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ADAPTING THE LOAD-BEARING STRUCTURE OF A GONDOLA CAR FOR TRANSPORTING HIGH-TEMPERATURE CARGOES

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This paper determines the load on the load-bearing structure of a universal gondola car during the transportation of cargo with a temperature of 700 °C in it. It has been established that the maximum equivalent stresses, in this case, significantly exceed permissible ones. The maximum temperature of the cargo, at which the strength indicators of the carrying structure of the gondola do not exceed the permissible values, is 94 °C. At the same time, the temperature of the cargo transported in the cars by rail can be much higher. In this regard, in order to use gondola cars for the transportation of cargoes with high temperatures, it is possible to arrange them in heat-resistant containers of open type – flatcars. Therefore, in this study, a structure of the flatcar with convex walls has been proposed. Such configuration of the sidewalls makes it possible to increase the usable volume of the container by 8 % compared to the prototype. As a flatcar material, a composite with heat-resistant properties is used. To justify the proposed solution, the strength of a flatcar was calculated. It has been established that the maximum equivalent stresses in the carrying structure of the flatcar are about 300 MPa and do not exceed permissible ones.

To determine the main indicators of the dynamics of the gondola car loaded with flats, its dynamic load was mathematically modeled. The calculation results showed that the accelerations that operate in the center of the mass of the load-bearing structure of a gondola car are about 1.5 m/s²**. The vertical dynamics coefficient is 0.22. The estimated dynamics indicators are within the permissible values.

The study reported here could contribute to improving the efficiency of the use of gondola cars and to further advancements in the design of innovative vehicles

Keywords: transport mechanics, load-bearing structure, body load, temperature impact, heat-resistant flatcar

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1. Introduction

Trends in the development of the transport industry necessitate increasing the requirements for railroad vehicles in order to maintain the leadership position of the railroad industry. By rail, a very wide range of cargoes is transported, including flammable, high-temperature, acidic, etc. At the same time, different types of cars are used depending on the type of cargo transported.

It is important to note that the lack of rolling stock may result in a cargo delay while it is awaited. This leads to additional operating expenditures and affects the economic performance of transport. Therefore, it is important to adapt the existing fleet of freight cars to the transportation of a wide range of cargoes.

Among the most disadvantaged cargoes in terms of load-bearing structures are those with high temperatures. Their temperature can reach 700 °C. An example of such cargo is hot sinter. It is transported by rail mainly in hopper cars. However, in order to ensure the timely delivery of cargoes in the case of a shortage of hopper cars, it is necessary to adapt the existing fleet of cars for transportation.

It is known that one of the most common types of cars in operation is gondola cars. At the same time, the bearing structure of these cars is not intended for the transportation of high-temperature cargoes. Their use for such transportation causes damage to the bearing structure and the need to carry out unscheduled types of repair or exclusion of the car from the inventory fleet. In addition, the transportation of high-temperature cargoes by rail requires special attention in terms of ensuring environmental friendliness. Therefore, a study that addresses the adaptation of universal gondola cars to the transportation of high-temperature cargoes while ensuring the strength, safety, and environmental friendliness of the transportation process is both relevant and important.

2. Literature review and problem statement

The main indicators of strength of the bearing structure of a car are determined in [1]. The main causes of defects in the components of the car were analyzed. Measures were proposed to improve the load-bearing structure of the gondola car by installing reinforcing elements in the most loaded zones of the frame. However, the proposed structural improvements do not contribute to the possibility of using the car to transport high-temperature cargoes in it.

The design of the BCNHL freight car is analyzed in [2]. The possible options for improving the technical and economic indicators of wagons are given. At the same time, the authors of the cited work do not specify the possibilities of using universal cars for the transportation of high-temperature cargoes.

Work [3] reports the results of determining the load on a load-bearing structure of the car with composite walls. At the same time, the authors considered only the normative values of the loads that apply to the car in operation. Additionally, they did not pay attention to determining the temperature load on a load-bearing structure of the car, which is scientifically interesting as its walls are made of composite material.

