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IDENTIFYING PATTERNS IN LOADING A GONDOLA CAR BODY WITH REINFORCING BELTS IN THE STRUCTURE OF SIDE WALLS

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The object of this study is the processes of occurrence, perception, and redistribution of loads in the body of a gondola car with reinforcing belts in the structure of side walls.

In order to improve the strength of side walls of the gondola car body, it is proposed to strengthen them with additional belts. At the same time, it is reinforced with diagonal belts in three sections of the body on the side of the consoles, and in the middle section, 1/3 of the height from the lower strapping, with a horizontal belt. To determine the parameters for the execution of profiles in the reinforcing belts, the calculation of the gondola car body as a rod system was carried out. Based on the resulting values of bending moments, the moment of resistance of the cross-section of the profiles of the reinforcing belts was determined. The calculation of the strength of the body of the gondola car under the main modes of its loads in operation (I and III calculation modes) was carried out. It was found that the resulting stresses were 10.3 % lower than those occurring in a typical design of a gondola car body. The movement of the gondola car in the empty and loaded states was evaluated.

A feature of the reported research results is that the improvement of the strength of the side walls of the gondola car body is achieved by increasing the rigidity of its frame.

The field of practical use of the results is the engineering industry, in particular, railroad transport. The conditions for the practical application of results are the symmetrical distribution of reinforcing belts along the length of the gondola car body.

This study results may contribute to improving the durability of gondola car bodies in operation, and accordingly to reducing costs for unscheduled repairs. Also, the findings could prove useful for designing modern structures of railroad cars

Keywords: transport mechanics, gondola car improvement, gondola car frame, body load, body strength

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1. Introduction

Railroad transport has been a leading component of the economy of many European countries for a long time [1, 2]. It meets the needs of the national economy not only in internal but also in external transportation [3]. Currently, the fleet of freight cars, as one of the most important components of railroad transport, has a large number of car types depending on design features [4, 5]. However, gondola cars are one of the most common. For example, the share of this type of car on Ukrainian railroads is more than 50 % of the car fleet.

At present, gondola cars transport mostly bulk and loose cargoes. But, given appropriate modernization, it is possible to engage them in the transportation of other types of cargo, including those that need protection from atmospheric precipitation.

Analysis of the current state of existing fleet of gondola cars allows us to conclude that one of the most damaged elements of their load-bearing structure is the side walls, including the cladding. This situation is due to the significant dynamic load of their structures under operating conditions. The most common types of damage to the side walls are cracks in the structural components, deformations, rupture of the cladding, etc. The presence of such damage on the way forward poses a threat to the safety of the movement of the carriage as part of the train. This is also dangerous from the point of view of the environmental friendliness of freight transportation by rail. In this regard, the issue of improving the side walls of gondola car bodies in operation is urgent.

2. Literature review and problem statement

In work [6], the issue of improving the strength of the paneling of the gondola car body by using corrugations is considered. Due to the increase in the moment of resistance of the cladding in the transverse plane of symmetry, its strength is improved in the perception of operational loads. This solution is based on theoretical calculations on the strength of the supporting structure of the gondola car. However, this implementation contributes to the improvement of the strength of cladding, but not of the side wall in general.

Improving the strength of the side walls of the body is also possible through the use of materials with improved physical and mechanical properties.

Paper [7] investigates the strength of a composite panel with step-variable thickness under external loads. Zones of stress concentration in the panel were determined. The results were confirmed experimentally. However, the authors did not consider the possibility of using this panel as a side wall of a gondola car body.

It must be said that the use of composite panels as paneling of the gondola car walls would contribute to increasing their strength under operational loads. At the same time, it is possible to determine the stresses in the zones of interaction of these panels with the body struts using the method described in [8]. However, the use of such panels requires significant capital investment, which prevents their widespread use in railcar construction.

Work [9], which highlights the features of the design of the car body from extruded aluminum panels, has a similar drawback. At the same time, structural optimization was applied. The proposed technical solutions were confirmed by complex calculations on the strength of the car body. In addition, the introduction of composite materials can contribute to a significant reduction in the weight of the vehicle [10]. Under the condition of its movement in an empty state, this worsens the dynamics.

Work [11] proposed the introduction of steel grades 16G2AF and 18G2AFps for the manufacture of body wall cladding. To determine the optimal thickness of body components, appropriate calculations were carried out. At the next stage, the strength of the improved structure of the gondola car body was determined and the capability of the proposed solutions was proven. At the same time, this improvement does not contribute to the improvement of the frame strength of the gondola car body.

