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DETERMINING THE INFLUENCE OF SANDWICH-TYPE COMPONENTS ON THE LOAD OF A HATCH COVER IN A UNIVERSAL OPEN WAGON

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The object of the study reported here is the processes of occurrence, perception, and redistribution of loads in the improved structure of the hatch cover in a universal open wagon.

In order to reduce the load on the cover of an open wagon hatch, and, accordingly, to improve its strength, it is proposed to improve its design by introducing sandwich components. The thickness of the sheets that form the hatch cover has been determined. The dynamic loading of the hatch cover in the vertical plane was studied. It was found that the accelerations acting on the hatch cover with the proposed improvement are almost 20 % lower than those acting on the typical structure. The basic strength indicators of the hatch cover under the operational modes of its load have been determined. The results of the calculation showed that the maximum stresses in the hatch cover are 22 % lower than permissible ones. In addition, within the framework of the study, the main indicators of the dynamics of the open wagon equipped with the proposed structure of hatch covers were determined. The movement of the open wagon under the condition of movement in an empty state is rated as "good". At the same time, the maximum accelerations in the center of mass of the supporting structure of an open wagon were 4.6 m/s^2, and the coefficient of vertical dynamics was about 0.6.

Special features of the results within the framework of this study are that the proposed improvement of the hatch cover helps improve its strength by reducing the dynamic load, and not by strengthening the structure.

The scope of practical application of the results is the engineering industry, in particular, railroad transport. The conditions for the practical use of the research results are the use of energy-absorbing material in the sandwich-type components that form the hatch cover.

The study reported here could contribute to devising recommendations for the construction of components in the structures of modern freight cars, thereby reducing the costs of maintaining them in operation, as well as increasing the profitability of railroad transportation

Keywords: railroad transport, open wagon hatch cover, hatch cover strength, open wagon load

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1. Introduction

It is known that one of the determining factors for the successful development of the economy is the coordinated functioning of the transport industry [1, 2]. At the same time, railroad transport plays a key role as a leading component of the transport industry. One of the most common types of cargo transported by rail is bulk or bulk cargo. Such goods are most often transported in open wagons, designed for the transportation of goods that do not require protection from atmospheric precipitation. On the railroads of the 1520 mm gauge, open wagons with a solid bottom or with a floor formed by the covers of unloading hatches have been widely used.

Analysis of statistical data on damage to open wagons in operation in recent years has allowed us to conclude that one of the most damaged components is the covers of unloading hatches. At the same time, one of the most frequent causes of their damage during operation is loading and unloading. Therefore, the greatest amount of damage to hatch covers is observed at loading and unloading enterprises, including seaports.

The most frequent damage to hatch covers is cracks in the structure, deformations of the floor, broken welding seams, etc. The presence of such damage makes it necessary to carry out unplanned types of repairs of cars, which increases the operational costs of their maintenance. In addition, the presence of such damage affects the safety of carriages in trains. It is also dangerous from the point of view of the environmental friendliness of the transportation of goods by railroad. Therefore, issues related to devising and implementing solutions aimed at improving the strength of covers of unloading hatches of universal open wagons are relevant.

2. Literature review and problem statement

Studies of the load and improvements of hatch covers in operation are reported in a considerable number of scientific papers. For example, the improved design of the hatch cover is proposed in [3]. At the same time, reinforced strapping, the use of a smooth sheet, and the installation of cast brackets are implied. In addition, the structure of the hatch cover is equipped with additional braces to ensure strength in its most heavily loaded parts. To substantiate the proposed improvement, appropriate calculations were performed on the strength of the hatch cover. The results of these calculations confirmed the effectiveness of the proposed advancement. At the same time, it should be noted that the authors did not take into account the dynamic loads that act on the hatch cover during operation when performing strength calculations.

Ensuring the strength of hatch covers in operation is possible through the use of the advanced materials in their construction. Thus, in work [4], the justification of the use of polymer composite materials for the manufacture of covers of unloading hatches is given. In addition, the cited paper reports the results of calculating the strength of the hatch cover, which proved that such an implementation was expedient.

Similar studies are described in [5], which also suggests the use of composite materials for the manufacture of component structures of freight cars, in particular, the floor covering.

It must be said that in works [4, 5] the strength of the hatch cover of the improved design was not investigated when it absorbed dynamic loads. This is quite important since these loads significantly affect its strength in operation. In addition, the use of composite materials in the construction of vehicles requires additional capital investments and an appropriate maintenance and repair system.

