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DETERMINING THE FEATURES OF TEMPERATURE INFLUENCE ON THE LOAD-BEARING STRUCTURE OF A HOPPER CAR WITH A COMPOSITE CLADDING WHEN TRANSPORTING PELLETS TO METALLURGICAL ENTERPRISES

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This paper reports the improved load-bearing structure of a hopper car for transporting pellets and hot sinter. In order to increase the strength of the load-bearing structure of a hopper car under the influence of high temperatures from the transported cargo, the use of cladding made of composite material has been proposed. This solution also contributes to a 5 % reduction in the wagon's tare compared to the prototype car.

The dynamic load on the load-bearing structure of a hopper car was determined. This study was carried out for the case where an empty wagon was moving over an irregularity between the rail joints. The calculations showed that the studied dynamics indicators did not exceed the permissible values. At the same time, the ride of a hopper car is rated as "excellent".

The main indicators of the strength of the carrying structure of a hopper car were determined taking into consideration the proposed improvement. That took into account the temperature effect exerted on the load-bearing structure of a hopper car by hot sinter. It was established that the maximum equivalent stresses occur in the zone of interaction of the girder beam with the pivot beam and are about 290 MPa. At the same time, stresses in the cladding of a hopper car are about 200 MPa, which is 12 % lower than those in a regular structure.

Modal analysis was carried out to determine the frequencies and shapes of the natural oscillations of the bearing structure of a hopper car with a composite cladding. The calculation results demonstrated that the first natural frequency exceeds 8 Hz. Therefore, the safety of the wagon is provided.

The coefficient of fatigue resistance of the load-bearing structure of a hopper car was calculated. It was established that its value is almost twice as high as the permissible one. That is, the resistance to fatigue of the supporting structure is provided.

The research reported here could contribute to ensuring the strength of the load-bearing structures of hopper cars, reducing the cost of maintenance, and increasing the efficiency of their operation

Keywords: transportation mechanics, hopper car, load-bearing structure, composite material, dynamic load, strength, fatigue resistance

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1. Introduction

The operational efficiency in the transportation industry necessitates the introduction of modern vehicles. Since the main segment of the transportation process is given to railroad transport, special conditions should be imposed on the design of modern car structures. In particular, this applies to their load-bearing structures.

One of the most common types of railroad cars used on the tracks of industrial enterprises is hopper cars for the transportation of pellets and hot sinter. In this case, the temperature of the hot sinter can reach 700 °C. In addition, when pellets are transported over long distances in hopper cars between mining-enriching plants and transport and cargo complexes of metallurgical plants, they freeze during the period of negative environmental temperatures. Before unloading pellets from hopper cars, they are defrosted in convective garages under the influence of temperature exposure.

Due to the significant temperature impact and force load on the supporting structure of a hopper car, its damage may occur. The most common is body cladding corrugation, deformations, cracks, etc. That predetermines the need to replace the cladding, and, accordingly, requires additional resources for maintaining the car. Disrupting the strength of a hopper car along the way threatens the stability of its movement and overturning, and, accordingly, causes damage to the rail infrastructure given the high temperature of the transported cargo [1–3]. This also poses a threat to the environmental as well as economic safety of railroad transportation. Therefore, in order to prevent emergencies in the transportation of hot pellets and sinter by rail, transport safety issues require special attention [4, 5].

Thus, it is important to carry out relevant studies aimed at improving the strength of the load-bearing structures of hopper cars, as well as the efficiency of their operation.

2. Literature review and problem statement

Work [6] examines the design process based on structural optimization of the body of a railroad car made of extruded aluminum panels. The proposed technical solutions were confirmed by the comprehensive calculations of a car body for strength. Paper [7] considers the feasibility of using magnesium alloys in the bearing structures of vehicles. A given solution could help reduce the tare of cars compared to prototype designs.

At the same time, the cited works do not investigate the impact of temperature load on the load-bearing structures of cars made of those materials.

A study into the impact strength of a railroad car made of composite materials reinforced with fiber is reported in [8]. It was established that the effect of the initial tension is more significant in the case where the load acts in parallel to the direction of the main fiber. However, the cited work does not define the impact of the use of composite materials on the dynamic load on cars.

Work [9] justifies the use of polymer composite materials in the car building industry. Those materials have been proposed to be used in the manufacture of flooring of the car. The results of experimental studies using the method of pressing a composite in the mold were reported. It is important to say that the possibility of using a given material in the manufacture of load-bearing body elements has not been considered by the authors.

Features of the calculation of a freight car with laminated composite walls are described in [10]. The calculation was implemented by using a finite-element method in the Ansys 14.5 software package. The results of determining the optimal thickness of the walls of a car body were reported subject to providing for its strength. At the same time, when determining the stressed state of the car's load-bearing structure, the authors limited themselves to the normative values of loads. That is, no study was not carried out into the dynamic loading, as well as the fatigue strength of the car, taking into consideration the use of composite materials.