In work [12], the use of laminated composite panels is proposed to improve the strength of the side walls of the car body. The authors determined the optimal thickness of these panels under the condition of ensuring strength. However, this implementation helps increase the cost of manufacturing the car. This restrains the serial implementation of this solution into operation.

The expediency of the introduction of composite panels for the manufacture of wall cladding of the car body is determined in work [13]. This solution is proposed mostly from the standpoint of reducing corrosion damage to the body, as well as facilitating its unloading in winter conditions. It is noted that it is possible to implement this improvement not only at the stage of production, but also during the modernization of cars. At the same time, the use of such panels does not contribute to improving the strength of the car body frame.

In order to improve the strength of the side walls of the freight car, study [14] proposed their manufacture in the form of sandwich panels. Each panel is formed by two sheets between which a layer of energy-absorbing material is placed. Improving the strength of the side walls is achieved by reducing the dynamic loads acting on the body during operational modes. However, the use of such panels in practice complicates the process of maintenance and repair of cars. Also, this implementation helps increase the cost of manufacturing a car.

In work [15], the improvement of the strength of the side walls of the gondola car is implemented using a composite material. At the same time, a reduction in the weight of the body, an improvement in corrosion resistance, etc. is also achieved. The justification of this implementation is carried out on the example of the end wall of the body.

Similar studies are also reported in [16], in which, to improve the strength of the body, it is proposed to introduce polymer composite materials as its components. The value of this work is in the fact that the authors conducted experimental studies, the results of which proved the feasibility of such implementation.

The disadvantage of the studies cited in works [15, 16] is that this implementation does not contribute to improving the strength of the body frame, and also increases the cost of manufacturing the car.

In work [17], a new design of a gondola car with a carrying capacity of 80 t is proposed. The design feature of this gondola car is that it has a lower center of gravity compared to existing analogs. To improve the strength of the vertical pillars of the body, they have a variable height section with a maximum width at the base. This design is based on a set of theoretical calculations using modern methods involving modeling tools. At the same time, this design of the semi-trailer does not provide solutions aimed at improving the strength of the side walls of the body.

Our review of the literature [6–17] reveals that the issue of improvements to the body of a gondola car to ensure the strength of the side walls under operating load modes requires additional research.

3. The aim and objectives of the study

The purpose of our study is to identify the patterns of loading of the improved design of the body of a gondola car with reinforcing belts in the structure of side walls under the main operating modes of loads. This will contribute to improving the durability of gondola car bodies in operation and reducing costs for unscheduled repairs.

To achieve this goal, the following tasks are set:

– to determine the execution of profile for the reinforcing belts in the frame of a gondola car body and carry out its strength calculation;

– to determine basic indicators of the gondola car body dynamics, taking into account measures for its improvement.

4. The study materials and methods

The object of our research is the processes of occurrence, perception, and redistribution of loads in the body of a gondola car with reinforcing belts in the structure of side walls.

The main hypothesis of the study assumes that the strength of side walls could be improved by increasing the stiffness of the frame. To this end, it is proposed to strengthen it with additional belts (Fig. 1).

In this case, it is reinforced with diagonal belts in three sections of the body on the side of the consoles, and in the middle section, 1/3 of the height from the lower strapping, with a horizontal belt.

To justify the proposed solution, the load of the gondola car body was calculated. The gondola car model 12-295 was chosen as the prototype. In this gondola car model, the side wall is formed by vertical posts, upper and lower binding, and a smooth metal sheet of variable thickness.

The execution of profiles for reinforcing belts were determined by their moment of resistance. In this case, the moment of resistance *W* was calculated based on the known value of the bending moment *M* acting on the reinforcing belts, as well as the allowable stresses σ of their execution, i.e., *W*=*M*/σ [18]. To determine the bending moments that act on the reinforcing belts, the gondola car body was considered a rod system. The calculation was carried out in PC "Lira – CAD" (Ukraine) [19]. It is taken into account that the vertical load P_v acts on the body, as well as the pressure of the spacer of the bulk cargo P_{bc} (Fig. 2).

The vertical load P_v was defined as the sum of the vertical static load P_v^{st} and the vertical dynamic load P_v^d. In this case, the vertical dynamic load P_v^d was determined from formula (1) in accordance with DSTU 7598:2014. Freight cars. General requirements for calculations and design of new and modernized cars of 1520 mm gauge (non-self-propelled). Foreign analog of this standard: "EN 12663-2. Railroad applications – structural requirements for railroad vehicle bodies – Part 2: Freight cars":

$$P_v^d = P_v^{st}\cdot k_{dv}, \qquad (1)$$

where k_{dv} is the coefficient of vertical dynamics.

