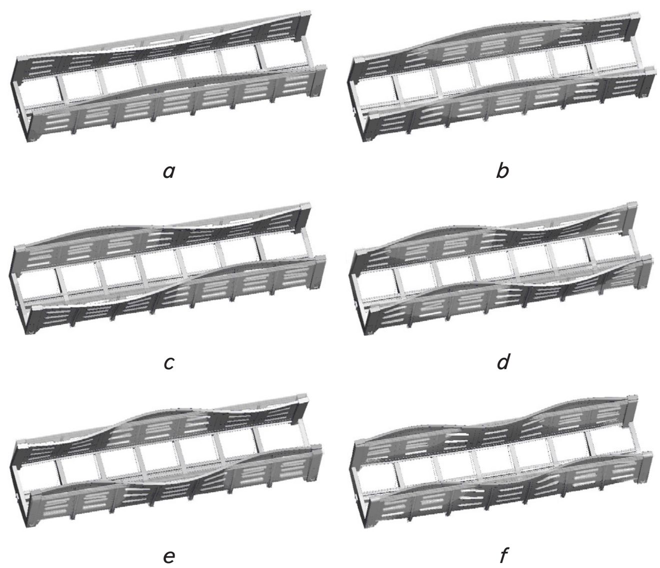

Fig. 9. Vibration forms of the modernized supporting structure of the gondola: *a* – first mode ($\nu_1 = 8.4$ Hz); *b* – second mode ($\nu_2 = 11.08$ Hz); *c* – third mode ($\nu_3 = 12.4$ Hz); *d* – fourth mode ($\nu_3 = 15.1$ Hz); *e* – fifth mode ($\nu_6 = 17.1$ Hz); *f* – sixth mode ($\nu_6 = 19.7$ Hz)

The safety of the open wagon was assessed using the first natural frequency of oscillation, which was $\nu_1 = 8.4$ Hz. Since this frequency exceeds 8 Hz, it is concluded that the safety of movement from the point of view of modal analysis is observed.

6. Discussion of the results of determining the features of the longitudinal loading of the modernized supporting structure of an open wagon

To enable the transportation of long-length cargo in open wagons, it is proposed to modernize their design. It is assumed to dismantle the end walls or doors of the open wagon. Such a solution contributes to reducing its packaging by more than 1 t, and accordingly, increasing the load capacity by the same amount.

To substantiate such a solution, a calculation was made for the strength of the open wagon under the condition of its movement as part of a train. The determination of dynamic loads acting on the open wagon was carried out by mathematical modeling. For this purpose, a mathematical model (2) was built, which takes into account the presence of three degrees of freedom of the open wagon: translational in the longitudinal, angular relative to the vertical axis, and vertical directions (Fig. 4).

The calculated acceleration value was taken into account when calculating the strength of the open wagon. The calculations showed that the maximum stresses occur in the middle part of the girdle beam (Fig. 5) and are equal to 179.4 MPa (Fig. 6), which is 14.5% lower than the permissible ones. A slight concentration of stresses is also recorded in the middle part of the girdle beam (Fig. 7). The maximum stresses in it were 157.3 MPa, which does not exceed the permissible values. Therefore, the strength of the open wagon body is maintained. The maximum displacements in the nodes of the modernized supporting structure of the open wagon arise in the middle part of the girdle beam and are equal to 3.7 mm (Fig. 8).

In addition, as part of the study, a modal analysis of the modernized supporting structure of the open wagon was conducted. This allowed us to determine the natural frequencies of oscillations of its structure. It was established that traffic safety from the point of view of modal analysis is observed, since the first natural frequency of oscillations exceeds 8 Hz (Fig. 9, *a*).

The advantage of this study in comparison with [1, 2] is that we conducted a study of the stressed state of the supporting structure of the open wagon as a whole, and not only its individual components. Unlike papers [3, 4], we also considered the case of transportation of long cargo in an open wagon. The advantage of this study in comparison with [5–8] is that we did not limit ourselves to the main load schemes of the open wagon in operation but also considered the possibility of transportation of long cargo in an open wagon.

The condition for using the results of our study is symmetrical loading of the body with cargo.

The main limitation of this study is that when building a spatial model of an open wagon, possible wear of its structure during operation was not taken into account.

This study has its drawbacks. The main one is that the spatial model of the modernized supporting structure of the open wagon is considered as a monolith and does not take into account welding seams.

The advancement of this study is to determine the strength of the supporting structure of the open wagon when transported by rail ferry by sea. This area is quite relevant for European countries that have access to international communication through sea areas.

Our studies will contribute to devising recommendations for increasing the efficiency of transportation of long-length cargo by rail.

7. Conclusions

1. A mathematical modeling of the longitudinal loading of the modernized supporting structure of the open wagon for transporting long-length cargo was carried out. For this purpose, a mathematical model was built that characterizes the movement of the open wagon in the train. The model has three degrees of freedom of the open wagon: translational in the longitudinal, angular relative to the vertical axis, and vertical directions. The results of the mathematical model solution established that the acceleration acting on the open wagon body is about 20 m/s^2.

2. A calculation of the strength and modal analysis of the supporting structure of the open wagon was carried out. It was established that the maximum stresses in the open wagon structure arise in the zones of interaction of the girdle beam with pivots and are equal to 179.4 MPa. In the middle part of the girdle beam there is also a slight concentration of stresses, which are equal to 157.3 MPa. These stresses are less than the permissible ones by 14.5%. The largest displacements occur in the middle part of the girdle beam and are equal to 3.7 mm. The results of the modal analysis of the modernized supporting structure of the open wagon showed that the first natural frequency of oscillations is 8.4 Hz. That is, the safety of the open wagon movement from the point of view of modal analysis is observed.

Conflicts of interest

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

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The study was conducted without financial support.

Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Authors' contributions

Alyona Lovska: conceptualization, formal analysis, funding acquisition, investigation, methodology, project administration, data curation, resources, validation, software, supervision, visualization, writing – original draft, writing – review & editing. **Nurlana Karimova:** formal analysis, funding acquisition, investigation, funding acquisition, investigation, writing – review & editing.

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