The strength of the bearing structure of a car made from composite material reinforced with fiber is investigated in [4]. The conclusions are drawn about the obtained stressed condition of the load-bearing structure of the car exposed to impact loads. However, the temperature load on the load-bearing structure of the car with composite components was not determined by the authors.

The possibility of modernization of the freight car by using composite panels in its components is analyzed in [5]. The expediency of introducing the proposed solution into the load-bearing structure of the car is substantiated. At the same time, the expediency of using composite materials for the purpose of transportation of high-temperature cargoes in cars is not paid attention to in the cited work.

Paper [6] justifies the use of composite panels in the modernization of the bodies of freight cars. The advantages of the proposed modernization and the prospects for its further development on narrow gauge cars are indicated. However, the stressed condition of the load-bearing structure of the freight car with composite components was not considered.

Work [7] highlights the peculiarities of the introduction of new polymer composite materials into transport engineering. The study reported was carried out using an example of the flooring of railroad cars. The prospects for the use of this material in passenger car construction are given. At the same time, it is interesting to use this material in freight car engineering since such cars experience a greater load in operation.

The physical-mechanical and insulating properties of composite materials reinforced with carbon fiber for the flooring of cars are analyzed in [8]. The expediency of using this material in car engineering is substantiated. However, the cited work does not pay attention to the issues related to determining the main indicators of strength of bearing structures of cars with composite components.

A method for calculating the components of the load-bearing structure of a gondola car for strength is improved in [9]. The load on a load-bearing structure of the car during operational modes is determined. Correction of normative documents regulating the requirements for the design and calculation of cars is proposed. However, the issue of determining the temperature load on the load-bearing structure of the car is not paid attention to.

Paper [10] determines the load on the main types of cars under operating modes. The substantiation of further operation of freight cars that have exhausted their regulatory resource is given. At the same time, the authors do not take into consideration the temperature loads that can act on the bearing structures of cars when transporting specific cargoes.

Our review of literary sources [1–10] allows us to conclude that the issues related to determining the temperature impact on the bearing structures of freight cars and their adaptation to the transportation of high-temperature cargoes are quite relevant. This necessitates research in this area to devise appropriate measures that would contribute to improving the efficiency of the operation of freight cars.

3. The aim and objectives of the study

The purpose of this study is to devise measures to adapt the bearing structures of gondola cars to the transportation of high-temperature cargoes. This could contribute to improving the efficiency of railroad transport operations and maintaining its leadership position in the transport industry.

To accomplish the aim, the following tasks have been set:

– to determine the load on the load-bearing structure of a gondola car when transporting high-temperature cargoes in it;

– to propose a conceptual solution for the adaptation of the load-bearing structure of a gondola car to the transportation of high-temperature cargoes;

– to define the main indicators of the dynamics of the load-bearing structure of a gondola car loaded with flats with a high-temperature cargo.

4. The study materials and methods

To determine the load on the load-bearing structure of a gondola car, when transporting hot sinter in it, a finite-element method was used [11–13], which is implemented in the SolidWorks Simulation software package (France). Graphic work on the construction of a spatial model of a gondola car was carried out in the SolidWorks software suite (France).

The finite-element model of the load-bearing structure of a gondola car is formed by isoparametric tetrahedra [14–16]. The optimal number of tetrahedra is calculated according to the graph-analytic method [17–19]. The essence of the method in solving a given problem is to build the dependence of maximum stresses on the number of finite elements [20]. When this dependence begins to be described by a horizontal line, it is an optimum of the number of finite elements. The number of elements of the grid was 352,435; the nodes – 116,609. The maximum size of the grid element was 100 mm, the minimum size was 20 mm; the maximum ratio of the sides of the elements was 38,400; the percentage of elements with a side ratio of less than three was 18.4; more than ten – 36.8. The number of elements in the circle was 9. The ratio of increasing the size of the elements was 1.7.

We calculated the bearing structure of a gondola car according to the Mises criterion since its material is steel, which has isotropic properties [21–25].

When assembling a finite-element model of an open-type container, a flatcar, we used isoparametric tetrahedra. The number of grid elements was 47,846; the number of nodes was 14,599.

