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DETERMINING PATTERNS OF THE VERTICAL LOAD ON A COVERED WAGON ROOF WITH A FRAME IN THE FORM OF A TRIANGULAR ARCH

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The object of this paper is the processes of perception and redistribution of loads in the roof of a railroad covered wagon with a frame in the form of a triangular arch.

To reduce the tare of the covered wagon, it is proposed to improve the structure of its roof. A feature of this improvement is that the roof frame is made in the form of a triangular arch with a reinforcing belt. This contributes to the reduction of the total mass of the roof compared to a typical structure. The selection of execution profiles of the beams forming the arch is carried out according to the maximum values of the moments that act in their cross-section. Taking into account the chosen profile of the arches, the calculation of the strength of the roof when it receives vertical loads was carried out. It was established that the strength of the roof under the considered load schemes is within the permissible stress values. Since the improvement of the roof structure contributes to the reduction of its weight by 1.8 % compared to the prototype, the movement of the covered wagon was evaluated under conditions of moving while empty. To this end, a mathematical modeling of the load of the covered wagon in the vertical plane during its movement along the joint unevenness was carried out. On the basis of the performed calculation, it was established that the movement of the wagon is assessed as "good".

Special feature of the results is that the reduction of the tare of the supporting structure of the wagon was achieved by improving its roof, as the least loaded unit.

The field of practical application of the results is railroad transport, including other areas of mechanical engineering. The conditions for the practical use of the results are a symmetrical roof load scheme in operation.

The results of this research could contribute to advancements related to the design of modern structures of freight cars with improved technical and economic indicators

Keywords: railroad transport, covered wagon, wagon roof, roof load, roof strength

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1. Introduction

One of the main factors in the development of the economy of European countries is the coordinated operation of railroad transport as the most used mode of transport at present [1, 2]. This is due not only to lower tariffs for the transportation process but also to the reliability of transportation. In order to maintain the leading position of railroad transport in the market of transport services, it is important to put into operation modern designs of vehicles with improved technical characteristics [3].

To provide a smooth transportation process, the fleet of freight wagons includes a large number of types of wagons for various types of cargo, including those that require protection from atmospheric influences. These are covered wagons that are equipped with a roof with loading hatches. This feature allows them to transport not only containers but also bulk cargo, for example, grain.

Increasing the efficiency of operation of covered wagons is possible through the reduction of their tare. One of the options for achieving this is the improvement of the roof as the least loaded node of the load-bearing structure in operation. This improvement may involve changing the geometry, profiles of the frame, using new materials, etc. The result of such an improvement could make it possible to increase the carrying capacity of the covered wagon by the amount of the received mass reserve of the supporting structure. This, in turn, makes it possible to modernize the existing fleet of covered wagons by reducing their tare without significant capital investment. Therefore, research aimed at improving the roof of a covered wagon is relevant.

2. Literature review and problem statement

In order to determine the general state of the problem of improving the structures of railroad wagons, an analysis of literary sources on this topic was carried out. So, for example, in work [4], in order to adapt gondola wagons to the transportation of goods that require protection from atmospheric precipitation, it is proposed to equip them with a removable roof. Such a roof has a frame made of rectangular pipes and is attached to the upper strapping of the wagon with a bolted connection. The justification for the use of such a roof is carried out by a set of theoretical calculations. As a disadvantage of the study, one should note that this roof does not have loading hatches, which reduces its demand in operation.

Work [5] reports the results from determining the stress state of the roof of a refrigerator wagon. The authors also determined the stability of the roof and performed vibration analysis. The shortcomings of this roof structure were identified, and its additional improvement was proposed. The feasibility of this improvement is confirmed by the results of the calculations. At the same time, the structure of such a roof is designed for a refrigerator wagon and its operation on a covered wagon is inappropriate.

Features of the calculation of the strength of the roof of a railroad wagon are given in [6]. The calculation was performed for the case of a piece of concrete weighing 100 kg falling onto the roof. To that end, the authors applied finite element analysis. The calculation was implemented on the condition that the roof is made of aluminum, as well as composite. However, the authors did not pay attention to the question of determining the dynamics of a wagon equipped with such a roof.

The results of determining the local load zones of the roof of a thermos wagon are reported in [7]. In this case, the authors performed theoretical calculations of the strength of the roof under the action of vertical loads. The results were compared with field studies of the technical condition of the roofs of the wagons of this type. Along with this, solutions aimed at improving the roof structure are not proposed in the work.

The main achievements related to the issues of the introduction of composite materials in the construction of railroad wagons are given in work [8]. The prospects for the use of fiber-reinforced composite materials in wagon construction are indicated, and possible options for the implementation of such implementation are given. The possibility of using these materials for the manufacture of roofs of railroad wagons has been agreed. However, the authors do not provide examples of the introduction of such materials into the construction of wagons, which are confirmed by relevant calculations.

Work [9] proposed measures to improve the design of the BCNHL covered wagon. This improvement is aimed at increasing the efficiency of loading and unloading operations by introducing improved doors on the wagon. However, the authors of the work did not pay attention to the issue of improving the roof of the wagon. This is explained by the fact that the work is aimed at improving the design of the wagon used on the Indian Railroads. At the same time, the authors noted that the issue considered in the paper is of primary importance for the operating conditions.

In paper [10], the authors proposed a new design of a removable roof of a railroad wagon. The shortcomings of the existing roofs are given, and the design of a new structure is substantiated. The proposed roof is made in one piece, it has a frame containing an interconnected lower frame, transverse beams with a sheathing fixed on top, and nodes for attaching the roof to the upper bodywork of the freight wagon. The main drawback of the roof is the lack of loading hatches in the structure, which limits the operational properties of this roof. In particular, we are talking about the process of unloading bulk cargo from the car.