Study [11] describes features of the use of environmentally friendly composites for the manufacture of automotive products. The results of calculating the strength of transportation means made of a given material were reported. It was established that the use of composites on a natural base is more rational, compared to the classic ones, from an economic and technical point of view.

The analysis of the properties of composite materials and the possibility of their application in vehicle designs is given in [12]. The study investigated a bus body. It was established that the use of composites helps reduce body weight by almost 20 % while ensuring conditions of strength and operational reliability. It is interesting to investigate the expediency of using those materials in the manufacture of load-bearing structures of railroad vehicles.

Features of production and use of modern polymer composite materials in the manufacture of railroad cars are reported in [13]. The study focuses on the development of nanocomposites from recycled polypropylene reinforced with natural fiber. It should be noted that the issue of determining the strength of the load-bearing structure of the car with the use of a given material was not paid attention to in the cited work.

The use of composite panels in the designs of freight cars to reduce the wear of their bodies in operation was substantiated in [14]. The authors reported the results of calculating the strength of a load-bearing structure of the car. They proposed a technique for placing composite panels inside the internal space of the body. In addition, they devised a technique for docking panels and their attachment to the steel lining of the body.

Work [15] highlights the features of the use of composite panels in the designs of freight cars. This advancement is proposed to be implemented during the modernization of cars to protect against corrosion damage and facilitate the unloading of cargoes in winter conditions. At the same time, the authors substantiated the application of composite elements (panels) using an example of sidewalls. However, the authors did not determine the feasibility of using composite panels in the load-bearing structures of hopper cars.

Our review of literary sources [6–15] reveals that the issues of improving the strength of vehicles through the introduction of new advanced materials are quite promising and relevant. At the same time, their development in relation to the use in car structures requires further research. In this regard, there is a need to conduct research and devise appropriate ways to address this area.

3. The aim and objectives of the study

The purpose of this study is to identify the peculiarities of temperature impact on the supporting structure of a hopper car with a composite cladding. This would help improve the strength of the carrying structure of a hopper car under the influence of high temperatures from hot sinter and reduce the tare of its load-bearing structure.

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

– to propose measures to improve the bearing structure of a hopper car;

– to determine the dynamic load on the improved hopper car design;

– to define the main indicators of strength for the improved hopper car design;

– to conduct a modal analysis and determine the coefficient of fatigue resistance of the load-bearing structure of a hopper car.

4. The study materials and methods

In order to determine the dynamic load on the improved load-bearing structure of a hopper car, mathematical modeling was carried out. The calculation was performed for the case where an empty car is moving since the greatest load on the load-bearing structure can be observed. It is taken into consideration that the car moves along the track that has elastic-viscous properties [16–18]. The track irregularity was expressed by a periodic function. The mathematical model was solved in the Mathcad software package (USA) using the Runge-Kutta method [19–21]. The initial movements and speeds were set to zero [22, 23]. The limitation of the estimation model is the lack of friction forces between the body stops and the bogie stops.

To determine the temperature effect on the strength of the load-bearing structure of a hopper car, the calculation was carried out in the SolidWorks Simulation software suite (France) [24–27]. In this case, the method of finite elements was applied. The grid was built on a solid body taking into consideration a curvature [28–30]. When performing the calculations, isoparametric tetrahedra were used whose optimal number was determined by the graphic-analytical method [31–34]. The number of elements in the grid was 373,185; the number of nodes was 125,608. The maximum size of the grid element was 60.0 mm, the minimum is 12.0 mm, the maximum ratio of the sides of the elements is 543.59, the percentage of elements with a side ratio of less than three was 7.64, more than ten – 32.6. The minimum number of elements in a circle was 12, the ratio of increasing the size of the element is 1.8. We fixed the model using the horizontal parts of the stops, that is, in the areas of rest on the running gear [35–38]. The material of the metal structure of the body was the steel of grade 09G2C; the cladding was a composite. In this case, the composite has linear elastic orthotropic properties. The strength limit in the direction of fibers is 1,100–1,300 MPa, and in the transverse direction – 650 MPa. It is important to note that a given composite withstands the strength value at a temperature of 700 °C. An example is a composite with a titanium matrix, which is reinforced with fibers of boron, borSIC, silicon carbide, beryllium, molybdenum.

When calculating the strength, the cladding was considered a shell. When building a finite-element model, the cladding was split into tetrahedra.

Since the main part of the carrying structure of a hopper car is made of steel, which is an isotropic material while the composite is orthotropic, the calculation was carried out according to two criteria – von Mises and maximum normal stresses.