We calculated the container according to the criterion of maximum normal stresses.

To determine the main indicators of the dynamics of a gondola car loaded with flats, mathematical modeling of its dynamic load was carried out [26, 27].

The differential equations of motion were solved according to the Runge-Kutta method [28–30] under the initial conditions equal to zero [31–33]. That is, one of the most frequent approaches used in solving the problems of car dynamics was applied.

5. Results of substantiating the measures for adapting the load-bearing structure of a gondola car to the transportation of high-temperature cargoes

5. 1. Determining the load on a load-bearing structure of the gondola car when transporting high-temperature cargoes in it

To determine the load on the load-bearing structure of a gondola car when transporting high-temperature cargoes in it, the semi-wagon of model 12-757 was chosen as a prototype. When assembling a spatial model, the elements of the structure were taken into consideration, which interact rigidly with each other – by welding or rivets.

The load-bearing structure of a gondola car was fixed in the areas where it rests on bogies. As a material of the structure, the steel of grade 09G2C was used, which has a fluidity limit of 345 MPa and a strength limit of 490 MPa. The steel elasticity module is $2{,}1 \cdot 10^5$ MPa, the displacement module is 0.28, the thermal expansion coefficient is $1{,}5 \cdot 10^{-5}$ K^{-1}. The coefficient of damping the material during the calculations was not taken into consideration since such a parameter is not required by the calculation program.

When drawing up the design scheme, it is taken into consideration that a vertical static load P_v^{st} operates on the bearing structure of the gondola car when utilizing the full load capacity of the gondola car (Fig. 1). Additionally, the model takes into consideration the longitudinal load that acts on the front stops of the auto-coupling P_l, that is, the movement of the car as part of the train was simulated. In addition, the pressure of stretching a bulk cargo P_b was accounted for. On the inner surface of the components of the load-bearing structure, the temperature P_t of 700 °C from the transported cargo was applied. When performing calculations, the damping coefficient of the structure was not taken into consideration since the calculation was carried out in statics.

Based on our calculations, it was established that the maximum equivalent stresses in the load-bearing structure of the gondola car are about 3800 MPa, therefore, they significantly exceed permissible ones (Fig. 2).

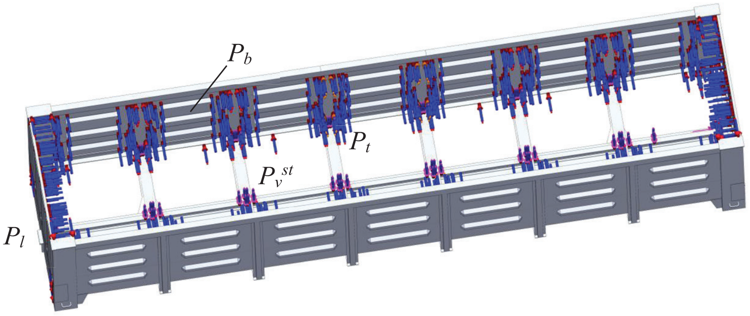


Fig. 1. Estimation scheme of the load-bearing structure of a gondola car

The calculation was carried out for other values of the temperature load as well. The calculation results are shown in Fig. 3.

Fig. 3 shows that the permissible stresses in the load-bearing structure of a gondola are observed at a temperature of the transported cargo of 94 °C. At the same time, the temperature of the transported hot sinter in cars by rail is much higher.