In order to reduce the tare of a covered wagon, it is also possible to introduce the latest materials into its construction. So, for example, in work [11], the characteristics of a composite panel, which has a stepped variable thickness, under the action of stresses and deformations are studied. The use of this panel is also possible in the constructions of railroad wagons. The authors conducted complex studies that included theoretical and experimental tests. The difference between the test results was about 7 %. At the same time, the authors did not carry out calculations of this panel under the condition of its use in the body of a covered wagon. Work [12] has the same drawback, where the effect of deflection in a composite material is determined in the case of a local violation of its integrity.

The feasibility of introducing magnesium alloys in the construction of vehicles is investigated in paper [13]. Extruded structural elements of the wagon body were designed using the optimization theory. The conducted set of theoretical studies proved the expediency of using these materials in the structure of the vehicle body. However, the authors did not conduct research on the use of this material in the construction of a covered wagon with a gauge of 1520 mm.

The rationale for the introduction of polymer composite materials in wagon construction is given in [14]. These materials are proposed to be used in the manufacture of the floor of the wagon. The results of experimental studies on the method of pressing the composite in a mold are highlighted. At the same time, the authors did not consider the possibility of using this material in the manufacture of load-bearing elements of bodies.

Features of the use of environmentally friendly composites for the manufacture of vehicles are highlighted in work [15]. The results of calculations on the strength of the vehicle structure from this material are given. It was established that the use of composites that have a natural basis in comparison with classical ones is a more rational solution from the economic and technical point of view. However, the study was conducted on the example of an automobile. The study of the feasibility of using such composites in the design of railroad wagons was not conducted by the authors.

Our review of the literature [4–15] proves that until now the main attention to the improvement of the component load-bearing structures of wagons, including roofs, has been mostly focused on the introduction of new profiles as components of the frame, as well as the use of new materials for its implementation. Significant attention was not paid to the possibility of changing the geometry of the roof itself. Therefore, the issues of improving the structure of the roof of the covered wagon require further research.

3. The aim and objectives of the study

The purpose of our study is to determine the characteristics of the vertical load of the roof of a covered wagon with a frame in the form of a triangular arch. This could make it possible to improve the technical and economic indicators of the covered wagon, and, accordingly, to increase the efficiency of its operation.

To achieve the goal, the following tasks were set:

– to determine the profile of the roof arches, as well as investigate its load in the vertical plane;

– to assess the movement of a covered wagon with a roof of the proposed design.

4. The study materials and methods

The object of our research is the processes of perception and redistribution of loads in the roof of a covered wagon with a frame in the form of a triangular arch.

The main hypothesis of this study assumes that the use of a roof with a frame in the form of a triangular arch could help reduce the total weight of the covered wagon.

A typical roof of a wagon consists of the lower frame 1 (Fig. 1), transverse beams 2 with a sheathing 3 fixed on top, arched beams 4 [4]. The roof covering is made of sheet steel.

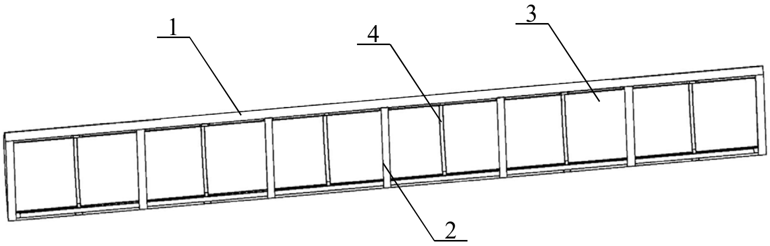


Fig. 1. Wagon roof

The roof is attached to the side and end walls of the covered wagon with rivets with a diameter of 10 mm [16]. The metal frame is lined with 1.5 mm thick sheets. Transoms are provided in the end parts of the roof, which prevent precipitation from entering the body. Transoms are made of metal sheets, 2 mm thick, and can be formed by punching to increase rigidity.

Arched beams are made of bent channels. The side bindings of the roof are formed by two corners. Sheets of outer cladding are welded to the arches and to the binding. Between themselves, the sheets of the roof are overlapped and, for greater rigidity, are made with transversely placed corrugations, which have a height of 22 mm.

On the inside, the roof is lined with moisture-resistant plywood in two layers.

It is proposed to reduce the mass of the roof by changing its geometry, namely by making a frame in the form of a triangular arch (Fig. 2) [17].

The roof was designed by the method of superimposing the contour on a typical roof structure (Fig. 3). In this case, the outline of a typical roof is marked in red, and the projected one is marked in black.

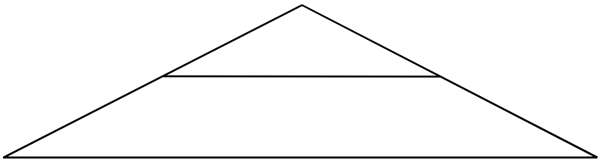


Fig. 2. Schematic image of the roof cross section (end view)

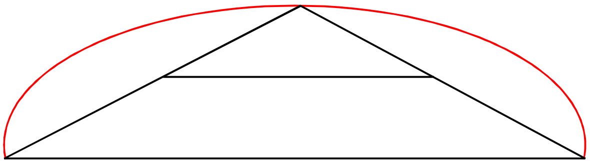


Fig. 3. Scheme of overlaying the contour of the designed roof on a typical cross section

The arch execution profile was determined by the moment of their resistance [18, 19]:

$$W=M/[\sigma],$$

where M is the bending moment acting in the cross-section of the beam; $[\sigma]$ – allowable stresses of the material of the beam (steel 09G2S).