We determined the natural frequencies and shapes of oscillations of the carrying structure of a hopper car by modal analysis implemented in the SolidWorks Simulation software suite (France) [39–42]. To calculate the coefficient of fatigue resistance of the carrying structure of a hopper car, the methodology specified in the normative documents on the design of car structures was applied.

5. Results of determining the temperature load on the bearing structure of a hopper car from composite materials

5. 1. Measures to improve the load-bearing structure of a hopper car

In a typical hopper car for the transportation of pellets and hot sinter, the load-bearing structure consists of a metal frame (Fig. 1). Unlike other types of cars, the cladding is not rigidly connected to the frame but is hung onto it. This solution eliminates body boxing under the influence of high temperatures and provides easy replacement if damaged.

In order to improve the strength indicators of the load-bearing structure of a hopper car, it is proposed to improve it by using a cladding made of a composite material (Fig. 2). In addition, the use of composite cladding helps reduce the car's tare by 5 % compared to the prototype.

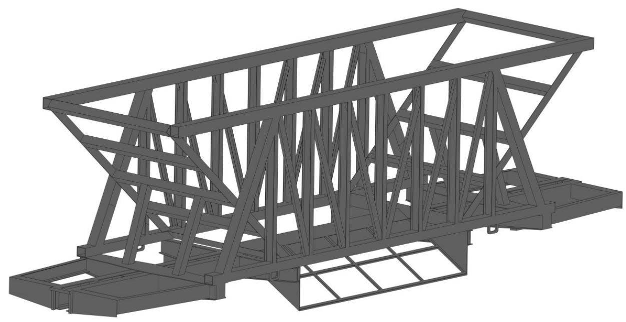

Fig. 1. The bearing structure of a hopper car

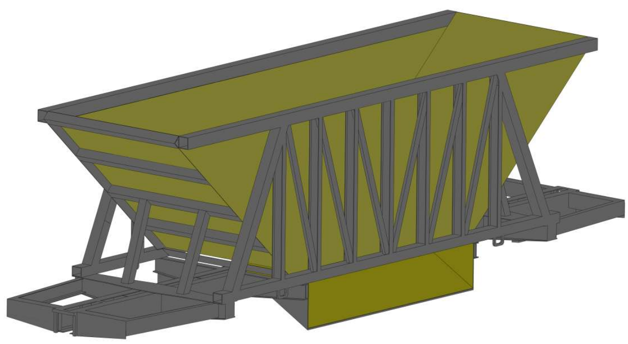

Fig. 2. The improved load-bearing structure of a hopper car

At the same time, the proposed advancement can be implemented during the manufacture of new car structures, as well as their modernization at car repair enterprises.

5. 2. Determining the dynamic load on the improved hopper car design

Since the proposed implementation contributes to the reduction of the car's tare, the main indicators of its dynamics have been defined. The estimation scheme is shown in Fig. 3. As a prototype, a hopper car of the model 20-9749 (Ukraine) was chosen.

We took into consideration the fluctuations of bouncing and galloping as the most common types of oscillations of the car in operation. The model accounted for the technical characteristics of bogies of the model 18-100.

$$M_1 \cdot \frac{d^2}{dt^2} q_1 + C_{1,1} \cdot q_1 + C_{1,3} \cdot q_3 + C_{1,5} \cdot q_5 = = -F_{FR} \cdot \left(\operatorname{sign}\left(\frac{d}{dt} \delta_1 \right) + \operatorname{sign}\left(\frac{d}{dt} \delta_2 \right) \right), \quad (1)$$

$$M_2 \cdot \frac{d^2}{dt^2} q_2 + C_{2,2} \cdot q_2 + C_{2,3} \cdot q_3 + C_{2,5} \cdot q_5 = = F_{FR} \cdot l \cdot \left(\text{sign}\left(\frac{d}{dt} \delta_1 \right) + \text{sign}\left(\frac{d}{dt} \delta_2 \right) \right), \quad (2)$$

$$M_3 \cdot \frac{d^2}{dt^2} q_3 + C_{3,1} \cdot q_1 + C_{3,2} \cdot q_2 + + C_{3,3} \cdot q_3 + B_{3,3} \cdot \frac{d}{dt} q_3 = = F_{FR} \cdot \text{sign}\left(\frac{d}{dt} \delta_1 \right) + + k_1 (\eta_1 + \eta_2) + \beta_1 \left(\frac{d}{dt} \eta_1 + \frac{d}{dt} \eta_2 \right), \quad (3)$$

$$M_4 \cdot \frac{d^2}{dt^2} q_4 + C_{4,4} \cdot q_4 + B_{4,4} \cdot \frac{d}{dt} q_4 = = -k_1 (\eta_1 - \eta_2) - \beta_1 \cdot a \cdot \left(\frac{d}{dt} \eta_1 - \frac{d}{dt} \eta_2 \right), \quad (4)$$