Fig. 1. Gondola car body with reinforcing belts on side walls

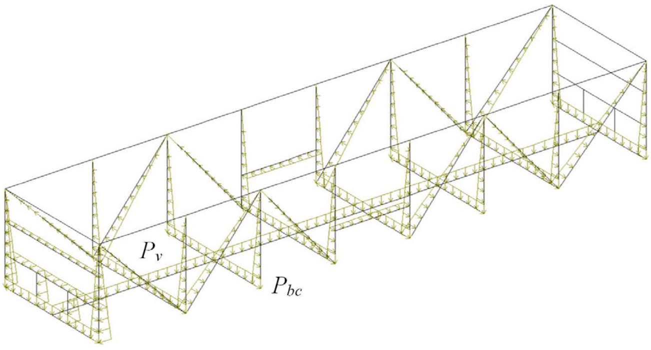


Fig. 2. Body estimation diagram

The coefficient of vertical dynamics was calculated according to the formula:

$$k_{dv} = \frac{\overline{k_{dv}}}{\beta}\sqrt{\frac{4}{\pi}\cdot\ln\cdot\frac{1}{1-\left(1-\exp\left(-\frac{\pi}{4}\cdot\frac{k_{dv}^2}{k_{dv}^2}\cdot\beta^2\right)\right)}}, \qquad (2)$$

$\overline{k_{dv}}$ – the average probable value of the coefficient of vertical dynamics; β is a distribution parameter.

Coulomb's formula with Synelnikov's correction was used to determine the pressure of the bulk cargo on side walls. In accordance with this formula, the pressure of bulk cargo can be determined as follows:

$$P = \gamma'\cdot h'\cdot\frac{\cos^2\left(\rho'+\alpha'\right)}{\left[1+\sqrt{\frac{\sin\rho'\cdot\sin\left(\rho'\pm\alpha'\right)}{\cos\alpha'}}\right]^2\cos\alpha'}\cdot g \pm F_{ad}, \qquad (3)$$

where γ′ is the volumetric mass of the cargo; *h*′ – height of the gondola car body; ρ′ – angle of internal friction; α′ – angle of inclination of the gondola car relative to the longitudinal axis; *g* – acceleration of free fall; F_{ad} – additional pressure due to the inertial component acting on the load under conditions of angular movement of the body relative to the longitudinal axis.

With:

$$F_{ad} = \frac{F}{L_b\cdot h_b}, \qquad (4)$$

where *F* is the inertial force acting on the load;

L_b is the length of the side wall of the gondola car body;

h_b – height of the side wall of the gondola car body.

The calculation was carried out on the example of hard coal. Fixing of the model was carried out by the hinges of the body [20, 21]. The results of the calculation made it possible to determine the moment of resistance of the cross-section of the profile of the reinforcing belts.

Taking into account the parameters of the selected profile of the side wall, a spatial model of the body of the gondola car was built and its calculation was carried out. The spatial model of the body of a gondola car includes elements that rigidly interact with each other. In this case, the model does not take into account welding seams. The main loading modes of the car body in operation are taken into account – I and III. The strength calculation was carried out using the finite element method. To this end, the SolidWorks Simulation (France) software package was used [22, 23]. This software package was applied because it is widely used in the calculation of vehicle strength.

The resting of the body on bogies was simulated by placing rigid connections on its heels, i.e., the frictional forces between the body heels and the bogie heels were not taken into account.

In connection with the fact that the use of reinforcing belts helps increase the tare of the gondola car compared to the prototype, the main indicators of the dynamics of the gondola car during its movement along the joint unevenness in the empty and loaded states were determined. In this case, the mathematical model given in [24] was used. The parameters of the disturbing action are taken to be identical to those specified in this work, and the solution of the system of differential equations of motion was carried out in Mathcad (USA) [25, 26].

5. Results of identifying patterns of loading of the body of a gondola car with reinforcing belts in the structure of side walls

5. 1. Determining the execution of profiles for reinforcing belts of the gondola car body frame and its strength calculation

Based on the calculations performed according to the scheme shown in Fig. 2, a diagram of bending moments acting on the body of a gondola car was built (Fig. 3). These moments are given in the Z plane to reflect exactly those moments acting on the walls.