To determine the bending moment M, an external load curve was constructed. In this case, the roof frame is considered a rod system with five hinges (Fig. 4) [17]. It was assumed that hinges A, C, E are recessed, and B, D are attached. Given this assumption, bending moments do not occur in recessed hinges.

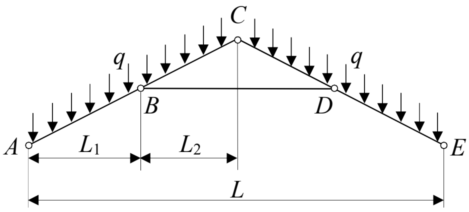


Fig. 4. Design diagram of the roof

The calculation was carried out according to the III calculation mode in accordance with the regulatory document [20]. The international analog of this standard is [21]. This mode was taken into account because it is one of the main ones from the point of view of force impact on the roof.

In accordance with this regime, the following combination of loads acting on the roof was taken into account:

– the power of the roof's natural weight;

– vertical dynamic force, which is calculated as the product of the force of the roof's natural weight and the coefficient of vertical dynamics.

The strength of the roof's natural weight is assumed to be equal to that of a typical structure.

The following formula from [20] was used to determine the vertical dynamic load acting on the roof:

$$P_v^d = P_v^{st} \cdot \frac{\overline{k_{dv}}}{\beta} \sqrt{\frac{4}{\pi} \cdot \ln \cdot \frac{1}{1-\left(1-\exp\left(-\frac{\pi}{4} \cdot \frac{k_{dv}^2}{\overline{k}_{dv}^2} \cdot \beta^2\right)\right)}}, \tag{1}$$

where P_v^{st} is the vertical static load; k_{dv} – coefficient of vertical dynamics; $\overline{k_{dv}}$ – the average probable value of the coefficient of vertical dynamics; β is a distribution parameter.

Our results were taken into account when constructing the diagram of bending moments (Fig. 5).

Analyzing this diagram, we can conclude that the moment has the maximum value in the area where the hinge B is located. Its numerical value was determined from the following formula [17]:

$$M_B = \frac{q \cdot \left(L_1^3 + L_2^3\right)}{4L}, \qquad (2)$$

where q is a uniformly distributed load acting on the roof; L_1 is the horizontal distance from hinge A to hinge B (Fig. 4); L_2 – horizontal distance from hinge B to hinge C; L is the horizontal distance from hinge A to hinge E.

Taking into account the determined bending moment, the profile of the roof arches was selected. Using this profile, a spatial model of the roof of the covered wagon was built (Fig. 6, 7). In this case, the SolidWorks (France) software package was used. When constructing the model, welding seams between structural elements of the roof were not taken into account, that is, the structure was considered monolithic.

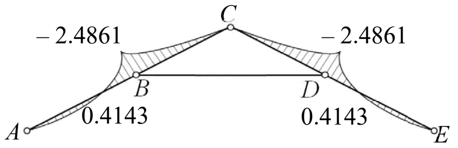
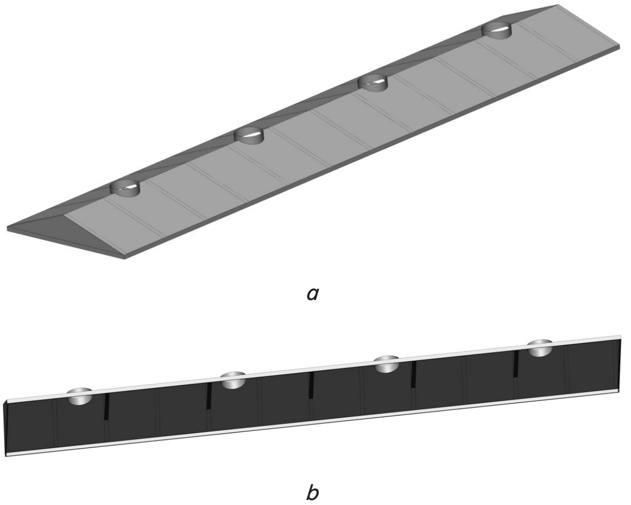


Fig. 5. Diagram of bending moments (kN·m)



a

b

Fig. 6. Spatial model of the roof: *a* — side view; *b* — bottom view

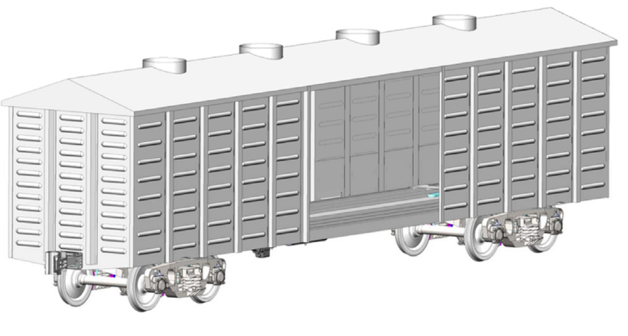


Fig. 7. A covered wagon with an improved roof structure

We determined the main indicators of the strength of the roof using the finite element method, which was implemented in SolidWorks Simulation (France) [22, 23]. The finite element model of the roof was formed by tetrahedra [24, 25]. This type of element was chosen due to the fact that the mesh was formed on a solid body. When it was built, the option of automatic sealing was used in places of roundings and transitions in the structure. The number of grid elements was determined by the graph-analytical method. The essence of this method is to construct the dependence of maximum stresses on the number of finite elements. When this dependence begins to be described by a horizontal line, this is the optimum number of finite elements. Based on the calculations, the number of nodes in the model was 276,749, and the number of elements was 830,301. The strength calculation was carried out according to the Mises criterion [26, 27] since the roof is made of steel with isotropic properties.