$$M_5 \cdot \frac{d^2}{dt^2} q_5 + C_{5,1} \cdot q_1 + C_{5,2} \cdot q_2 + + C_{5,5} \cdot q_5 + B_{5,5} \cdot \frac{d}{dt} q_5 = = F_{FR} \cdot \text{sign}\left(\frac{d}{dt} \delta_2 \right) + + k_1 (\eta_3 + \eta_4) + \beta_1 \left(\frac{d}{dt} \eta_3 + \frac{d}{dt} \eta_4 \right), \quad (5)$$

$$M_6 \cdot \frac{d^2}{dt^2} q_6 + C_{6,6} \cdot q_6 + B_{6,6} \cdot \frac{d}{dt} q_6 = = -k_1 \cdot a \cdot (\eta_3 - \eta_4) - \beta_1 \cdot a \cdot \left(\frac{d}{dt} \eta_3 - \frac{d}{dt} \eta_4 \right), \quad (6)$$

where M_1, M_2 are, respectively, the mass and moment of inertia of the supporting structure of a hopper car; M_3, M_4 are, respectively, the mass and moment of inertia of the first bogie; M_5, M_6 are, respectively, the mass and moment of inertia of the second bogie; B_{ij} is the scattering function; a is the bogie's semi-frame; q_i is the generalized coordinates corresponding to the translational and angular movements around the vertical axis, respectively, of the body of a hopper car, the first and second bogies; k_B is the rigidity of spring suspension of bogies; β_i is the damping coefficient; F_{FR} is the friction force arising in a spring set.

Our calculations have made it possible to determine the main indicators of the dynamics of a hopper car: acceleration in the center of the masses, acceleration in the regions of resting on bogies, and the coefficient of vertical dynamics (Fig. 4–6).

Our calculations of the dynamic load on the car have shown that the determined dynamics indicators do not exceed the permissible values. The acceleration that operates in the center of the masses of the supporting structure is about 0.4g. The acceleration of the load-bearing structure of a hopper car in the regions of resting on bogies is 0.53g, and the coefficient of vertical dynamics is 0.52. At the same time, the ride of a hopper car is rated as "excellent".

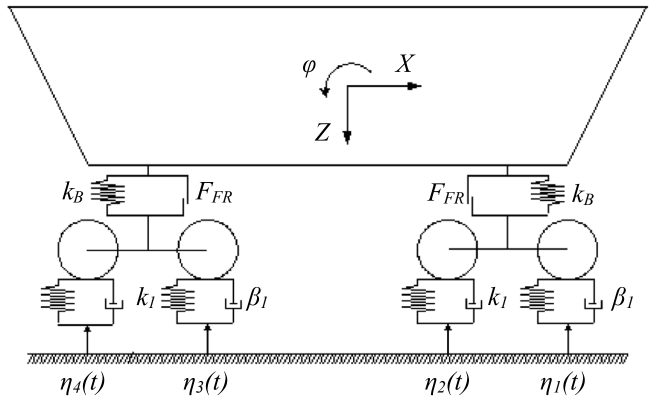

Fig. 3. Estimation scheme of a hopper car

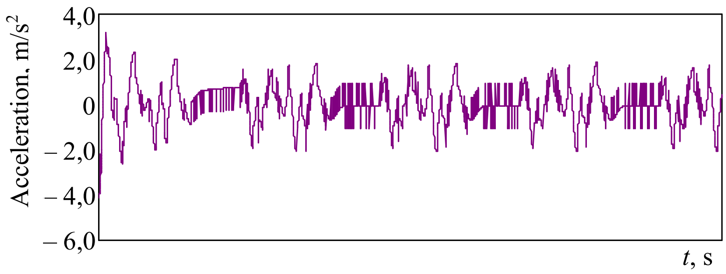

Fig. 4. Acceleration of the load-bearing structure of a hopper car in the center of masses

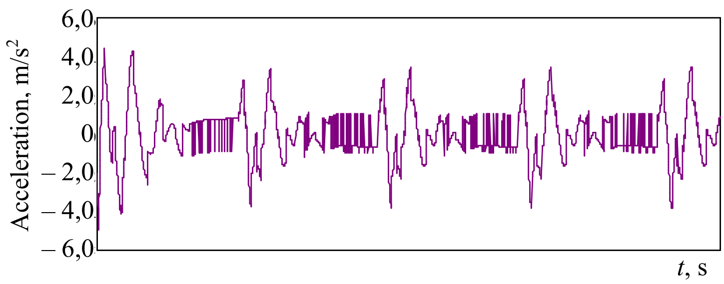

Fig. 5. Acceleration of the load-bearing structure of a hopper car in the regions of resting on bogies