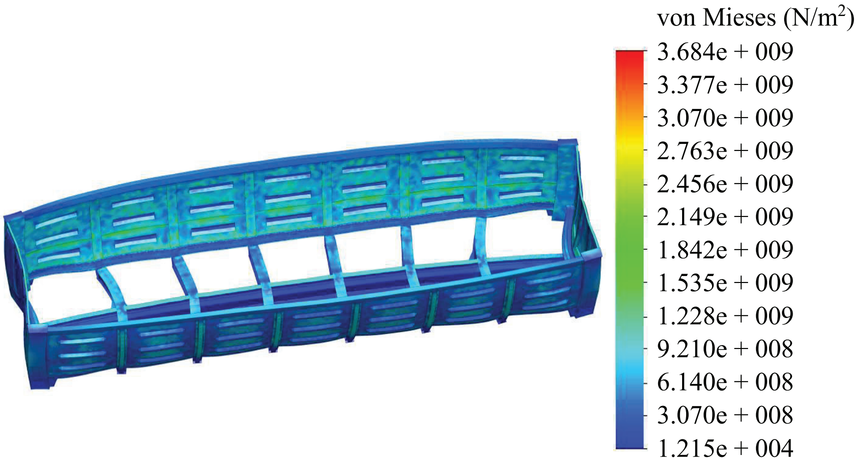


Fig. 2. The stressed state of the load-bearing structure of a gondola car (scale of deformations – 40:1)

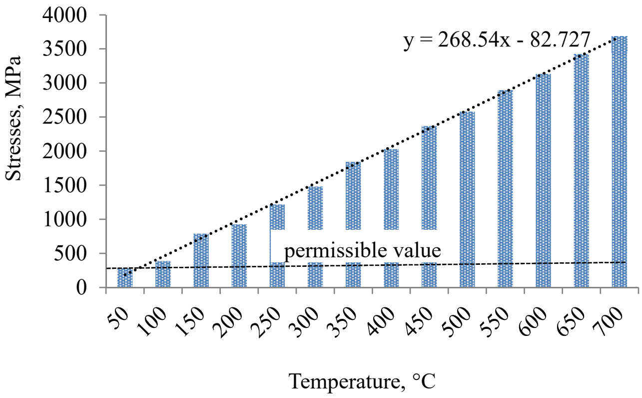


Fig. 3. The dependence of stresses in the load-bearing structure of a gondola car on the temperature of the cargo transported

5. 2. Conceptual solution for adapting the load-bearing structure of a gondola car to the transportation of high-temperature cargoes

In order to use gondola cars for the transportation of cargoes with elevated temperatures, it is possible to arrange them in heat-resistant containers of open type, that is, flatcars (Fig. 4).

A special feature of the proposed flatcar is that its walls have a convex configuration. Such configuration of the sidewalls makes it possible to increase the usable volume of the container by 8 % compared to the prototype [31]. The value of the deflection of the side and end walls is determined for technological reasons, namely, provided that the size of a flatcar is preserved in accordance with the prototype. As a flatcar material, a composite with heat-resistant properties is used, which can withstand a heating temperature of 700 °C and has the following strength limit: in the direction of fibers – 1100–1300 MPa, across the fibers – 650 MPa. The container was fixed using the horizontal parts of fittings.

To justify the proposed solution, we calculated the strength of the flatcar. The estimation scheme is shown in Fig. 5.

When drawing up the design scheme, it is taken into consideration that the flatcar is subject to a vertical static load P_v^{st} the pressure of cargo stretching P_c, as well as the temperature load P_t.

The pressure of cargo stretching was determined from the formula given in [34]

$$P_c=\gamma\cdot g\cdot H\cdot \mathrm{tg}^2\left(\frac{\pi}{4}-\frac{\phi}{2}\right), \qquad (1)$$

where γ is the density of bulk cargo;

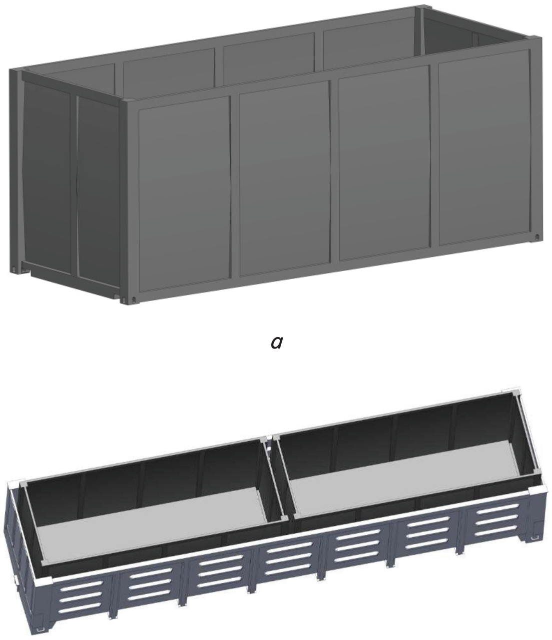
H – the height of the sidewall;

φ – the angle of natural slanting of a cargo;

g – the acceleration of a free fall.