The structure of an open car hatch cover, proposed by the authors of work [6], is of interest. This design has a convex configuration, which makes it possible to increase the carrying capacity of an open car by almost 1 ton compared to the prototype. The results of the strength calculation of the proposed hatch cover structure are presented. It is important to say that when determining the basic strength indicators of the hatch cover, the authors took into account only one calculation mode of its load.

Paper [7] highlights the new design of the hatch cover of the open car. The originality of its structure is the use of additional reinforcing belts, which have a rectangular closed section. In order to justify such a design of the hatch cover, the authors calculated its strength. The results of these calculations proved that the strength of the hatch cover under the considered load modes is ensured. Along with this, the authors of the cited work did not investigate the dynamic loading of an open car equipped with an improved design of hatch covers. This does not make it possible to fully assess the effectiveness of putting such hatch covers into operation.

In order to improve the strength of the hatch cover, paper [8] proposed the introduction of flexible connections into its design. This is achieved by making the cover of the hatch from two corrugated sheets. Around the perimeter, these sheets interact through a W-shaped binding. It must be said that the use of the proposed strapping configuration causes difficulties in the maintenance and repair of the hatch cover during operation. In addition, it must be said that when modeling the dynamic load of the hatch cover, the authors neglect the dissipative component, which can cause a corresponding error in the research. In addition, in the cited work, as in [7], the dynamic loading of the open car with the proposed structure of hatch covers was not determined.

Measures to reduce the dynamic load of cars by introducing flexible connections into their structure are covered in [9]. The authors considered the expediency of using sandwich panels in the load-bearing structure of rolling stock. To determine the optimal parameters of sandwich panels, such parameters as stiffness and weight were used. The results of the study made it possible to substantiate the proposed solutions regarding the construction of the body.

In addition, the authors of work [10] investigated the effectiveness of using sandwich panels made of composite material. The cited paper reports the results of endurance tests of composite panels. A procedure for testing sandwich panels is described. However, the authors of works [9, 10] did not investigate the expediency of using sandwich panels as components of the hatch cover of an open car.

Review of the literature [3–10] allows us to conclude that not enough attention was paid to the study of the influence of structural components of the sandwich type on the load capacity of the hatch cover of a universal open car. In this regard, these issues require further research.

3. The aim and objectives of the study

The purpose of our study is to justify the feasibility of using sandwich-type components in the design of a hatch cover for a universal open car. This will help reduce the load on the hatch cover, reduce costs for maintaining open cars, and increase the efficiency of their operation.

To achieve this goal, the following tasks are defined:

– to determine the thickness of the hatch cover material with sandwich-type components in the structure;

– to investigate the dynamic loading of the hatch cover and calculate its strength under the basic load modes;

– to determine the main indicators for the dynamics of an open car equipped with an improved structure of hatch covers.

4. The study materials and methods

The object of our research is the processes of occurrence, perception, and redistribution of loads in the improved design of a hatch cover for a universal open car.

The main hypothesis of the research assumes that improving the strength of the hatch cover is possible through the introduction of sandwich-type components into its structure.

The hatch cover is a structural component of a universal open car that forms its floor [11] (Fig. 1).

A typical structure of a hatch cover consists of sheet 1, to which strap 2, hinges 3, and locking brackets 4 are attached (Fig. 2).

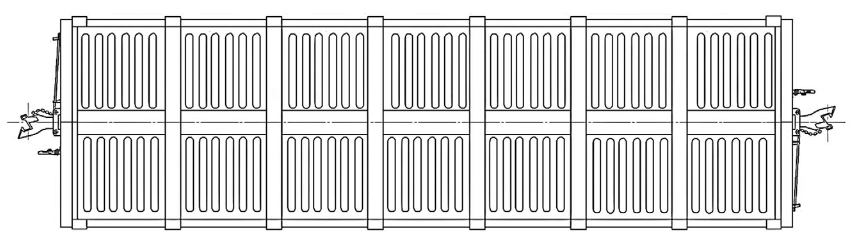

Fig. 1. Placement of hatch covers on an open car body (top view)

The hatch cover works as follows. Loads from the cargo transported in the universal open car act on sheet 1 and, from it, are transmitted to strapping 2. Locking brackets 4 enables fixation of the hatch cover in an open car in a horizontal (closed) position. Hinges 3 ensure the retention of the hatch cover in the structure of the open car and the possibility of its opening and closing.