Therefore, the maximum value of the bending moment acting on the reinforcing belts is 62.16 kN m and is concentrated in the zone of interaction of the pivot strut with the reinforcing belt. Taking into account the fact that the body is made of 09G2S steel, the moment of resistance of the cross-section of the reinforcing belt is 296 cm^3. Based on this moment of resistance, the profile of the reinforcing belts was selected – a U-shaped profile with a wall thickness of 3.5 mm (Fig. 4). This choice is justified by the manufacturability of mounting this profile in the frame of the gondola car body.

Taking into account the selected execution of profile for reinforcing belt, a spatial model of the gondola car body was built, and its strength was calculated.

The finite element model was constructed using tetrahedra [27, 28]. The choice of finite element type is explained by the fact that the mesh was built on a solid body. The optimal number of finite elements was calculated by the graph-analytic method (Fig. 5).

When drawing up the calculation diagram of the body of a gondola car, it is taken into account that the vertical load P_v acts on it, taking into account the full carrying capacity of the car (Fig. 6, *a*).

The pressure of the spacer of the bulk cargo P_{bc} on the side walls of the gondola car body was taken as a distributed load according to the law of a triangle with a maximum at the base (Fig. 6, *b*).

A longitudinal load was applied to the stops of the auto coupling in accordance with the calculation mode – I or III.

Strength was calculated according to the Mises criterion [29–31]. The choice of this calculation criterion is due to the fact that the body material is steel, which is an isotropic material. This criterion is used for the calculation of structures made of such materials. In this case, the calculation was carried out in quasi-statics. As an example, Fig. 7–9 show the results of calculation of the body of the gondola car for strength at "impact". The maximum stresses in the side wall are about 128 MPa (Fig. 7). They are observed in the zones of interaction of vertical racks with lower binding (Fig. 8). The resulting stresses are 10.3 % lower than those occurring in a typical gondola car body design and 60 % lower than allowable. Permissible stresses for this mode in accordance with DSTU 7598:2014. Freight cars. General requirements for calculations and design of new and modernized cars of 1520 mm gauge (non-self-propelled) are set at 0.9 σ_y, where $\underline{\sigma_y}$ is the yield strength of the material (345 MPa).

The distribution of stresses in the side wall behind the lower strapping is shown in Fig. 9. Stress readings along the length of the lower strapping were taken using the probing option, which is present in the calculation software package. The maximum stresses occur in the zones of interaction of the middle struts with the lower binding. In the zones of interaction of the second racks from the cantilever side with the lower strapping, these stresses have slightly lower values and are about 120 MPa. In the zones of interaction of the pivot struts with the lower strapping, these stresses were about 100 MPa.

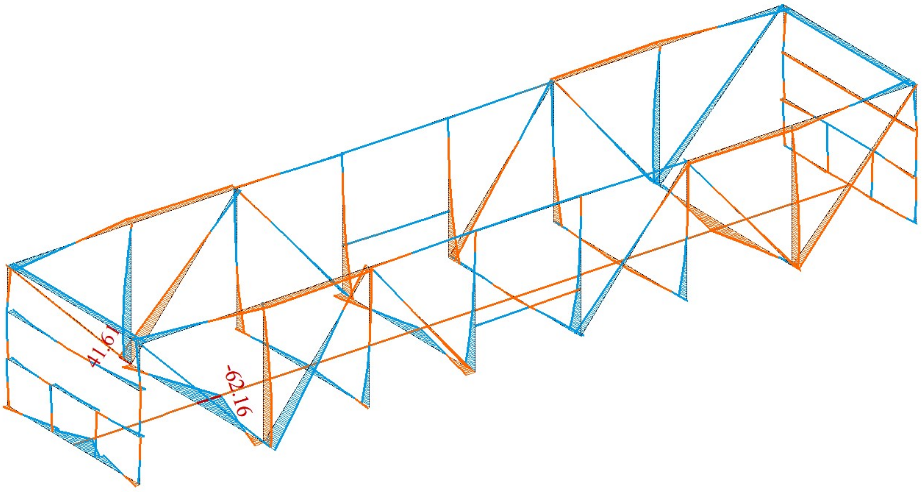


Fig. 3. Diagram of bending moments acting on the gondola car body (kN·m)

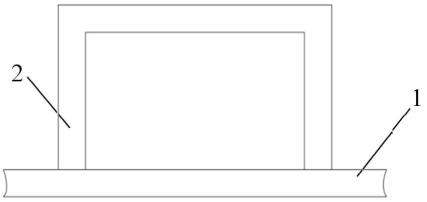


Fig. 4. The execution of profile for reinforcing belts: 1 – body cladding; 2 – reinforcing belt