The calculation results showed that the maximum equivalent stresses in the bearing structure of a flatcar do not exceed permissible ones (Fig. 6).

At the same time, the maximum stresses are about 300 MPa and are concentrated in the flatcar racks. In the cladding, the maximum equivalent stress was about 260 MPa. In transverse beams – 210 MPa.



a

b

Fig. 4. Open-type container for transporting hot sinter: *a* – spatial model; *b* – arrangement of containers in a gondola car

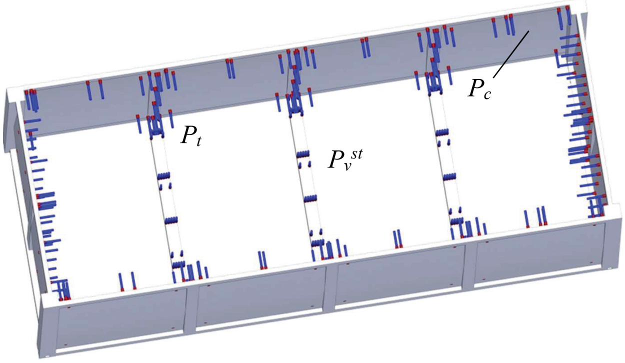


Fig. 5. Flatcar estimation scheme

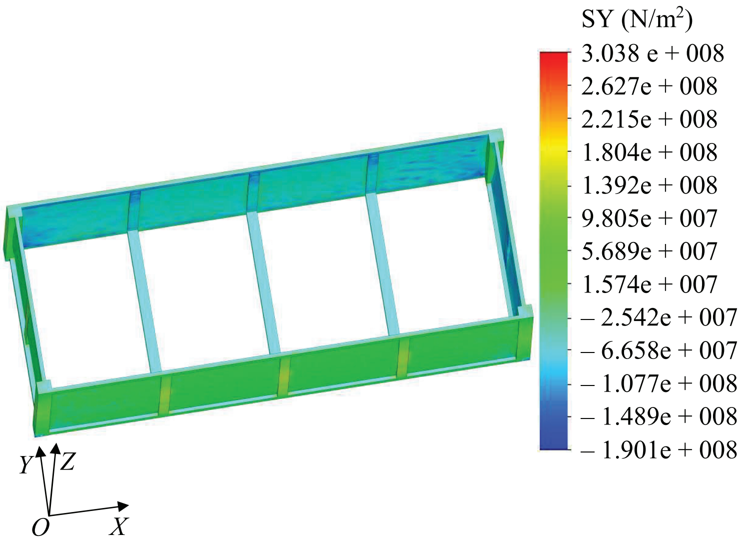


Fig. 6. The stressed state of a container

5. 3. Defining the main indicators of the dynamics of the load-bearing structure of a gondola car loaded with flatcars with a high-temperature cargo

To determine the main indicators of the dynamics of the gondola car loaded with flatcars, the dynamic load was calculated. The study was carried out in a flat coordinate system. It was taken into consideration that the car moves over a butt irregularity with elastic-viscous properties. That is, the conditions described and verified in [23] were taken into consideration. When constructing differential equations of movement, it was taken into consideration that the flatcars do not have their natural degree of freedom and move together with the body of the car.

The estimation scheme of a gondola car is shown in Fig. 7.

