The object of the research is the processes of occurrence, perception, and redistribution of loads in the load-bearing structure of an open wagon body, taking into account the use of an intermediate adapter.

To reduce the vertical dynamic loads acting on the supporting structure of the railroad car, it is suggested to use an intermediate adapter between the frame and the load. The dynamic load of the supporting structure of the open wagon was modeled, taking into account the use of an intermediate adapter. The research was carried out in the vertical plane during the oscillations of the bouncing of the car. The results of the calculations showed that the acceleration acting in the center of mass of the supporting structure of the open wagon is 4.2 % lower than that acting on the supporting structure of the open wagon without using an adapter. The obtained acceleration results are taken into account when determining the strength of the supporting structure of the open wagon. It was established that the use of an intermediate adapter contributes to the reduction of stresses in the supporting structure of the open wagon by 6 % compared to the typical scheme of cargo transportation.

A feature of the results is that the proposed solution to reduce the dynamic load of the supporting structure of the car can be implemented without improving its design.

The field of practical use of the results is the engineering industry, in particular, railroad transport. The conditions for the practical use of the research results are the placement of the adapter over the entire floor area of the car body.

The research will contribute to devising recommendations on reducing the load on the load-bearing structures of cars, the costs of their unplanned repairs, and to increasing the efficiency of railroad transport operation

Keywords: railroad transport, intermediate adapter, open wagon strength, open wagon dynamic loading, cargo safety

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DETECTING THE EFFECT OF AN INTERMEDIATE ADAPTER ON THE LOAD OF THE BEARING STRUCTURE OF AN OPEN WAGON

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1. Introduction

Ensuring a sustainable economy of Eurasian states depends on the coordinated and reliable operation of the transport industry [1–3], the most priority component of which is railroad transport. Currently, all types of cargo are transported by railroad, which determines the demand for its services in the transportation segment.

One of the most important factors that affects the work of the railroad industry is the availability of technically serviceable rolling stock. The freight fleet consists of cars of different design and processing technology. However, the largest percentage of the fleet is formed by semi-trailers. This type of car is used mostly for transporting goods that do not require protection from atmospheric precipitation. Along with this, taking into account the relevant modernizations, it is possible to use it for the transportation of goods that need shelter from precipitation.

Replenishment of the car fleet with certain types of cars requires appropriate capital investments. Therefore, from an economic point of view, it is more appropriate to implement technical solutions aimed at extending the life of the existing fleet. One of these solutions is to reduce the load on the load-bearing structures of cars in operation, in particular dynamic ones. The cyclicity of the action of these loads is due to the peculiarities of the operation of cars (transient modes of movement, joint unevenness, etc.). Under the conditions of their constant action, damage to the components of the car structure may occur. Such damage on the way of the train is especially dangerous as it threatens traffic safety. In this regard, there is a need to devise measures to reduce the load on the load-bearing structures of cars in operation.

2. Literature review and problem statement

Many papers report research into the improvement of load-bearing structures of vehicles in order to reduce their load during operation. For example, in order to reduce the transverse dynamic loads acting on the walls of an open wagon, [4] suggested the use of sandwich panels. Such panels are removable, which makes it possible to replace them if the car needs to be repaired. The proposed improvement is also appropriate at the stage of modernization of the car. At the same time, such a solution requires additional capital investments to improve the load-bearing structures of cars.

The justification for the introduction of sandwich components in the construction of a railroad vehicle is given in article [5]. The authors present an algorithm for optimizing the load-bearing structure of the vehicle. The results of the calculations showed that this implementation helps reduce the weight of the supporting structure by more than 16 % compared to the prototype. However, the authors did not consider the possibility of reducing the vertical load of the vehicle.

In order to improve the strength indicators of a railroad car, the creation of its components in the form of multilayer elements is proposed in [6]. The article provides an implementation option for this advancement. The prospects of further research in the specified direction are highlighted and the expediency of using such a car design in operation is substantiated. It must be said that this design solution contributes to improving the strength of the structure but not the safety of the cargo transported in it.

In order to ensure the safety of transported goods in railroad cars, paper [7] proposed the introduction of extruded aluminum panels into their construction. The main design features of the panels and the method of their mounting on the car are specified. However, such a solution does not contribute to reducing the dynamic load of the car, and accordingly, the cargo, in the vertical plane.

In [8], the expediency of using sandwich panels as components of a freight car body is considered. At the same time, the authors investigated the possibility of using them instead of lining the side walls of the body. The peculiarity of the proposed improvement is that it is expedient not only during the manufacture of cars but also during modernization. In contrast to work [8], paper [9] proposed the introduction of composite panels in the construction of railroad vehicles. The rationale for the proposed implementation is proven by increasing the durability of vehicle bodies in operation. However, the authors of works [8, 9] did not investigate the possibility of using such panels as components of the floor of vehicles. After all, vertical oscillations are one of the most common in the operation of cars and contribute to cyclic loading of their structures, which negatively affects strength.