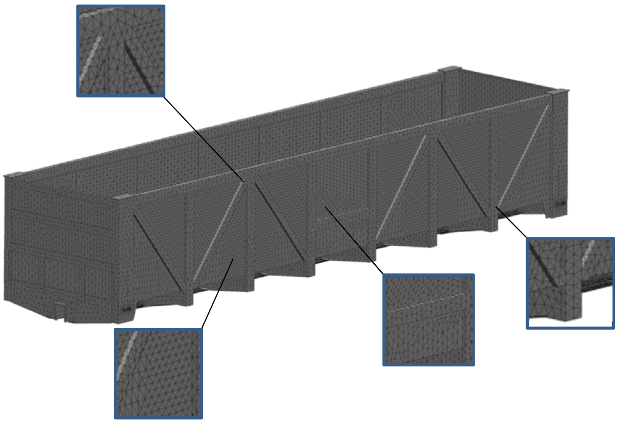
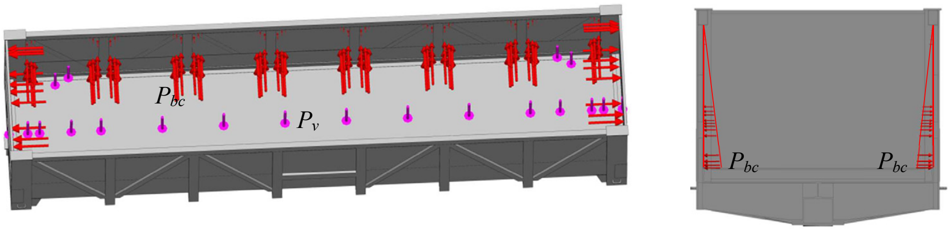


Fig. 5. Finite element model of a gondola car body



a *b*

Fig. 6. Calculation diagram of the gondola car body: *a* — top view; *b* — action of the strut pressure on side walls