To ensure the strength of the cover in an open car hatch, it is proposed to improve its design. This improvement involves the introduction of sandwich-type components into its structure. To this end, the sheet of the hatch cover is made double and consists of upper and lower sheets, which are smooth (Fig. 3). The space between the hatch cover sheets is filled with energy-absorbing material with elastic-viscous properties. Such properties can be implemented, for example, by aluminum foam. The insignificant volumetric weight of such material will not contribute to a significant increase in the mass of the hatch cover, and, accordingly, the weight of the car.

At the same time, the frame of the hatch cover is formed by an Ω-shaped profile that runs along the perimeter of the hatch cover (Fig. 4).

The finite element method implemented in SolidWorks Simulation (France) [12, 13] was used to determine the strength of the sheet. In this case, it was taken into account that the vertical load, which includes a vertical static and a vertical dynamic component, is equal to 69.6 MPa.

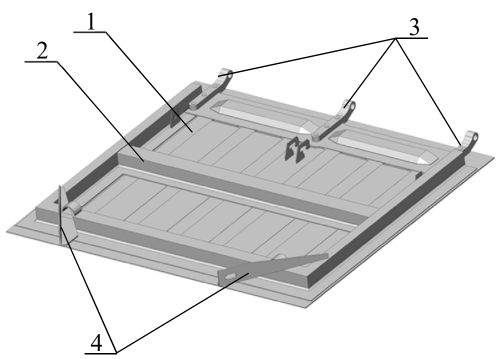

Fig. 2. Hatch cover in a universal open car

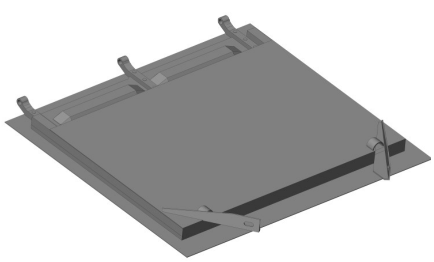

Fig. 3. Improved hatch cover of an open car

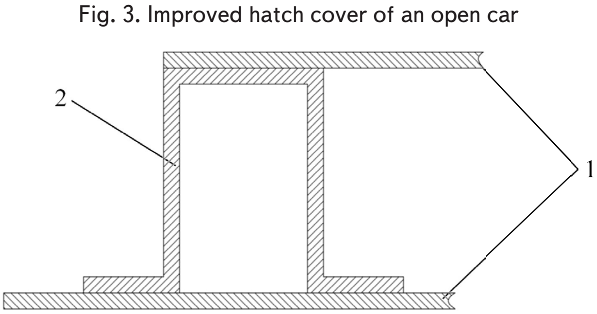

Fig. 4. Cross section of hatch cover strapping:
1 – sheet; 2 – Ω-shaped profile

At the next stage of research, mathematical modeling of the vertical load of the hatch cover was carried out, taking into account the proposed improvement. To construct a mathematical model, the LaGrange method of the II kind was used for non-conservative systems [14, 15], that is, with energy dissipation. The results, namely acceleration, as a component of the dynamic load, are taken into account when determining the strength of the hatch cover.

Since the proposed improvement of the hatch cover contributes to a slight increase in its mass, the basic indicators for the movement of an open car in an empty state were determined as this is when the greatest accelerations acting on it occur. In this case, the mathematical model given in [16] was used. The model takes into account the vertical movements of the car, i.e., bouncing oscillations. It is assumed that the car moves along a track that has joints. The track is considered to be elastic-viscous [16–18]. The estimation model is formed by three bodies – a supporting structure with a load, as well as two bogies. It was taken into account that the car is equipped with bogies of the 18-100 model, typical for the 1520 mm track, with the appropriate characteristics of mass, stiffness of the spring suspension, and coefficient of friction in the spring suspension.

5. Results of the scientific substantiation of the introduction of sandwich-type components in the structure of a hatch cover for a universal open car

5. 1. Determining the thickness of the hatch cover sheet with sandwich-type components in the structure

The Bubnov-Galyorkin method was used to determine the thickness of the sheets that would form the sheet of the hatch cover. The sheet is considered as a plate that is clamped around the perimeter. A uniformly distributed load P acts on the surface of the plate (Fig. 5).