In study [10], a solution was proposed to reduce the load of a modular vehicle during operational modes. This is achieved by introducing flexible connections into its construction. The feasibility of such a solution is confirmed by the results of mathematical and computer modeling. However, this implementation contributes to reducing the longitudinal load of the vehicle, not the vertical.

The implementation of flexible connections in the load-bearing structure of vehicles to reduce their load was also studied in [11]. At the same time, the authors proposed the use of sandwich panels as components of the floor of the car. The calculation was carried out on the example of a platform car. In this case, the implementation of such a solution requires significant capital investments, which may hinder its implementation.

Our review of the literature [4–11] shows that improving the load-bearing structures of vehicles to reduce their load in operation is relevant. However, it is important to say that due attention has not yet been paid to measures to reduce the vertical load of cars under the action of cyclic loads. Therefore, there is a need to conduct relevant research in the specified area.

3. The aim and objectives of the study

The purpose of this study is to identify the influence of the intermediate adapter on the loading of the load-bearing structure of an open wagon during fluctuations in the vertical plane. This will contribute to the reduction of the vertical load on the load-bearing structures of cars in operation, the improvement of their strength indicators, as well as the reduction of their maintenance costs.

To achieve this goal, the following tasks are defined:

– to determine the strength of the intermediate adapter when vertical loads are applied to it;

– to determine the dynamic load of the supporting structure of an open wagon, taking into account the use of an intermediate adapter;

– to determine the main indicators of the strength of the supporting structure of an open wagon.

4. The study materials and methods

The object of our research is the processes of occurrence, perception, and redistribution of loads in the load-bearing structure of an open wagon body, taking into account the use of an intermediate adapter.

The main hypothesis of the research assumes that the reduction of the vertical load of the supporting structure of the open wagon and the cargo placed in it is possible due to the use of an intermediate adapter between them.

To reduce vertical dynamic loads acting on the load-bearing structure of a railroad car, it is suggested to use an intermediate adapter between the frame and the load (Fig. 1).

A special feature of the adapter is that it consists of two metal sheets 1 (Fig. 2), between which a layer 2 of energy-absorbing material is placed. Thanks to this solution, the dynamic loads acting on both the car frame and the cargo placed in it during operational modes are reduced. The side parts of the adapter have elliptical cutouts to limit the movement of the energy-absorbing material within the dimensions of the adapter.

The thickness of the adapter sheets is determined on the condition that they represent a plate that perceives a concentrated load (Fig. 3).

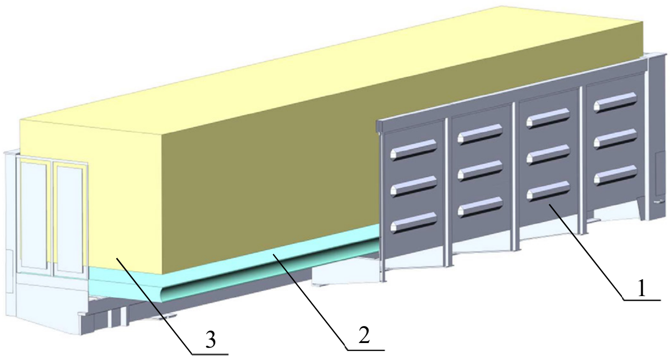

Fig. 1. Placement of the adapter in an open wagon body: 1 — open wagon body; 2 — adapter; 3 — cargo

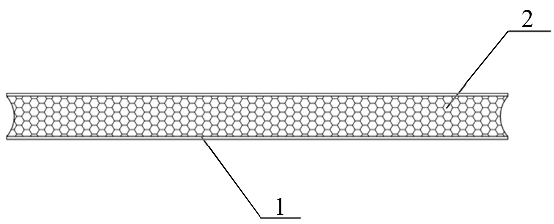

Fig. 2. Cross-section of the intermediate adapter: 1 — metal sheet; 2 — a layer of energy-absorbing material

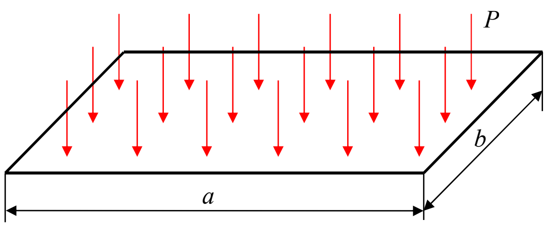

Fig. 3. Plate design diagram

Taking this into account, with a known material for making the plate, its thickness will be [12]:

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

where P is the load acting on the plate; a – plate width; b – plate height; μ is Poisson's ratio; σ – permissible stresses of the plate material.

The calculation is implemented on the example of a universal open wagon, model 12-757, the floor of which is formed by the covers of the unloading hatches. It was established that with P=69 t, a=12.228 m, b=2.964 m, and the physical and mechanical properties of steel grade 09G2S, the thickness of the plate will be about 18.0 mm.