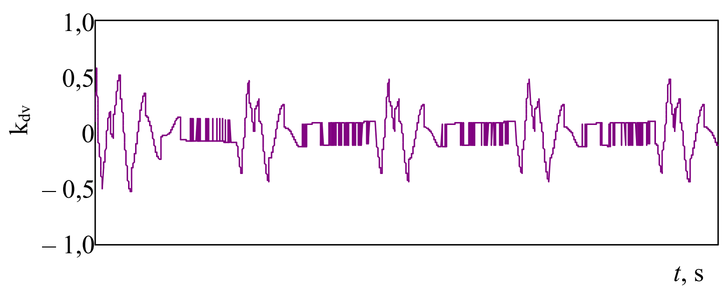

Fig. 6. Hopper car vertical dynamics coefficient

5. 3. Determining the main indicators of strength for the improved hopper car design

The estimation scheme of the load-bearing structure of a hopper car to determine the indicators of its strength is shown in Fig. 7. When constructing the model, it is taken into consideration that the full carrying capacity of a hopper car is used. At the same time, the body is exposed to a vertical static load P_v^{st}, the pressure of bulk cargo P_p, as well as a longitudinal load on the front stop of the car autocoupling P_a, which is equal to 2.5 MN. That is, the model takes into consideration the movement of a car as part of the train. In addition, the temperature load P_t was applied to the model, which was taken equal to 700 °C.

The results of the strength calculation are shown in Fig. 8. It was established that the maximum equivalent stresses according to von Mises criterion occur in the zone of interaction of the girder beam with the pivot beam, and are about 290 MPa. The stresses in the cladding of a hopper car, according to the criterion of maximum normal stresses, are about 200 MPa, which is 12 % lower than those in the typical structure (Fig. 9). At the same time, the trend line y_s describes the distribution of stresses for the height of the rack in the structure of a car with a steel cladding, and y_c – with a composite one.

The distribution of stresses along the length of the girder beam of the frame is shown in Fig. 10.

The maximum stresses occur, in this case, in the console parts of the frame. In the middle part, they were about 200 MPa.

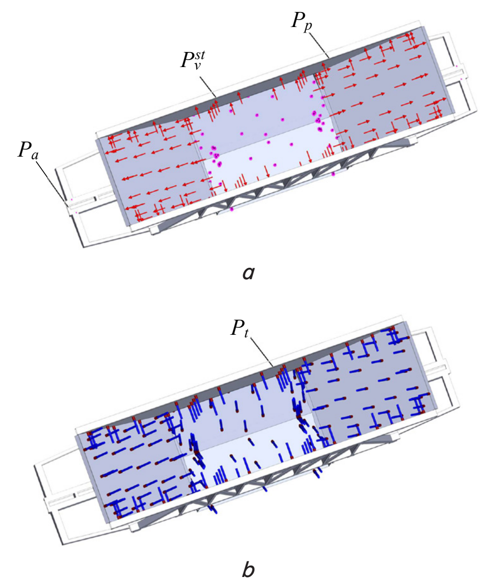

Fig. 7. Estimation scheme of the load-bearing structure of a hopper car: *a* – force factors; *b* – temperature load