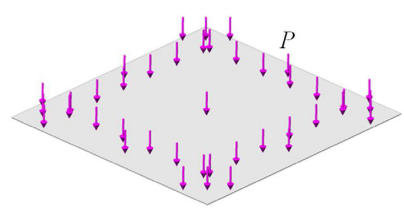

Fig. 5. Calculation diagram of the hatch cover

Then, knowing the characteristics of the hatch cover material (09G2S steel), one can write down a formula for determining the plate thickness:

$$\delta=\sqrt{\frac{P\cdot 96\cdot\left(b^2+\mu\cdot a^2\right)\cdot a^2\cdot b^2}{\sigma\cdot\pi^4\cdot\left(a^2+b^2\right)^2}}, \tag{1}$$

where a is the width of the plate; b – plate length; μ is Poisson's ratio; σ – permissible stresses of the material of the plate.

Based on our calculations, the thickness of the sheet was 8 mm.

To determine the strength of the hatch cover sheet, its spatial model was built, and FEM analysis was carried out. The number of elements in the finite element model (FEM) is determined by the graph analytic method [19–21]. Taking this into account, the number of elements of the model, namely the tetrahedra that make it up, was 16,643, and the number of nodes was 49,158. The calculation results are shown in Fig. 6, 7.

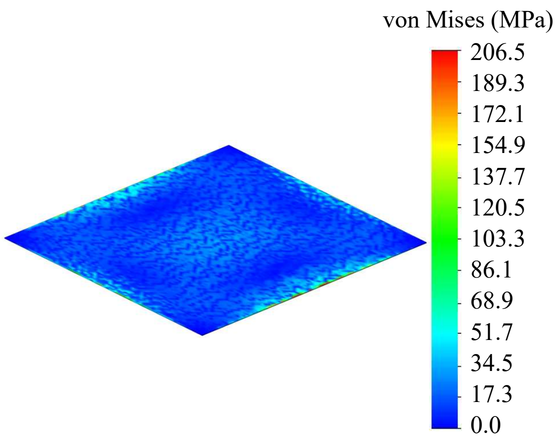

Fig. 6. Stressed state of the plate

Fig. 6 shows that the maximum stresses in the plate occur in its side parts and amount to 206.5 MPa. This distribution of stress fields can be explained by the fact that the fixing of the plate took place along its perimeter. This can also explain the displacement distribution fields in the plate (Fig. 7).

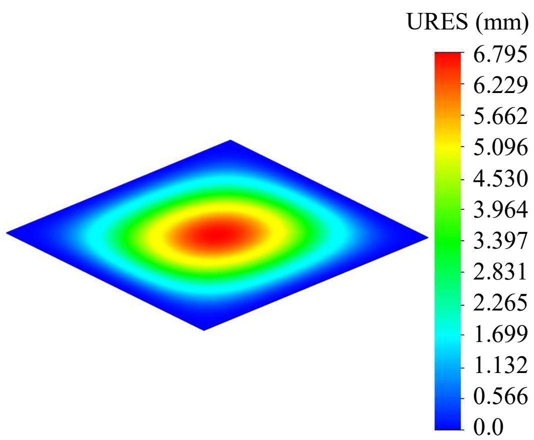

Fig. 7. Displacements in the plate

The maximum displacements occur in the middle part of the plate and are about 6.8 mm. The minimum value of displacements is observed closer to the zones of securing the sheet around the perimeter.

5. 2. Studying the dynamic loading of the hatch cover and its strength calculation under the main load modes

Mathematical modeling was carried out to determine the dynamic load of the improved design of the hatch cover. The calculation diagram of the hatch cover is shown in Fig. 8.

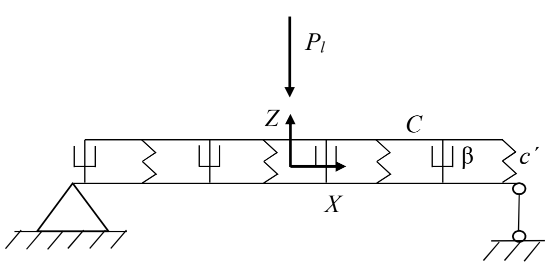

Fig. 8. Calculation diagram of the hatch cover

The case of a cargo weighing 150 kg falling onto the hatch cover is considered.