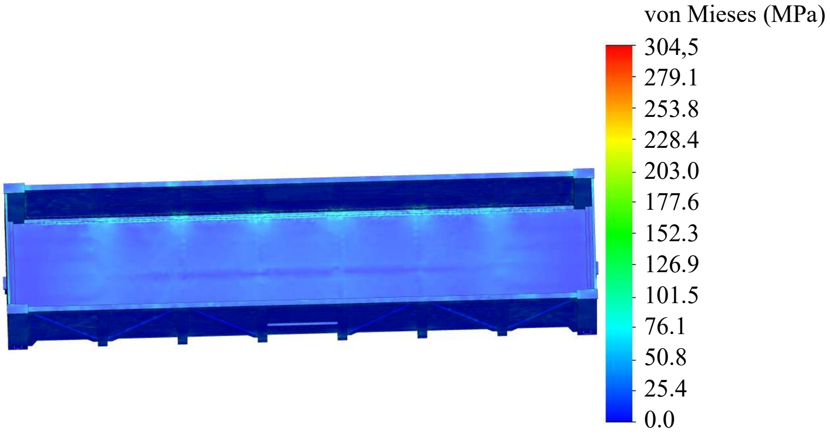


Fig. 7. The stressed state of the gondola car body

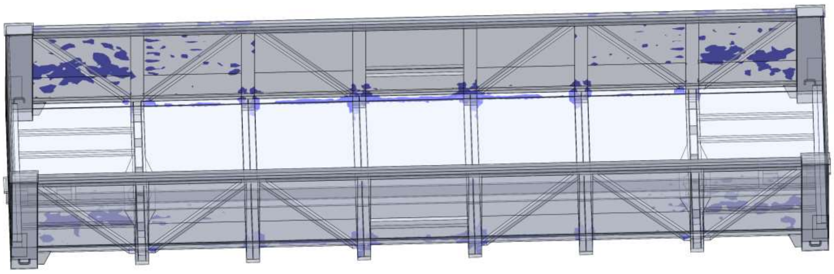


Fig. 8. The most heavily loaded areas of the gondola car body

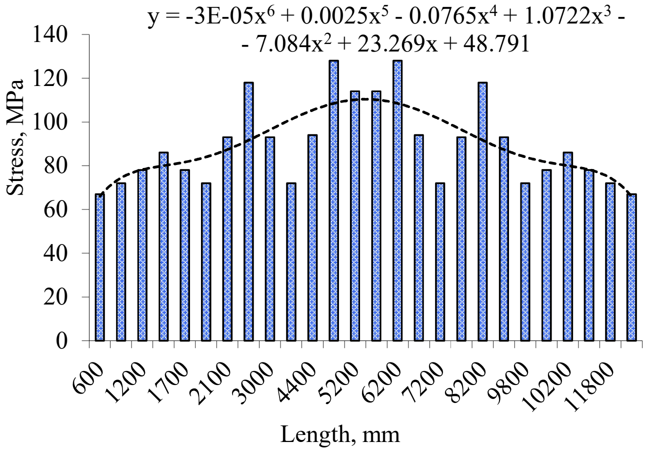


Fig. 9. Distribution of stresses in the side wall behind the lower strapping

The maximum movements in the side wall occur in its upper binding and amount to 5.17 mm (Fig. 10, 11). This distribution of displacement fields can be explained by the fact that the end parts of the side wall interact with the corner posts, and its lower part with the frame beams. In this case, the upper binding is free. Therefore, maximum movements occur here.

The calculation of the strength of the body of the gondola car was also implemented with other calculation schemes of the load. The main indicators of the strength of the side wall in the considered schemes are summarized in Table 1.

Table 1

Main indicators of the strength of the side wall

Strength index	Load mode				
	Mode I			Mode III	
	im-pact	com-pression	jerk – elongation	impact-com-pression	jerk – elongation
Stress, MPa	128	117	117.4	116.5	116.8
Displacement in nodes, mm	5.17	5.1	5.1	4.98	4.98

The performed calculation allows us to conclude that the introduction of reinforcing belts into the structure of the body of a gondola car helps reduce the stresses that occur in its side wall by 8–10.3 % compared to a typical structure.

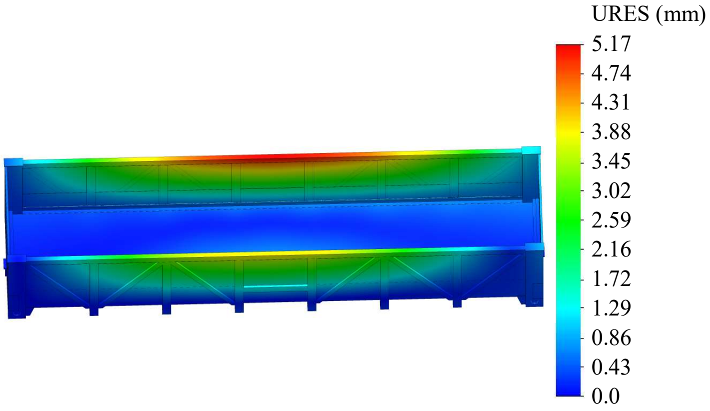


Fig. 10. Movement in gondola car body nodes

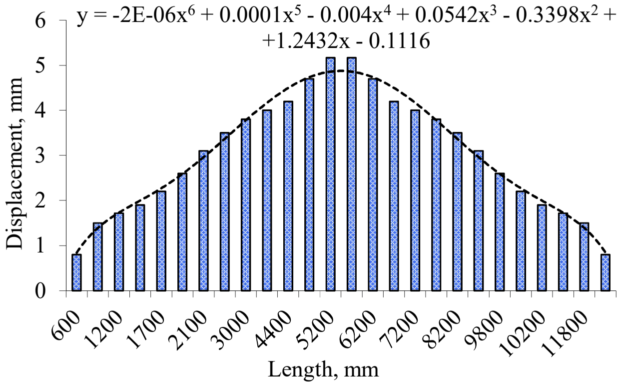


Fig. 11. Distribution of movements in the side wall by the upper binding

5. 2. Determining main indicators of the gondola car body dynamics, taking into account measures for its improvement

To determine the movement indicators of the improved design of the gondola car, appropriate calculations were carried out during its movement in empty and loaded states. At the beginning, the calculation was carried out under the condition that the gondola car was moving in an empty state. The calculation results are shown in Fig. 12–15.

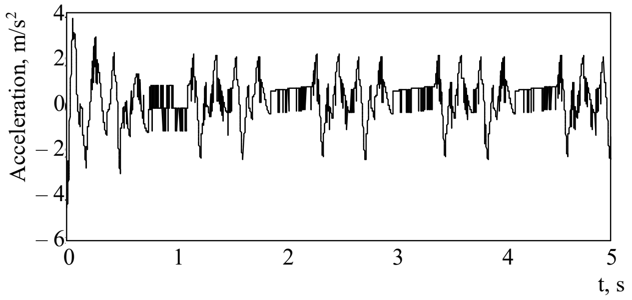


Fig. 12. Acceleration of the gondola car body in the center of mass

So, under the conditions of the movement of the gondola car in an empty state, the maximum acceleration in its center of mass was 4.5 m/s^2. This acceleration occurs at the moment when the car passes over a joint bump. Further, its value decreases and is about 2.6 m/s^2 (Fig. 12).