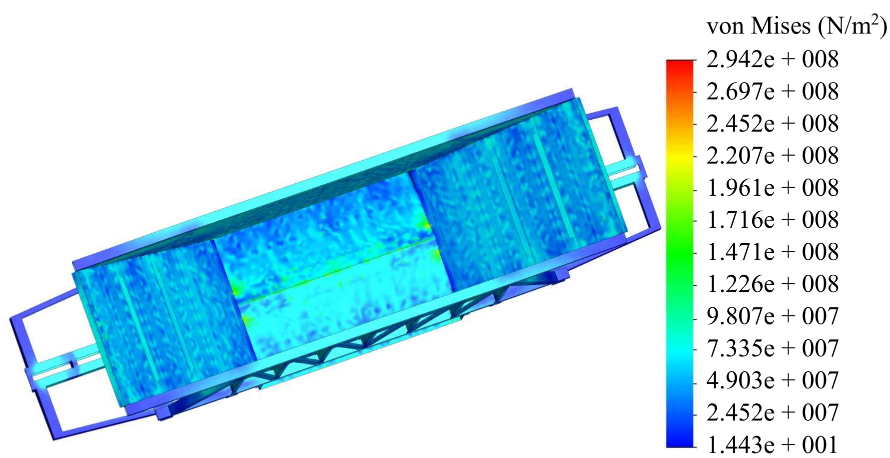

Fig. 8. The stressed state of the load-bearing structure of a hopper car

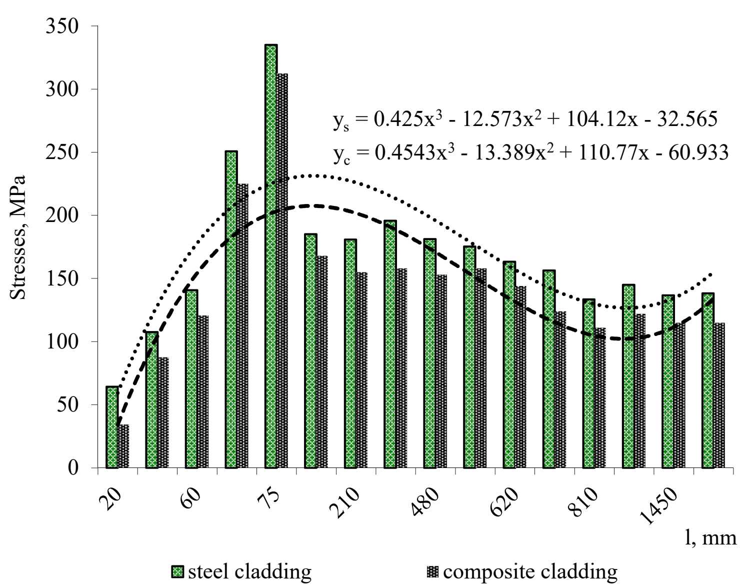

Fig. 9. The distribution of stresses for the height of the intermediate body rack

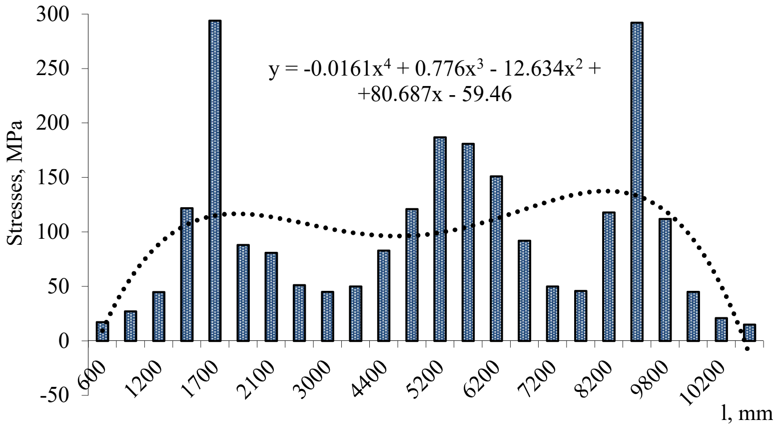

Fig. 10. The distribution of stresses in the girder beam by its length

In addition, within the framework of the study, the strength of the load-bearing structure of a hopper car under the influence of temperature exposure during the thawing of pellets during the period of negative environmental temperatures – 10–15 °C was determined. For this purpose, we used the results of our previous studies on modeling the temperature regime of defrosting of pellets in hopper cars [43, 44]. The experimental studies were carried out at the transport and cargo complex of PRAT "Mariupol Metallurgical Plant named after Illich", which accepts and unloads pellets in hopper cars.

According to those studies, in the first stage of defrosting, in the time range from 0 to 2 hours, there is an intensive temperature rise in a garage section, to 110–120 °C. In the second stage, the heat carrier consumption gradually decreases. At the same time, the temperature in the section in the time range from 2 to 4 hours was maintained at the level of 100–120 °C. After the stage of active thawing, the supply of the heat carrier to the section was stopped.

When calculating the temperature effect on the load-bearing structure of a hopper car, the temperature of pellet thawing of 120 °C was taken into consideration. The calculation was performed according to the scheme shown in Fig. 7. However, the loads acting on the frame through the autocoupling were not taken into consideration. The maximum equivalent stresses occur in racks and are about 123 MPa, which are lower than the permissible values by two times. The results of our experimental studies and strength calculations of the load-bearing structure of a hopper car under the influence of temperature exposure of up to 120 °C showed that when thawing pellets, the safety and integrity of the load-bearing structure and equipment of hopper cars are provided.

5. 4. Modal analysis of the improved hopper car design

To determine the frequencies and shapes of the natural oscillations of the load-bearing structure of a hopper car with a composite cladding, a modal analysis was carried out. The calculation was based on the estimation scheme shown in Fig. 7, *a*.

Some natural shapes of oscillations of the load-bearing structure of a hopper car are shown in Fig. 11.

The results of calculating the oscillations of the load-bearing structure of a hopper car have established that the first natural frequency takes a value of 11.7 Hz, that is, not lower than the permissible one – 8 Hz. Therefore, the safety of the car is provided [45, 46].

In addition, within the framework of the study, the resistance to fatigue of the load-bearing structure of a hopper car was calculated.