The mathematical model of the dynamic load on the hatch cover in the vertical plane takes the following form:

$$M_{hc}\cdot\ddot{z}+C\cdot z=P_l-\beta\cdot\dot{z}-c'\cdot z, \qquad (2)$$

where M_{hc} is the mass of the hatch cover; C – stiffness of the hatch cover; P_l is the impact force acting on the hatch cover; β is the coefficient of viscous resistance of the energy-absorbing material; c' is the stiffness of the energy-absorbing material; $\ddot{z}$, $\dot{z}$, z are, respectively, the generalized acceleration, speed, and movement of the hatch cover under the impact of an impact load on it.

It is taken into account that the origin of the coordinate system is located in the center of mass of the hatch cover. The input parameters to the mathematical model are the characteristics of the hatch cover, as well as the impact force.

The mathematical model was solved in the Mathcad software package [22, 23]. In this case, the Runge-Kutta method was used [24–26]. Initial velocities and displacements are assumed to be zero [27–30].

Generalized accelerations were calculated in the array:

$$ddq_{j,1}=\frac{P_l-\beta\cdot q_2-c'\cdot q_1-C}{M_{hc}}, \qquad (3)$$

where $q_1=z;\ \frac{d}{dt}z_1=q_2.$

Based on our calculations, it was established that the acceleration acting on the hatch cover is about 4.5 m/s^2 (Fig. 9). The resulting acceleration value is almost 20 % lower than that acting on a typical hatch cover.

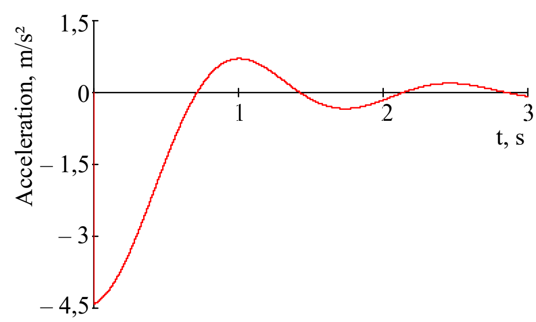

Fig. 9. Accelerations acting on the hatch cover

To determine the strength of the hatch cover taking into account the proposed improvement, its strength calculation was carried out. Two hatch cover load schemes are taken into account in accordance with the modes specified in document [31]:

– action on the hatch cover area of a uniformly distributed load of P=69.9 kN, which consists of the force of the gross weight of the hatch cover and the dynamic load;

– dropping a 150 kg cargo from a height of 3000 mm onto the hatch cover.

The calculation scheme of the hatch cover for load mode I is shown in Fig. 10. It is taken into account that the load P is evenly distributed over the area of the sheet. Reaction P_p was applied to the locking brackets, which is caused by the load P. Fixing of the model took place by hinges. At the same time, a hard pinching was applied. To model the elastic-viscous connections in the hatch cover, the options of the SolidWorks Simulation software package were used, which allow modeling the "spring-damper" connection. These ties were placed between sheets over the entire area of the hatch cover.

The FEM was built using tetrahedra. The hatch cover FEM has 1340850 elements and 295535 nodes. The maximum size of the element was 10 mm, and the minimum – 2 mm. The calculation results are shown in Fig. 11, 12.

The maximum stresses in the hatch cover occur in the hinges and amount to 163.8 MPa. These stresses are lower than permissible by 22 % 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). The international analog of the specified standard is EN 12663-2. Railroad applications – structural requirements of railroad vehicle bodies – Part 2: Freight cars.

The maximum movements occur in the locking brackets and amount to 3.3 mm.

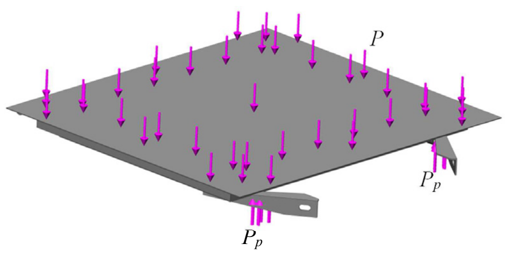

Fig. 10. Calculation diagram of the hatch cover (mode I)

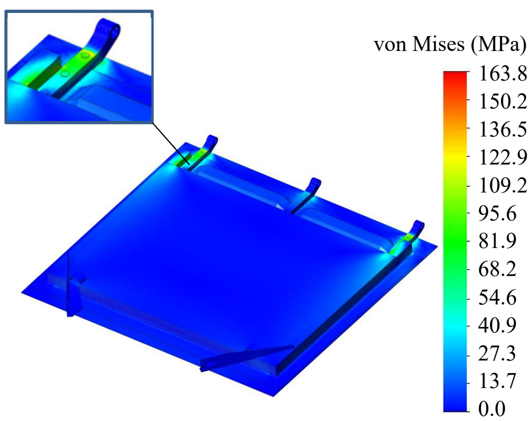

Fig. 11. Stressed state of the hatch cover (mode I)