The frequencies of oscillations were determined for the proposed roof structure.

Due to the fact that this roof design is less in weight compared to the typical design, it contributes to the reduction of the overall tare of the covered wagon. Such a situation affects the change in its dynamics, in particular when moving while empty. In the loaded state, these indicators will be compensated by the possibility of increasing the carrying capacity of the wagon. Therefore, as part of the research, mathematical modeling of the vertical dynamics of a covered wagon with an improved roof structure was carried out when moving while empty. The solution to the equations of motion of the covered wagon was found by using the Runge-Kutta method in Mathcad (USA) [28, 29]. When performing the calculations, it was assumed that the track has elastic-viscous properties. It was also taken into account that the geometric parameters of the wagon have nominal dimensions, that is, the wear of its components was not taken into account.

5. Results of determining the vertical load of the roof of a covered wagon with a frame in the form of a triangular arch

5. 1. Determining the profile of the roof arches, as well as the study of its load in the vertical plane

In accordance with the constructed diagram shown in Fig. 5, the maximum value of the bending moment was about M=2.5 kN·m. Taking into account the fact that the allowable stresses for steel grade 09G2S under the III design regime are 220 MPa, then W=11.3 cm^3. On the basis of our calculations, channel No. 6.5 (Fig. 8) and W=15.0 cm^3 were chosen as the profile of the arches. This profile was selected for technological reasons, namely, the convenience of mounting the cladding sheets to the frame.

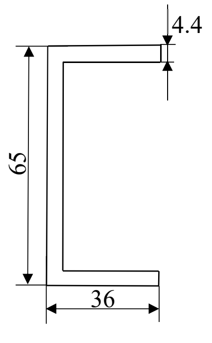


Fig. 8. Geometric dimensions of the channel

The mass of the proposed roof design is 1.8 % lower than that of a typical structure.

At the next stage of the calculation, the main indicators of the strength of the roof when vertical loads are perceived were determined. The calculation scheme of the roof is shown in Fig. 9. This scheme takes into account the effect on the entire roof area of the uniformly distributed load P_v, which includes the force of the weight of the roof, as well as the dynamic load.

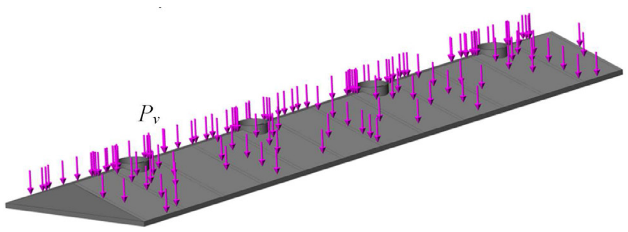


Fig. 9. Design diagram of the roof

Fixation of the roof was modeled by placing rigid connections in the areas of its abutment on the body. Frictional forces between the roof and the body were not taken into account. The calculation results are shown in Fig. 10, 11.

The maximum stresses in the roof were recorded in the loading hatch areas and amounted to 190.5 MPa (Fig. 10). These stresses do not exceed the allowable ones, which are 220 MPa in accordance with the III calculation regime.

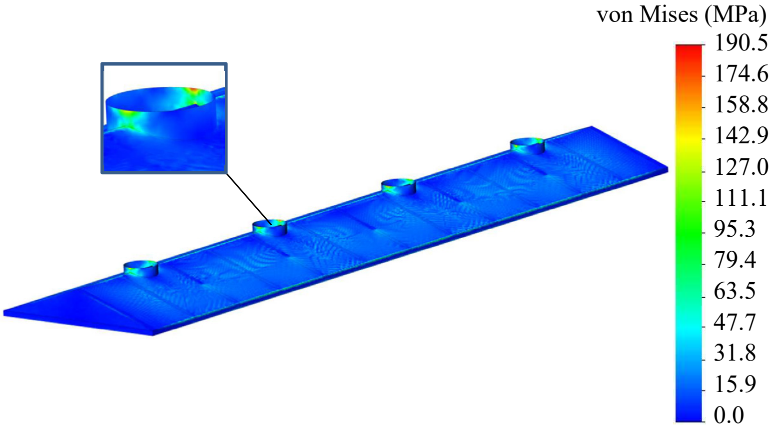


Fig. 10. Stressed state of the roof

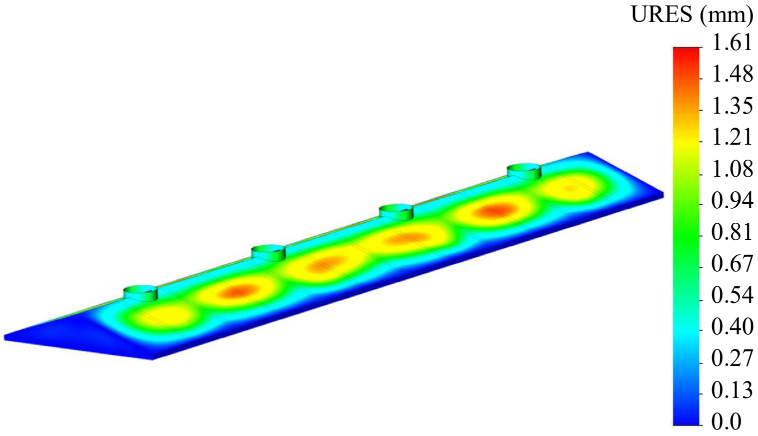


Fig. 11. Displacements in the nodes of the roof structure

Fig. 11 shows the location of displacements in the roof structure. The maximum movements are concentrated in the area between the first side of the end parts and the second loading hatches. These movements are equal to 1.61 mm.