The calculation of fatigue resistance was carried out taking into consideration the coefficient of reserve *n* according to the following formula from [45, 46]:

$$n=\frac{\sigma_{-1L}}{\sigma_{a,s}}\geq[n], \tag{7}$$

$\sigma_{a,s}$ is the calculated value of the dynamic stress amplitude of the conditional symmetric cycle, reduced to base N_0, equivalent in terms of the damaging effect of the amplitude value under a real mode of operational random stresses during the project lifetime, MPa;

$[n]$ is the permissible coefficient of fatigue resistance reserve.

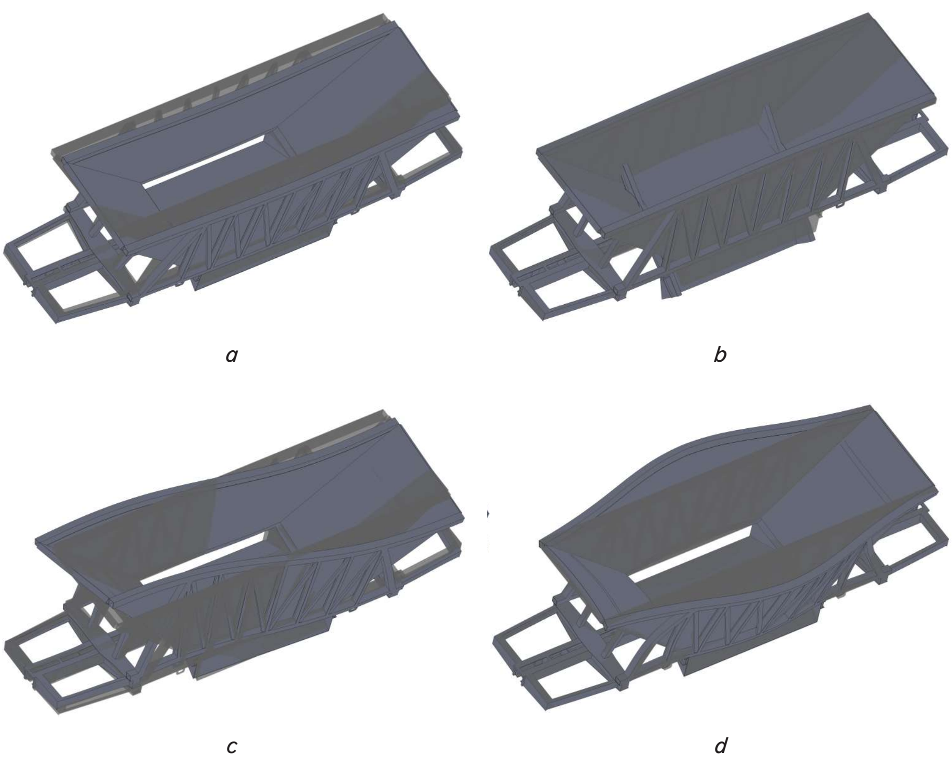

Fig. 11. Some shapes of oscillations of the load-bearing structure of a hopper car (deformation scale 20:1): *a* — mode 1; *b* — mode 2; *c* — mode 3; *d* — mode 4

The equivalent consolidated amplitude of dynamic stresses for strength calculation $\sigma_{a,s}$, in the case of a break function of the distribution of stress amplitudes, is determined as [47, 48]

$$\sigma_{a,s} = \sqrt[m]{\frac{N_c}{N_0} \sum_{i=1}^{k} P_{vi} f_v \sum_{i=1}^{k} \sigma_{ai}^m P_i}, \tag{8}$$

where N_c is the total number of cycles of dynamic stresses over the estimated service life; $p_{\sigma i}$ and p_{vi} are, respectively, the probability of stresses at level σ_i in a given interval of speeds and the proportion of time for the operation of a car at speed v_i; σ_{ai} is the level (charge) of stress amplitude, MPa; $k_{\sigma i}$ and k_{vi} is the number of digits of sampling, respectively, of the amplitude of stresses and the range of motion speeds.

The results of calculating the equivalent consolidated amplitude of dynamic stresses showed that at the probability of stresses at level σ_i, which is 0.95, the value $\sigma_{a,s}$=51.3 MPa. Hence, the coefficient of fatigue resistance is 4.5. At the same time, due to the lack of experimental data, the permissible value for the fatigue resistance reserve coefficient was taken equal to 2. 2 [48]. Consequently, condition (7) is met, and the fatigue strength of the load-bearing structure of a hopper car is provided.

6. Discussion of results of defining the peculiarities of temperature load on the load-bearing structure of a hopper car made from composite materials

To ensure the strength of the load-bearing structure of a hopper car for the transportation of pellets and sinter, improvement measures have been proposed. It is proposed to use, instead of a metal cladding, the cladding made of a composite (Fig. 2). In addition, this solution helps reduce a hopper car's tare by 5 % compared to the prototype.