Acceleration in the areas where the body rests on bogies when the car passes over the bump was about 5.8 m/s^2. Over time, this acceleration value decreases and is equal to about 5 m/s^2 (Fig. 13).

The maximum force in the spring suspension of the bogie when passing the joint unevenness is equal to 43.5 kN. During the subsequent oscillating process, this force is about 40 kN (Fig. 14).

The coefficient of vertical dynamics of the gondola car at the moment of passing the butt bump was about 0.6. Further, the value of this coefficient decreases slightly and is about 0.5 (Fig. 15).

Under the conditions of movement of the gondola car in a loaded state, its acceleration at the center of mass was 1.7 m/s^2. The acceleration of the body in the zones of support on the bogies is about 2.3 m/s^2. The maximum force in the spring suspension is 81 kN. The coefficient of vertical dynamics of the gondola car was 0.2.

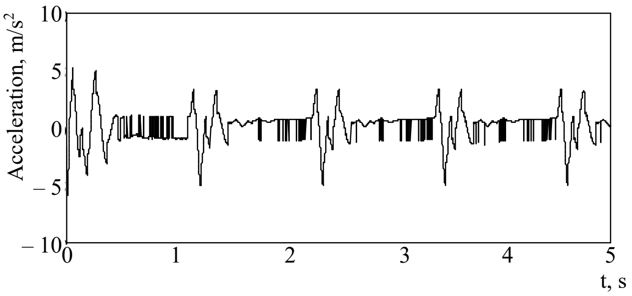


Fig. 13. Acceleration of the gondola car body in areas that rest on bogies

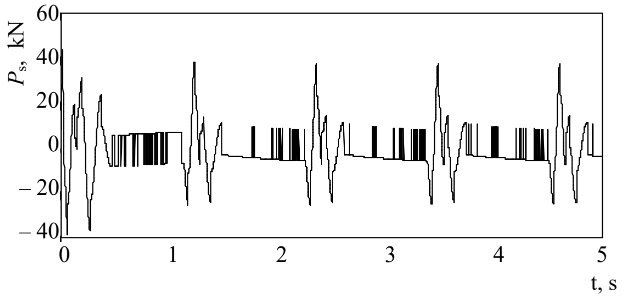


Fig. 14. Values of the forces arising in the spring suspension of bogies

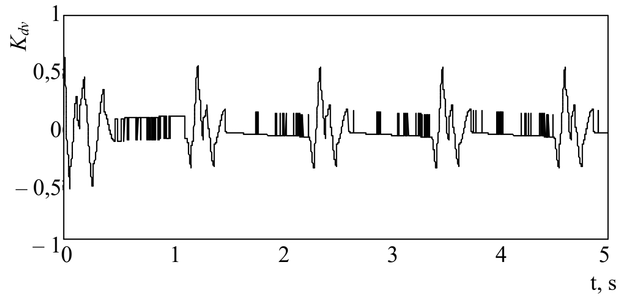


Fig. 15. Vertical dynamics coefficient

The movement of the gondola car was evaluated based on the accelerations occurring in its center of mass and the coefficient of vertical dynamics. In this case, the movement of the gondola car is in accordance with DSTU 7598:2014. Freight cars. The general requirements for calculations and design of new and modernized cars of 1520 mm gauge (non-self-propelled), when moving in an empty state, can be rated as “good”. Given the loaded state of the gondola car, its movement is rated as “excellent”.

6. Discussion of results of identifying regularities in loading the gondola car body

In order to improve the strength of the side walls of the gondola car body, it is proposed to strengthen them with additional belts (Fig. 1). Namely, the use of diagonal belts is expected for the three sections of the body from the side of the consoles. In the middle section of the body, at a height of 1/3 from the lower strapping, a horizontal belt is supposed to be installed.

The determination of the parameters of the performance profiles of the reinforcing belts was carried out by the moments of resistance of their cross-sections. To this end, a plot of bending moments arising in the body of a gondola car was constructed (Fig. 3). Given the known values of the bending moments, as well as the material of the body, the moments of resistance of the components of its structure are determined. This made it possible to choose the profile of the reinforcing belts – a U-shaped profile (Fig. 4).