Therefore, the strength of the roof under the action of vertical loads is ensured.

Also, as part of the research, the self-oscillation frequencies of the roof were determined. To this end, its modal analysis was carried out in accordance with the calculation scheme shown in Fig. 9. The calculation was carried out using SolidWorks Simulation software options, which includes a special module for such a calculation. This module allows one to determine the frequencies and forms of the object's natural oscillations when it is subjected to an external disturbance. The calculation results are summarized in Table 1.

Table 1

Numerical values of frequencies of oscillations of the roof of a covered wagon

Mode number	Frequency value, Hz	Mode number	Frequency value, Hz
1	81.02	6	89.15
2	84.53	7	89.81
3	86.44	8	94.12
4	88.64	9	102.81
5	88.94	10	108.38

Operational safety was assessed by the first natural frequency of oscillations, which according to [20] should have a value of at least 8 Hz. Therefore, this condition is met with the applied design scheme of the roof.

5. 2. Assessing the movement of a covered wagon with a roof of the proposed design

Mathematical modeling of its vertical load was carried out to assess the movement of a covered wagon with a roof of the proposed design. The calculation scheme of the covered wagon is shown in Fig. 12. It takes into account the presence of six degrees of freedom of the wagon: translational and angular movements of the body, as well as translational and angular movements of the first and second bogies in the course of movement. The unevenness of the track was set in the form of a harmonic law.

The equations of motion of the estimated model are of the following form [30]:

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

$$M_2 \cdot \frac{d^2}{dt^2} q_2 + C_{2,2} \cdot q_2 + C_{2,3} \cdot q_3 + C_{2,5} \cdot q_5 = = F_{FR} \cdot l \cdot \left(\operatorname{sign}\left(\frac{d}{dt} \delta_1 \right) - \operatorname{sign}\left(\frac{d}{dt} \delta_2 \right) \right), \tag{4}$$

$$M_3 \cdot \frac{d^2}{dt^2} q_3 + C_{3,1} \cdot q_1 + C_{3,2} \cdot q_2 + C_{3,3} \cdot q_3 + B_{3,3} \cdot \frac{d}{dt} q_3 = = F_{FR} \cdot \operatorname{sign}\left(\frac{d}{dt} \delta_1 \right) + k_1 (\eta_1 + \eta_2) + \beta_1 \left(\frac{d}{dt} \eta_1 + \frac{d}{dt} \eta_2 \right), \tag{5}$$

$$M_4 \cdot \frac{d^2}{dt^2} q_4 + C_{4,4} \cdot q_4 + B_{4,4} \cdot \frac{d}{dt} q_4 =$$
$$= -k_1 (\eta_1 - \eta_2) - \beta_1 \cdot a \cdot \left(\frac{d}{dt} \eta_1 - \frac{d}{dt} \eta_2 \right), \qquad (6)$$

$$M_5 \cdot \frac{d^2}{dt^2} q_5 + C_{5,1} \cdot q_1 + C_{5,2} \cdot q_2 + C_{5,5} \cdot q_5 + B_{5,5} \cdot \frac{d}{dt} q_5 =$$
$$= F_{FR} \cdot \mathrm{sign} \left(\frac{d}{dt} \delta_2 \right) + k_1 (\eta_3 + \eta_4) + \beta_1 \left(\frac{d}{dt} \eta_3 + \frac{d}{dt} \eta_4 \right), \quad (7)$$

$$M_6 \cdot \frac{d^2}{dt^2} q_6 + C_{6,6} \cdot q_6 + B_{6,6} \cdot \frac{d}{dt} q_6 =$$
$$= -k_1 \cdot a \cdot (\eta_3 - \eta_4) - \beta_1 \cdot a \cdot \left(\frac{d}{dt} \eta_3 - \frac{d}{dt} \eta_4 \right), \qquad (8)$$

where M_1, M_2 – mass and moment of inertia of the covered wagon body during translational and angular movements, respectively; M_3, M_4 – respectively, the mass and moment of inertia of the first moving bogie during translational and angular movements; M_5, M_6 – respectively, the mass and moment of inertia of the second bogie in the course of movement during translational and angular movements; C_{ij} – characteristic of the elasticity of the elements of the oscillating system; B_i is the scattering function; a – half of the bogie base (model 18-100); q_i – generalized coordinates corresponding to translational and angular movements of the wagon; k_i – track stiffness; β_i – damping coefficient; F_{FR} – friction force in spring suspension; η_i is a joint inequality.

The input parameters of the mathematical model are the technical characteristics of the body of a covered wagon, the spring suspension of bogies, as well as the disturbing action. The basic parameters of the disturbing action are summarized in Table 2 [30].

The calculation was performed on the example of a covered wagon moving at a speed of 70 *km*/h. The initial movement of the body was taken to be equal to 0.004 m, and the bogies to 0.003 m [30]. The initial velocities were assumed to be zero [31, 32]. On the basis of the performed calculations, the indicators of the dynamics of the covered wagon, which are used to assess its movement, were determined.