The main indicators of the dynamics of the load-bearing structure of a hopper car have been determined (Fig. 4–6). The calculated dynamics indicators do not exceed the permissible values. At the same time, the ride of a hopper car is rated as "excellent". It is important to note that the current research was carried out subject to the condition of an empty car's movement over an irregularity between rail joints.

The strength of the load-bearing structure of a hopper car has been calculated, taking into consideration the effect of the temperature load from the transported cargo. The maximum equivalent stresses, according to the von Mises criterion, occur in the zone of interaction of the girder beam with the pivot beam and are about 290 MPa (Fig. 8). The stresses in the cladding of a hopper car, according to the criterion of maximum normal stresses, are about 200 MPa, which is 12 % lower than those in the typical design (Fig. 9).

Therefore, the use of composite cladding makes it possible to not only reduce the tare of the load-bearing structure of a car but also improve its strength characteristics due to the better heat resistance of the composite compared to steel.

The results of our calculation of the strength of the load-bearing structure of a hopper car when thawing pellets during the period of negative environmental temperatures have proven that the strength indicators are within the permissible limits.

The natural frequencies and shapes of oscillations of the load-bearing structure of a hopper car have been determined (Fig. 11). It was established that the first natural frequency does not exceed the permissible values. The coefficient of fatigue resistance of the load-bearing structure of a hopper car has been calculated. It was established that the fatigue strength of the load-bearing structure is provided.

The advantage of this study compared to [6–15] is that the model that we built regarding the strength of the load-bearing structure of a hopper car makes it possible to take into consideration the different materials in the components of its load-bearing structure. This makes it possible to improve the strength characteristics of a hopper car compared to the typical structure during operational load modes.

The results of the research make it possible to us to evaluate the effectiveness of the use of composite cladding in the supporting structure of a hopper car in terms of load under the most adverse operating modes.

The limitation of this study is the fact that when building a model of strength of the load-bearing structure of a hopper car, we did not take into consideration the welding seams between its components. In addition, the model does not take into consideration the friction forces between the body stops and the bogie stops.

The mathematical model of the dynamic load on the load-bearing structure of a hopper car (1) to (6) does not take into consideration the movements of hot sinter during oscillations.

A disadvantage of the study worth noting is the need to experimentally determine the dynamics and strength indicators for the load-bearing structure of a hopper car. This could be done by the similarity method involving a prototype of the hopper car, which is planned to be carried out at the following stages of our work. In addition, our studies could be advanced by determining the longitudinal load on the load-bearing structure of a hopper car.

The research reported here would contribute to ensuring the strength of the load-bearing structures of hopper cars, reducing the cost of maintenance, and increasing the efficiency of their operation.

7. Conclusions

1. Measures have been proposed to improve the load-bearing structure of a hopper car. To improve the strength indicators of the load-bearing structure of a hopper car, it is proposed to use a cladding made of a composite material that has heat-resistant properties. The strength limit of the material in the direction of fibers is 1,100–1,300 MPa, and in the transverse direction – 650 MPa. The use of cladding made of a composite material helps reduce the car's tare by 5 % compared to the prototype.

2. We have determined the dynamic load of the improved hopper car structure. The calculation results have shown that the determined dynamics indicators do not exceed the permissible values. The acceleration, which acts in the center of masses of the load-bearing structure, is about 0.4*g*. The acceleration of the load-bearing structure of a hopper car in the regions of resting on bogies is 0.53*g*, and the coefficient of vertical dynamics is 0.52. At the same time, the ride of a hopper car is rated as "excellent".

3. The main indicators of strength for the improved hopper car design were defined. The maximum equivalent stresses occur in the zone of interaction of the girder beam

with the pivot beam and are about 290 MPa. At the same time, the stresses in the cladding of a hopper car are about 200 MPa, which is 12 % lower than those in a typical structure. In other words, the strength of the load-bearing structure is ensured. The results of our experimental studies and calculations of the strength of the bearing structure of a hopper car under the influence of temperature exposure of up to 120 °C have shown that when thawing pellets, the safety and integrity of the load-bearing structure and equipment of hopper cars are provided. It should be noted that the equivalent stresses of the load-bearing structure of a hopper car are 123 MPa, and are within the permissible values.

4. Modal analysis was carried out; the coefficient of fatigue resistance of the load-bearing structure of a hopper car was determined. The calculation results established that the first natural frequency takes a value of 11.7 Hz, which is not lower than the permissible one – 8 Hz. Therefore, the safety of the car movement is ensured.

The coefficient of fatigue resistance of the load-bearing structure of a hopper car was 4.5, which is almost twice as high as the permissible one.

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