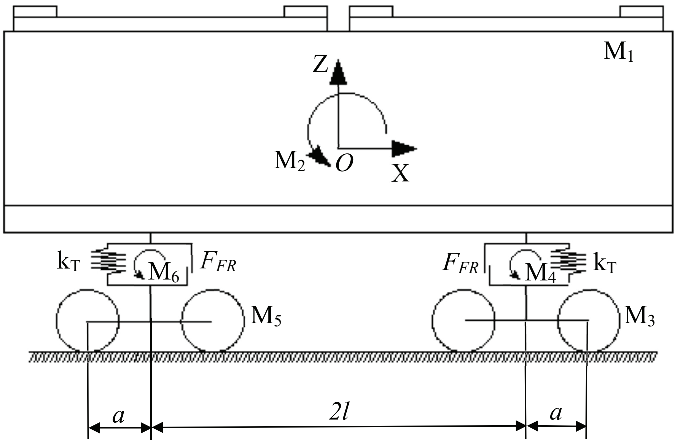


Fig. 7. Gondola car estimation scheme

The equations of motion of a gondola car take the form [23, 24]:

$$M_1 \cdot \frac{d^2}{dt^2} q_1 + 2k_T \cdot q_1 - k_T \cdot q_3 - k_T \cdot q_5 = P_z, \tag{2}$$

$$M_2 \cdot \frac{d^2}{dt^2} q_2 + \left(2 \cdot l^2 \cdot k_T\right) \cdot q_2 + \left(l \cdot k_T\right) \cdot q_3 - \left(l \cdot k_T\right) \cdot q_5 = P_\varphi, \tag{3}$$

$$\begin{gathered} M_3 \cdot \frac{d^2}{dt^2} q_3 - k_T \cdot q_1 + \left(l \cdot k_T\right) \cdot q_2 + \\ + \left(k_T + 2 \cdot k_1\right) \cdot q_3 + 2 \cdot \beta_1 \cdot \frac{d}{dt} q_3 = P_{T_1}^z, \end{gathered} \tag{4}$$

$$M_4 \cdot \frac{d^2}{dt^2} q_4 + \left(2 \cdot a^2 \cdot k_1\right) \cdot q_4 + 2 \cdot \beta_1 \cdot \frac{d}{dt} q_4 = P_{T_1}^\varphi, \tag{5}$$

$$\begin{gathered} M_3 \cdot \frac{d^2}{dt^2} q_3 - k_T \cdot q_1 + \left(l \cdot k_T\right) \cdot q_2 + \\ + \left(k_T + 2 \cdot k_1\right) \cdot q_3 + 2 \cdot \beta_1 \cdot \frac{d}{dt} q_3 = P_{T_1}^z, \end{gathered} \tag{6}$$

$$M_6 \cdot \frac{d^2}{dt^2} q_6 + \left(2 \cdot a^2 \cdot k_1\right) \cdot q_6 + 2 \cdot \beta_1 \cdot \frac{d}{dt} q_6 = P_{T_2}^\varphi, \tag{7}$$

$$P_z = -F_{FR} \cdot \left(\operatorname{sign}\left(\frac{d}{dt} \delta_1 \right) + \operatorname{sign}\left(\frac{d}{dt} \delta_2 \right) \right), \tag{8}$$

$$P_\varphi = F_{FR} \cdot l \cdot \left(\operatorname{sign}\left(\frac{d}{dt} \delta_1 \right) + \operatorname{sign}\left(\frac{d}{dt} \delta_2 \right) \right), \tag{9}$$

$$\begin{gathered} P_{T_1}^z = F_{FR} \cdot \operatorname{sign}\left(\frac{d}{dt} \delta_1 \right) + \\ + k_1 \left(\eta_1 + \eta_2 \right) + \beta_1 \left(\frac{d}{dt} \eta_1 + \frac{d}{dt} \eta_2 \right), \end{gathered} \tag{10}$$

$$P_{T_1}^\varphi = -k_1 \cdot a \cdot \left(\eta_1 - \eta_2 \right) - \beta_1 \cdot a \cdot \left(\frac{d}{dt} \eta_1 - \frac{d}{dt} \eta_2 \right), \tag{11}$$

$$\begin{gathered} P_{T_1}^z = F_{FR} \cdot \operatorname{sign}\left(\frac{d}{dt} \delta_2 \right) + \\ + k_1 \left(\eta_3 + \eta_4 \right) + \beta_1 \left(\frac{d}{dt} \eta_3 + \frac{d}{dt} \eta_4 \right), \end{gathered} \tag{12}$$