Table 2

Input parameters to the mathematical model

Parameter name	Value
Damping coefficient, kn·s/m	200
Rigidity of track, kn/m	100,000
Amplitude of irregularity, m	0.01
The length of the irregularity, m	25

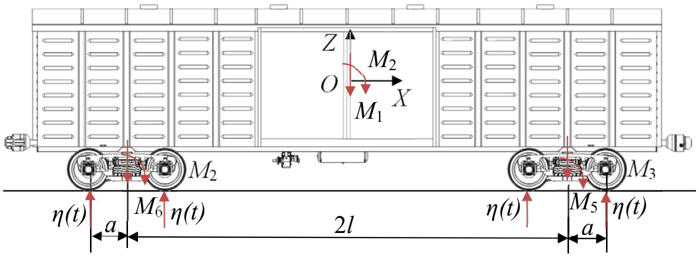


Fig. 12. Covered wagon design diagram

Accelerations acting on the load-bearing structure of the covered wagon at the center of mass amounted to 4.2 m/s^2 (0.42 g); they occur when the wagon passes the bump (Fig. 13).

At the same time, the coefficient of vertical dynamics of the covered wagon was about 0.6 (Fig. 14).

The calculations allow us to conclude that the wagon's movement is assessed as "good" in accordance with regulatory documents.

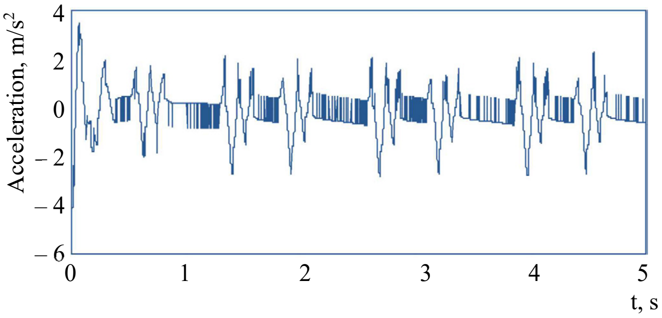


Fig. 13. Acceleration in the center of mass

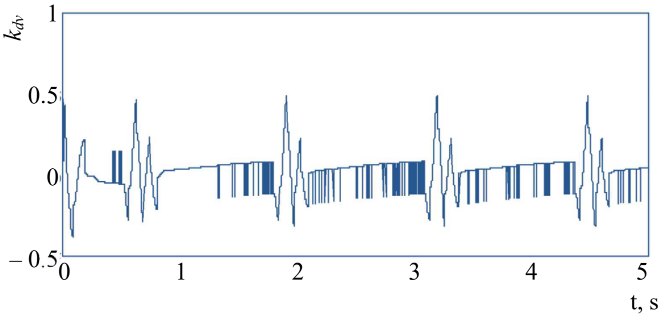


Fig. 14. Vertical dynamics coefficient

6. Discussion of results of analyzing the vertical load on the roof of a covered wagon with a frame in the form of a triangular arch

To reduce the tare of the covered wagon, it is proposed to improve the roof by making it in the form of a triangular arch (Fig. 2). In order to determine the execution profiles of the arches, the calculation of the bending moments acting in its cross-section from a uniformly distributed load was carried out (Fig. 5). The results made it possible to establish that the channel is the most rational arch profile (Fig. 8). To justify the use of this profile, a spatial model of the roof was built (Fig. 6) and strength calculations were performed. The results of these calculations established that the maximum stresses in the roof are 190.5 MPa (Fig. 10). These stresses are recorded in the areas where loading hatches are located. It must be said that they do not exceed the allowable values and the strength of the roof when vertical loads are perceived is observed. The maximum displacements amounted to 1.61 mm and were concentrated in the area between the first from the side of the end parts and the second loading hatches (Fig. 11). A modal analysis of the roof was carried out for the safety of its operation. The results of our calculation showed that the value of the first natural frequency of oscillation was more than 8 Hz (Table 1). This allows us to conclude that from the point of view of frequency analysis, operational safety is provided for.

Since the improvement of the roof contributes to the reduction of its mass, the movement of the covered wagon while empty was evaluated by the joint unevenness. It was established that the accelerations acting on the body of the covered wagon at the center of mass were 4.2 m/s^2 (Fig. 13) with a coefficient of vertical dynamics of 0.6 (Fig. 14). Therefore, the movement of the wagon is assessed as "good".

For the convenience of maintaining the wagon, the roof can be supplemented with appropriate tools.

This study has certain advantages in comparison with known ones. Thus, in contrast to works [4, 10], the roof design assumes the presence of loading hatches. This allows transportation and safe unloading of bulk cargo from the wagon. Compared to the roof design suggested in [5], the proposed structure is much simpler and more convenient in maintenance. In contrast to work [6], we have proposed not only an improved roof design but also evaluated the movement of a covered wagon equipped with this roof. In comparison with the results reported in [7], we have suggested measures to improve the roof structure, which contribute to reducing its mass. A distinctive feature of our results compared to those in [8] is that we have not only proposed the improvement of the roof but also carried out its scientific justification. In comparison with the results in [9], the improvement of the technical indicators of the wagon was achieved by improving its roof. Unlike works [11–15], the proposed improvement does not require significant capital investments. Note that the introduction of advanced materials in the construction of railroad wagons is a rather expensive measure.