The validity of our results is confirmed by calculations on the strength of the gondola car body under the main modes of its loads in operation. It was established that the maximum stresses in the body of a gondola car take place under calculation mode I (Fig. 7). However, they do not exceed the permissible values. In the side wall, the maximum stresses are concentrated in the zones of interaction of the middle struts with the lower strapping (Fig. 9). The maximum movements in the side wall take place in the upper binding (Fig. 10) and amount to 5.17 mm (Fig. 11).

The calculation was also carried out for other body load schemes (Table 1). It is established that its strength is ensured. In this case, stresses in the most loaded areas of the body frame are 10–17 % lower than those in a typical design. This is explained by the fact that the use of reinforcing belts helps increase the rigidity of the side walls, and, accordingly, reduce the stresses in them.

To evaluate the movement of the gondola car, the main indicators of its dynamics were determined for the empty state (Fig. 12–15) and the loaded state. The results of the calculation established that the movement of the gondola car in the empty state is evaluated as “good”, and in the loaded state – “excellent”. This can be explained by the fact that the use of reinforcing belts contributes to the increase of the car’s tare, therefore, when it moves in different states, a different evaluation of the course takes place.

It should be noted that this study has a number of advantages in comparison with known ones. For example, in comparison with work [6], the proposed solution helps improve the strength of the side wall in general, and not only the cladding. In contrast to the studies reported in [7–10], this improvement does not require significant capital investments, as it does not require the introduction of high-value materials into the body structure. Our results have the same advantage in comparison with works [12, 13, 15, 16]. In contrast to the results from study [11], the proposed improvement contributes to the improvement of the frame strength of the gondola car body, and not only its cladding. Compared to the solution to improve the body, highlighted in work [14], this implementation will not contribute to the complication of maintenance and repair of the car. In contrast to work [17], the improvement proposed in the framework of the study is aimed at improving the strength of the side walls as a rather vulnerable structural element in operation.

As a limitation of our research, it can be noted that when calculating the strength of the gondola car body, the frictional forces that arise between the load and its inner surface are not taken into account. Also, as a limitation, one should note the absence of frictional forces between the heels of the body and the heels of the bogies.

The shortcoming of this study is that when determining the main indicators of the dynamics of the gondola car, the leaning of the body on the bogies of the 18-100 model is taken into account. There are more promising bogie designs in use. However, this shortcoming can be justified by the fact that this type of bogie is one of the most common in operation.

The further development of this research is the determination of the strength of the load-bearing structure of the gondola car under the over-normalized modes of its loads, including during transportation on railroad ferries.

The results of this research will contribute to improving the durability of gondola car bodies in operation, and accordingly to reducing costs for unscheduled repairs. In addition, our results will be useful developments in the design of modern structures of railroad cars.

7. Conclusions

1. The execution of profiles for reinforcing belts of the frame of the gondola car body was determined and its strength was calculated. The results of calculations of the body of a gondola car as a rod system showed that the maximum bending moment acting in its components is equal to 62.16 kN·m. It was established that, subject to compliance with the strength of the reinforcing belts, their moment of resistance is 296 cm^3. Taking this into account, a U-shaped element with a wall thickness of 3.5 mm was chosen as the profile for the reinforcing belts.

The results of the calculation of the improved body design showed that its strength under the main load modes is ensured. In this case, the maximum stresses occur under calculation mode I. They are concentrated in the zones of interaction of vertical struts with the lower binding and amount to about 128 MPa. It should be noted that the obtained stresses are 10.3 % lower than those occurring in a typical structure of a gondola car body.

The maximum movements in the side wall occur in its upper binding and amount to 5.17 mm.

2. The main indicators of the dynamics of the gondola car body were determined, taking into account the measures for its improvement. The calculation was carried out under the conditions of movement of the gondola car in empty and loaded states. When the gondola car was moving in an empty state, the maximum acceleration in its center of mass was 4.5 m/s^2. Acceleration in the areas where the body rests on the bogies when it passes over a bump is about 5.8 m/s^2. The maximum force in the spring suspension of the bogie is 43.5 kN. The coefficient of vertical dynamics of the gondola car was about 0.6.

Under the conditions of movement of the gondola car in a loaded state, its acceleration at the center of mass was 1.7 m/s^2. The acceleration of the body in the zones of support on the bogies is about 2.3 m/s^2. The maximum force in the spring suspension is 81 kN. The coefficient of vertical dynamics of the gondola car was 0.2.

Therefore, the movement of the gondola car when moving in an empty state can be rated as “good”. Under the condition of the loaded state, the movement of the gondola car is rated as “excellent”.

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 and the results reported in this paper.

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Data availability

All data are available 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.

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