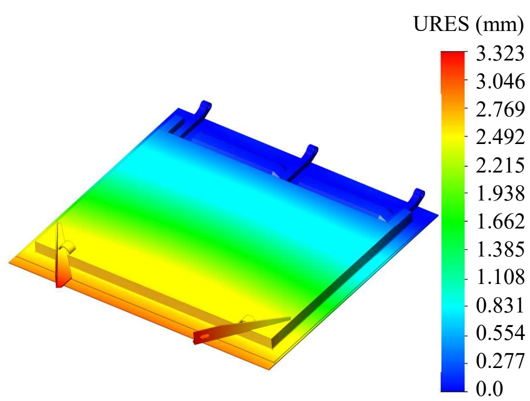

Fig. 12. Movement in hatch cover nodes (Mode I)

At the next stage of the study, the strength of the hatch cover under load mode II was determined. Its calculation scheme is shown in Fig. 13. A force P from the load was applied behind the center of the hatch cover, and a reaction P_p from this force was applied to the locking brackets.

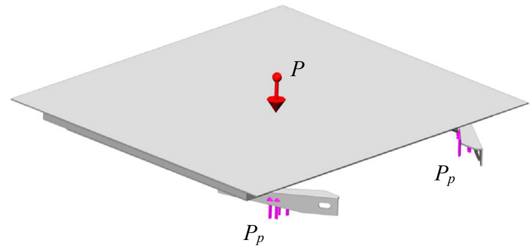

Fig. 13. Calculation diagram of the hatch cover (mode II)

The calculation results are shown in Fig. 14, 15. The maximum stresses, again, occur in the hinge, and amount to 195.1 MPa (Fig. 14). The resulting stresses are 7 % lower than permissible ones.

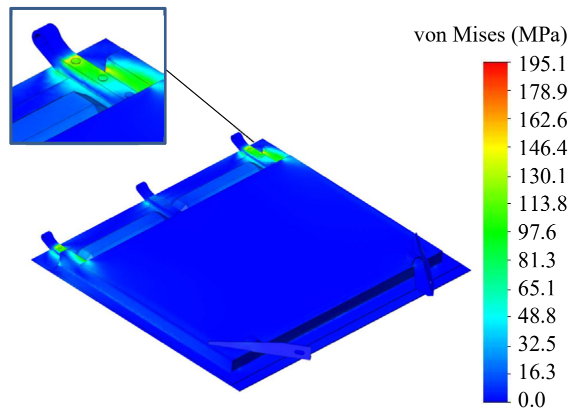

Fig. 14. Stressed state of the hatch cover (mode II)

The maximum displacements take place in the locking brackets and are equal to 3.6 mm (Fig. 15).

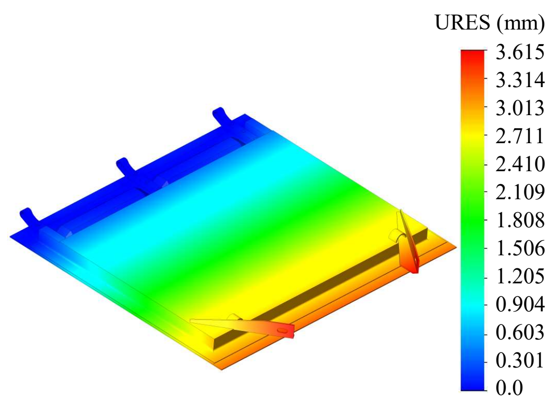

Fig. 15. Movement in hatch cover nodes (mode II)

Our analysis of the strength of the hatch cover under the applied load modes allowed us to conclude that its strength is maintained.

5. 3. Determining the main indicators for the dynamics of an open car equipped with the improved structure of hatch covers

It must be said that the proposed structure of a hatch cover has a mass that is 1.6 % greater than that of a typical one. This contributes to a slight increase in the car's tare.