$$P_{T_2}^\varphi = -k_1 \cdot a \cdot \left(\eta_3 - \eta_4 \right) - \beta_1 \cdot a \cdot \left(\frac{d}{dt} \eta_3 - \frac{d}{dt} \eta_4 \right), \tag{13}$$

where M_1, M_2 are, respectively, the mass and moment of inertia of the load-bearing structure of a gondola car exposed to the jumping and galloping oscillations; M_3, M_4 are, respectively, the mass and moment of inertia of the first bogie movement exposed to the vibrations of bouncing and galloping; M_5, M_6 are, respectively, the mass and moment of inertia of the second bogie exposed to the jumping and galloping oscillations; a is the half the base of the bogie (model 18-100); q_i – generalized coordinates corresponding to the translational movement relative to the vertical axis and angular movement around the vertical axis; k_i is the rigidity of the spring suspension of a gondola car; β_i is the damping factor; F_{FR} – the force of absolute friction in the spring kit; $\eta(t)$ is a periodic function that describes the butt irregularity.

The calculation results are shown in Fig. 8, 9.

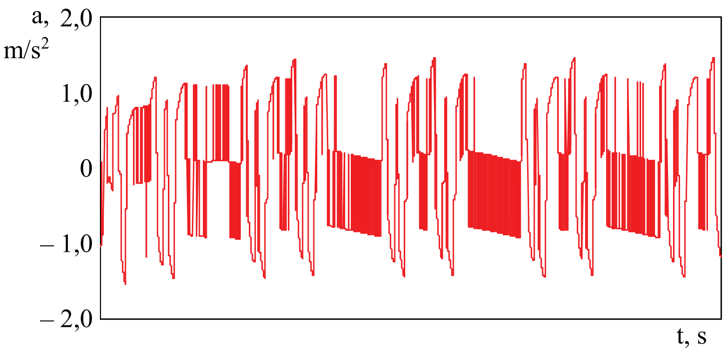


Fig. 8. Accelerations that act in the center of the mass of the load-bearing structure of a gondola car

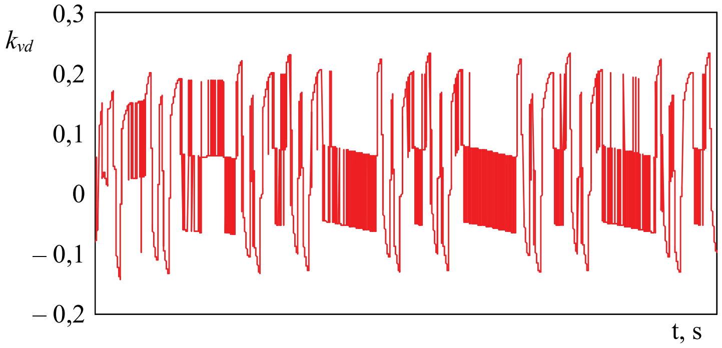


Fig. 9. Vertical dynamics coefficient

At the same time, the accelerations that act in the center of the mass of the load-bearing structure of a gondola car amounted to about 1.5 m/s^2 (0.15g). The vertical dynamics coefficient was 0.22. That is, the calculated indicators of dynamics are within the permissible values, and the movement of the car is estimated as “excellent”.

6. Justification of measures to adapt the load-bearing structure of a gondola car to the transportation of high-temperature cargoes

In order to use universal gondola cars for the transportation of high-temperature cargoes, the main indicators of their strength were determined. It was established that the permissible stresses in the load-bearing structure of a gondola car were observed at a temperature of the transported cargo of 94 °C (Fig. 3). This is due to the fact that the material of the supporting structure is the steel of grade 09G2S, which retains its physical properties at the specified temperature.

In order to be able to transport high-temperature cargoes in gondola cars, the use of flatcars made of heat-resistant material is proposed. A feature of the flatcar is also the presence of convex walls (Fig. 4). This increases its carrying capacity by 8 % compared to the prototype. The calculation of the strength of the flatcar under the influence of the temperature effect confirmed the feasibility of the proposed solution (Fig. 6).