The limitation of this study is that when calculating the strength of the roof, it was fastened around the perimeter of its lower strapping. In this case, rigid fixation was used. In reality, the roof is fastened with rivets or bolts, which are placed with the appropriate step. In the case of weakening of any of them, the degree of freedom of the roof may occur. This study does not consider such a case.

As a drawback of the study, we note that the roof was considered a monolithic structure during the calculations. That is, welding seams between its individual components were not taken into account.

The conditions for the practical use of the research results are a symmetrical roof load scheme in operation.

The further development of this research is the determination of the strength of the roof when it perceives longitudinal and lateral loads.

The potentially expected effect of using the results of our study is advancements in the design of modern freight wagon structures with improved technical and economic indicators.

7. Conclusions

1. The profile of arches for a wagon roof has been determined; its loading in the vertical plane was also investigated. The profile of the arches was selected according to the maximum bending moments. Taking into account our calculations, channel No. 6, 5 with a wall thickness of 4.4 mm and W=15.0 cm^3 were chosen for the profile of the arches.

The results of calculating the strength of the roof showed that the maximum stresses in the roof occur in the areas where loading hatches are located and amount to 190.5 MPa. In this case, these stresses are 13.4 % lower than permissible. This allows us to conclude that the strength of the roof under the applied design regime is ensured.

2. The movement of a covered wagon with a roof of the proposed design has been assessed. The calculation was performed on the example of a covered wagon moving at a speed of 70 km/h. It was established that the maximum accelerations acting on the body of the covered wagon at the center of mass were equal to 4.2 m/s^2. In this case, the coefficient of vertical dynamics was 0.6. Therefore, the movement of the covered wagon while empty can be rated as "good".

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, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

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

References

1. Lovska, A. (2018). Simulation of Loads on the Carrying Structure of an Articulated Flat Car in Combined Transportation. International Journal of Engineering & Technology, 7 (4.3), 140. https://doi.org/10.14419/ijet.v7i4.3.19724
2. Dižo, J., Blatnický, M., Steišūnas, S., Skočilasová, B. (2018). Assessment of a rail vehicle running with the damaged wheel on a ride comfort for passengers. MATEC Web of Conferences, 157, 03004. https://doi.org/10.1051/matecconf/201815703004
3. Dizo, J., Blatnicky, M., Harusinec, J., Falendysh, A. (2018). Modification and analyses of structural properties of a goods wagon bogie frame. Diagnostyka, 20 (1), 41–48. https://doi.org/10.29354/diag/99853
4. Fomin, O., Lovska, A. (2021). Justification of the use of square pipes in the frame of the removable roof of the open wagon. Eastern-European Journal of Enterprise Technologies, 4 (7 (112)), 18–25. https://doi.org/10.15587/1729-4061.2021.237157
5. Sepe, R., Pozzi, A. (2015). Static and modal numerical analyses for the roof structure of a railway freight refrigerated car. Frattura Ed Integrità Strutturale, 9 (33), 451–462. https://doi.org/10.3221/igf-esis.33.50
6. Cuartero, J., Miravete, A., Sanz, R. (2011). Design and calculation of a railway car composite roof under concrete cube crash. International Journal of Crashworthiness, 16 (1), 41–47. https://doi.org/10.1080/13588265.2010.501163