To determine the dynamics indicators of an open car equipped with improved hatch covers, a corresponding calculation was performed. Based on the calculations, the main indicators of the dynamics of an open wagon were determined (Fig. 16–20). Analyzing these dependences, it can be concluded that the maximum accelerations of the supporting structure are 4.6 m/s^2 and occur at the moment the car passes through the joint. Further, these accelerations decrease, and their value is about 2.5 m/s^2 (Fig. 16).

The acceleration of the bogies, the first and second in forward movement, is about 6 m/s^2 (Fig. 17, 18).

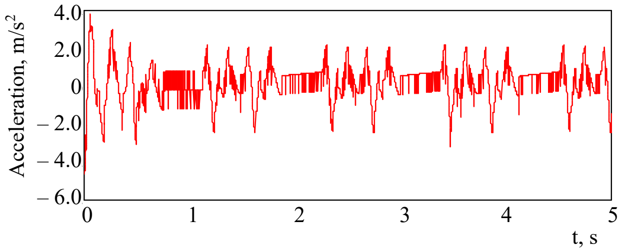

Fig. 16. Acceleration of the supporting structure of an open car in the center of mass

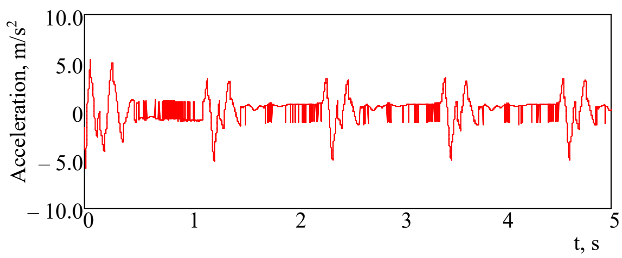

Fig. 17. Acceleration of the first bogie in forward movement

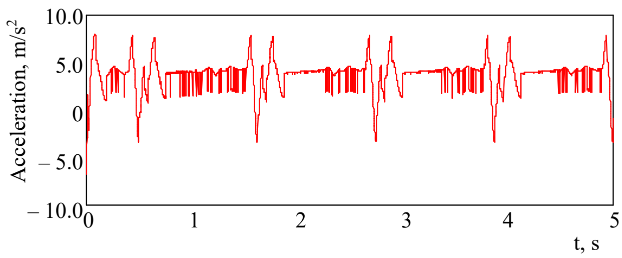

Fig. 18. Acceleration of the second bogie in forward movement

The force in the spring suspension of the bogie was determined as follows [16, 18]:

$$P_{ss} = k_s \cdot \delta + F_{fr} \cdot \operatorname{sign}\dot{\delta}, \tag{4}$$

where k_s is the stiffness of the spring suspension of a bogie; F_{fr} is the force of friction in the spring assembly of a bogie; δ, $\dot{\delta}$ are, respectively, the deformation of the elastic elements of the spring suspension and the rate of deformation.

After the corresponding calculations, the value of force in the spring suspension of the bogie when it passed the joint was 43.4 kN (Fig. 19). This force value occurs at the initial moment of the oscillatory process. Then it decreases and is about 20 kN.

The coefficient of vertical dynamics is determined by the formula from [16, 18]:

$$k_{dv} = \frac{P_{ss}}{P_b}, \tag{5}$$

where P_b is the loading force of the bogie by the car body.

Based on our calculations, the coefficient of vertical dynamics was about 0.6 (Fig. 20).

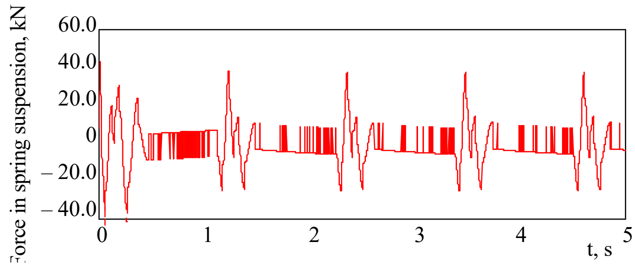

Fig. 19. Force in the spring suspension of a bogie

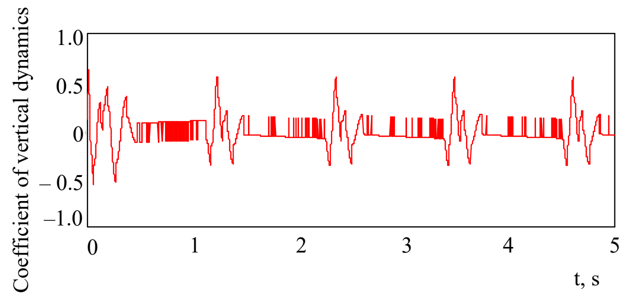

Fig. 20. Coefficient of vertical dynamics

The evaluation of the movement of an open car was carried out according to the vertical acceleration and the coefficient of dynamics. In this case, the movement of the open car is in accordance with DSTU 7598:2014. Freight cars. The general requirements for the calculations and design of new and modernized cars with a gauge of 1520 mm (non-self-propelled) can be rated as "good".