The main indicators of the dynamics of the gondola car during the transportation of flatcars in it were calculated. It was established that the studied indicators did not exceed the permissible values. The accelerations, which act in the center of the mass of the load-bearing structure of a gondola car, amounted to about 1.5 m/s^2 (Fig. 8). The coefficient of vertical dynamics was 0.22 (Fig. 9). Our results are explained by the fact that the gross weight of the transported flatcars does not exceed the payload of the gondola car.

The advantages of our study in comparison with those known are that a conceptual solution has been proposed regarding the possibility of using gondola cars for the transportation of high-temperature cargoes. A given type of car has not been used for such purposes before. However, due to the lack of rolling stock, it became necessary to adapt the existing fleet for the transportation of the appropriate range of cargoes.

In contrast to [1, 5], which proposed the modernization of the designs of cars to improve the efficiency of rail transportation, our results make it possible to ensure the multifunctionality of the car. This becomes possible due to its adaptation to the transportation of high-temperature cargoes.

In comparison with the studies reported in [2], we proposed conceptual solutions for the use of universal freight cars for the transportation of high-temperature cargoes.

In contrast to the results reported in [3, 4], which determined the load on the load-bearing structures of cars during operating modes, we established the temperature load on the load-bearing structure of the car. Our studies have made it possible to determine the permissible temperature of the transported cargo in a gondola car.

In comparison with the studies reported in [6 8], which proposed the introduction of promising materials in the supporting structures of vehicles, we proposed solutions for adapting the existing design of the car to the transportation of high-temperature cargoes. This becomes possible by using separate transport modules – flatcars with heat-resistant cladding.

The advantage of our study compared to [9, 10] is that in the calculations of the strength of the load-bearing structure of the car we also took into consideration the temperature load. Given this, the permissible limit of temperature impact on the bearing structure of the car was determined while ensuring the conditions of its strength.

Thus, the studies reported in the current paper have made it possible to determine the load-bearing structure of a universal car under the influence of temperature exposure. We propose conceptual solutions that allow the transportation of high-temperature cargoes in a typical structure of the car without its modernization.

At the same time, the calculations did not take into consideration the natural degree of freedom of a flatcar relative to the body under operating modes, which is a limitation of our study.

The next stage of our research is to determine the longitudinal load on the load-bearing structure of a gondola with flatcars placed in it. Also worth attention is the impact of the movement of transported cargo on the load of the flatcar and gondola car. In addition, we plan to conduct experimental studies into the temperature effect on the bearing structure of a gondola car, as well as the flatcar.

Our research will contribute to improving the efficiency of the use of gondola cars and further advancements in the design of innovative vehicle designs.

7. Conclusions

1. The load on the load-bearing structure of a gondola car has been determined when transporting high-temperature

cargoes in it. It was established that the maximum equivalent stresses in the load-bearing structure of a gondola car when transporting sinter with a temperature of 700 °C were about 3800 MPa, therefore significantly exceeding permissible ones. At the same time, the permissible stresses in the load-bearing structure of a gondola car are observed at the temperature of the cargo transported in it of 94 °C.

2. A conceptual solution for adapting the load-bearing structure of a gondola car to the transportation of high-temperature cargoes by placing them in heat-resistant flatcars made of composite material has been proposed. The calculation of the strength of the flatcar, taking into consideration the temperature effect on it of 700 °C, established that the maximum equivalent stresses were about 300 MPa and did not exceed the permissible values. In the cladding, the maximum equivalent stresses were about 260 MPa. In transverse beams – 210 MPa.

3. The main indicators of the dynamics of the bearing structure of a gondola car loaded with flatcars with high-temperature cargo have been defined. The accelerations that act in the center of the mass of the load-bearing structure of a gondola car amounted to about 1.5 m/s^2 (0.15g). The vertical dynamics coefficient was 0.22. Consequently, the calculated dynamics indicators are within the permissible values while the ride of the car is estimated as "excellent".

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