7. Fomin, O., Stetsko, A. (2018). Determination of means of contraindication of operative damage of superior wagon-thermal systems of the model TN 4-201. Collection of Scientific Works of the State University of Infrastructure and Technologies Series “Transport Systems and Technologies,” 32 (1), 135–146. Internet Archive. https://doi.org/10.32703/2617-9040-2018-32-1-135-146
8. Saeedi, A., Motavalli, M., Shahverdi, M. (2023). Recent advancements in the applications of fiber-reinforced polymer structures in railway industry – A review. Polymer Composites, 45 (1), 77–97. https://doi.org/10.1002/pc.27817
9. Chandra Prakash Shukla, Bharti, P. K. (2015). Study and Analysis of Doors of BCNHL Wagons. International Journal of Engineering Research And, 4 (04). https://doi.org/10.17577/ijertv4is041031
10. Levchenko, S. V., Tatianich, E. M., Konopatskyi, Yu. P., Yablonskyi, A. V., Shkabrov, O. A., Kryzhanovskyi, A. Yu. (2016). Pat. No. 109202 UA. Znimnyi dakh vantazhnoho vahona. No. u2016 03361; declareted: 31.03.2016; published: 10.08.2016. Available at: https://uapatents.com/8-109202-znimnijj-dakh-vantazhnogo-vagona.html
11. Kondratiev, A., Píštěk, V., Smovziuk, L., Shevtsova, M., Fomina, A., Kučera, P. (2021). Stress–Strain Behaviour of Reparable Composite Panel with Step-Variable Thickness. Polymers, 13 (21), 3830. https://doi.org/10.3390/polym13213830
12. Kondratiev, A., Gaidachuk, V., Nabokina, T., Kovalenko, V. (2019). Determination of the influence of deflections in the thickness of a composite material on its physical and mechanical properties with a local damage to its wholeness. Eastern-European Journal of Enterprise Technologies, 4 (1 (100)), 6–13. https://doi.org/10.15587/1729-4061.2019.174025
13. Lee, W. G., Kim, J.-S., Sun, S.-J., Lim, J.-Y. (2016). The next generation material for lightweight railway car body structures: Magnesium alloys. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 232 (1), 25–42. https://doi.org/10.1177/0954409716646140
14. Olmos Irikovich, Z., Rustam Vyacheslavovich, R., Mahmod Lafta, W., Yadgor Ozodovich, R. (2020). Development of new polymer composite materials for the flooring of rail carriage. International Journal of Engineering & Technology, 9 (2), 378–381. https://doi.org/10.14419/ijet.v9i2.30519
15. Fantuzzi, N., Bacciocchi, M., Benedetti, D., Agnelli, J. (2021). The use of sustainable composites for the manufacturing of electric cars. Composites Part C: Open Access, 4, 100096. https://doi.org/10.1016/j.jcomc.2020.100096
16. Horbenko, A. P., Martynov, I. E. (2007). Konstruiuvannia ta rozrakhunky vahoniv. Kharkiv: UkrDAZT, 150.
17. Vidy visyachih stropil’nyh sistem primenyaemyh v stroitel’stve. Available at: https://www.pinterest.com/pin/509610514079263558/
18. Chausov, M. H., Bondar, M. M., Pylypenko, A. P., Kutsenko, A. H. (2019). Prykladna mekhanika (opir materialiv). Kyiv. Available at: https://dglib.nubip.edu.ua/server/api/core/bitstreams/be589d1e-4513-4caf-8792-ebb016171ab2/content
19. Shvabiuk, V. I. (2016). Opir materialiv. Kyiv: Znannia, 400. Available at: https://btpm.nmu.org.ua/ua/download/navch-posib/%D0%A8%D0%B2%D0%B0%D0%B1%D1%8E%D0%BA.%D0%9E%D0%9C.%D0%9F%D1%96%D0%B4%D1%80%D1%83%D1%87%D0%BD%D0%B8%D0%BA.pdf
20. DSTU 7598:2014. Freight Wagons. General reguirements to calculation and designing of the new and modernized 1520 mm gauge wagons (non-self-propelled). Kyiv. Available at: https://online.budstandart.com/ua/catalog/doc-page.html?id_doc=73763
21. BDS EN 12663-2: 2010. Railway applications - Structural requirements of railway vehicle bodies - Part 2: Freight wagons (EN 12663-2: 2010).
22. Pustiulha, S. I., Samostian, V. R., Klak, Yu. V. (20189). Inzhenerna hrafika v SolidWorks. Lutsk: Vezha, 172. Available at: https://lib.lntu.edu.ua/sites/default/files/2021-02/%D0%86%D0%BD%D0%B6%D0%B5%D0%BD%D0%B5%D1%80%D0%BD%D0%B0%20%D0%B3%D1%80%D0%B0%D1%84%D1%96%D0%BA%D0%B0%20%D0%B2%20SolidWorks.pdf
23. Koziar, M. M., Feshchuk, Yu. V., Parfeniuk, O. V. (2018). Kompiuterna hrafika: SolidWorks. Kherson: Oldi-plius, 252. Available at: https://ep3.nuwm.edu.ua/22175/1/%D0%9A%D0%BE%D0%BC%D0%BF%27%D1%8E%D1%82%D0%B5%D1%80%D0%BD%D0%B0%20%D0%B3%D1%80%D0%B0%D1%84%D1%96%D0%BA%D0%B0.pdf
24. Caban, J., Nieoczym, A Gardy ski, L. (2021). Strength analysis of a container semi-truck frame. Engineering Failure Analysis, 127, 105487. https://doi.org/10.1016/j.engfailanal.2021.105487
25. Lovskaya, A. (2015). Computer simulation of wagon body bearing structure dynamics during transportation by train ferry. Eastern-European Journal of Enterprise Technologies, 3 (7 (75)), 9–14. https://doi.org/10.15587/1729-4061.2015.43749
26. Dižo, J. (2016). Analysis of a Goods Wagon Running on a Railway Test Track. Manufacturing Technology, 16 (4), 667–672. https://doi.org/10.21062/ujep/x.2016/a/1213-2489/mt/16/4/667
27. Vatulia, G., Lovska, A., Pavliuchenkov, M., Nerubatskyi, V., Okorokov, A., Hordiienko, D. et al. (2022). Determining patterns of vertical load on the prototype of a removable module for long-size cargoes. Eastern-European Journal of Enterprise Technologies, 6 (7 (120)), 21–29. https://doi.org/10.15587/1729-4061.2022.266855
28. Panchenko, S., Gerlici, J., Vatulia, G., Lovska, A., Rybin, A., Kravchenko, O. (2023). Strength Assessment of an Improved Design of a Tank Container under Operating Conditions. Communications - Scientific Letters of the University of Zilina, 25 (3), B186–B193. https://doi.org/10.26552/com.c.2023.047
29. Soukup, J., Skočilas, J., Skočilasová, B., Dižo, J. (2017). Vertical Vibration of Two Axle Railway Vehicle. Procedia Engineering, 177, 25–32. https://doi.org/10.1016/j.proeng.2017.02.178
30. Domin, Yu. V., Cherniak, H. Yu. (2003). Osnovy dynamiky vahoniv. Kyiv: KUETT, 269.
31. Gerlici, J., Lovska, A., Vatulia, G., Pavliuchenkov, M., Kravchenko, O., Solčanský, S. (2023). Situational Adaptation of the Open Wagon Body to Container Transportation. Applied Sciences, 13 (15), 8605. https://doi.org/10.3390/app13158605
32. Lovska, A., Dižo, J., Prokopovych, I., Zharova, O., Voronenko, S. (2023). Detecting the effect of an intermediate adapter on the load of the bearing structure of an open wagon. Eastern-European Journal of Enterprise Technologies, 6 (7 (126)), 19–25. https://doi.org/10.15587/1729-4061.2023.291247