6. Discussion of results of the scientific substantiation of introducing sandwich-type components in the structure of a hatch cover

To ensure the strength of the hatch cover in a universal open car, it is proposed to improve its design by introducing sandwich-type components (Fig. 3). To determine the thickness of the hatch cover sheets, appropriate calculations were performed, which were confirmed by the results of determining their strength using the finite element method (Fig. 6).

In order to determine the dynamic load on the hatch cover, mathematical modeling was carried out. It was established that the accelerations acting on the hatch cover, taking into account the proposed improvement, are almost 20 % lower than those acting on a typical structure (Fig. 9).

The strength indicators of the hatch cover under the main load modes were determined. It was established that the strength of the hatch cover is ensured (Fig. 11, 14).

Since the proposed improvement contributes to an increase in the mass of the hatch cover by 1.6 %, the basic indicators of dynamics of an open car when moving in an empty state were determined (Fig. 16–20). The results of our analysis showed that the movement of the open car is rated as "good".

As a limitation of this study, it can be noted that angular movements of the open car in the vertical plane were not taken into account.

The shortcoming of our study is that a typical 18-100 model bogie was taken into account when modeling the vertical loading of an open car. At present, there are more modern models of freight car bogies, which makes it necessary to take this aspect into account in the future.

The advantage of the current paper in comparison with works [3–5] is that we conducted not only an analysis of the strength of the hatch cover taking into account the proposed improvement but also studied its dynamic load. In contrast to [6], when determining the strength indicators of the hatch cover, the main modes of its load during operation are taken into account. In comparison with the results reported by the authors of [7, 8], not only the strength of the hatch cover but also the vertical load capacity of an open car equipped with improved hatch covers was investigated. In contrast to works [9, 10], we considered the feasibility of using sandwich-type components in the design of an open car hatch cover.

The further development of this research is conducting an experimental study of the strength of a hatch cover of an open car. To this end, it is possible to use the method of electrical tensometry, which can be implemented on a test sample under laboratory conditions.

Our study could contribute to the formation of recommendations for the construction of component structures for modern freight cars, reducing the costs of maintaining them during operation, as well as increasing the profitability of railroad transportation.

7. Conclusions

1. The thickness of a hatch cover sheet with sandwich-type components in the structure was determined and its strength was calculated. It was established that the maximum stresses in the sheet occur in its lateral parts and amount to 206.5 MPa. The resulting stresses do not exceed the allowable values for the steel of grade 09G2S. The maximum movements take place in the middle part of the sheet and are about 6.8 mm.

2. The dynamic loading on the hatch cover was studied and its strength was calculated under the main load modes. It was established that the acceleration acting on the hatch cover is about 4.5 m/s^2. The resulting acceleration value is almost 20 % lower than that acting on a typical hatch cover.

The results of calculating the strength of the hatch cover under load mode I showed that the maximum stresses occur in the hinges and are 163.8 MPa. However, these stresses are lower than permissible ones by 22 %. The maximum movements in the hatch cover occur in the locking brackets and amount to 3.3 mm.

The maximum stresses in the hatch cover under load mode II occur in the hinges and amount to 195.1 MPa. The resulting stresses are 7 % lower than permissible ones. The maximum movements take place in the locking brackets and are equal to 3.6 mm. Therefore, the strength of the hatch cover under the considered load modes is maintained.

3. The basic indicators for the dynamics of an open car equipped with the improved structure of hatch covers have been determined. The maximum accelerations in the center of mass of the supporting structure of the open car amounted to 4.6 m/s^2 and occur at the moment of its passage over the contact bump. Further, these accelerations decrease, and their value is about 2.5 m/s^2. The acceleration of the bogies was about 6 m/s^2. The forces in the spring suspension of the bogie when it passes through the bump are equal to 43.4 kN. The coefficient of vertical dynamics of the open car was about 0.6. At the same time, the movement of the open car 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 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 presented work.

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