The results are taken into account when determining the strength of the intermediate adapter. The calculation is implemented using the finite element method, as the most common method currently used in the engineering industry.

At the next stage of the research, the dynamic loading of the open wagon was determined, taking into account the use of an intermediate adapter. For this purpose, a mathematical model has been built that characterizes the vertical movements of the body during bounce oscillations. At the same time, the car is considered as a system formed by four bodies: a body, two bogies (model 18–100), and a cargo placed in the body. It is assumed that the rail track has elastic characteristics [13, 14]. At the same time, the adapter is considered as a component of the supporting structure of the open wagon, which completely repeats its movement trajectory. It is assumed that the energy-absorbing material placed in the adapter has elastic-frictional properties.

The solution of the mathematical model was carried out in the Mathcad software package (USA) [15–17] using the Runge-Kutta method [18–21]. This method was chosen as a calculation method due to the fact that it allows obtaining sufficient accuracy in theoretical calculations. The resulting accelerations, as components of the dynamic load, are taken into account when determining the strength of an open wagon body.

5. Results of studying the influence of the intermediate adapter on the loading of the load-bearing structure of an open wagon

5. 1. Determining the strength of the intermediate adapter under the action of vertical loads on it

Appropriate calculations were performed to determine the strength of the adapter. To this end, its spatial model was built in SolidWorks (France) (Fig. 4), and the strength calculation was carried out in SolidWorks Simulation (France) [22, 23], which implements FEM analysis.

Tetrahedrons were used in the construction of the finite element model [24, 25]. Their optimal number is determined by the graph-analytical method [26, 27]. Taking this into account, the number of model elements was 52,077, and nodes – 11,561. The maximum element size is 140 mm, the minimum is 46 mm.

Fixation of the model is carried out by the bottom sheet. In this way, its leaning on the floor of an open wagon was simulated. A vertical load P was applied to the upper sheet of the adapter, which was taken to be equal to 69 tons, that is, the usable load of the body (Fig. 5).

09G2S steel was used as the sheet material. The energy-absorbing material is considered on the example of aluminum foam with the properties specified in [28].

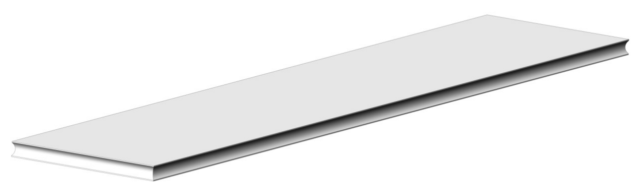

Fig. 4. Spatial adapter model

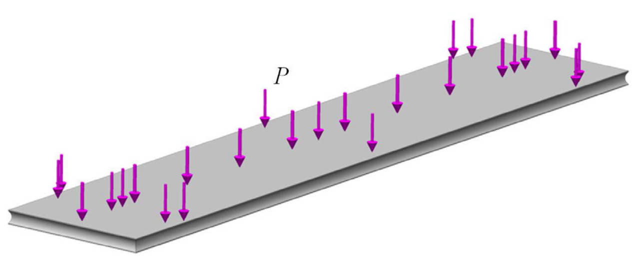

Fig. 5. Adapter design diagram

The results of the calculation showed that the maximum stresses in the adapter occur in its corner parts and amount to about 180 MPa (Fig. 6) and do not exceed the allowable ones 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 foreign analog of this standard is EN 12663-2. Railroad applications – structural requirements of railroad vehicle bodies – Part 2: Freight cars. These stresses take place in its upper sheet. In the lower sheet, stresses have insignificant values. This situation is due to the fact that the adapter was attached to the bottom sheet.

The maximum movements in the design of the adapter take place in its console parts and amount to 1.86 mm (Fig. 7).

The calculation allows us to conclude that the strength of the adapter is ensured.

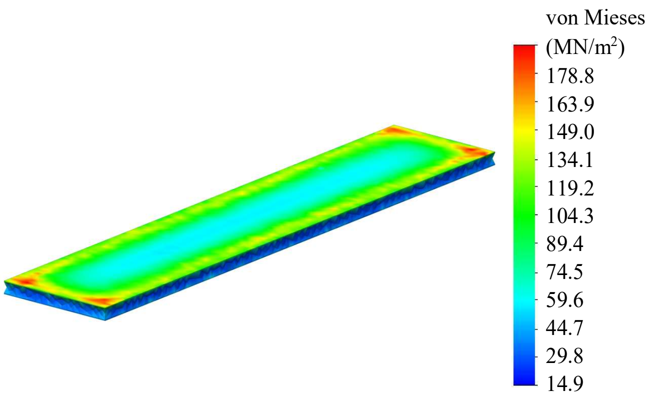

Fig. 6. Adapter stressed state

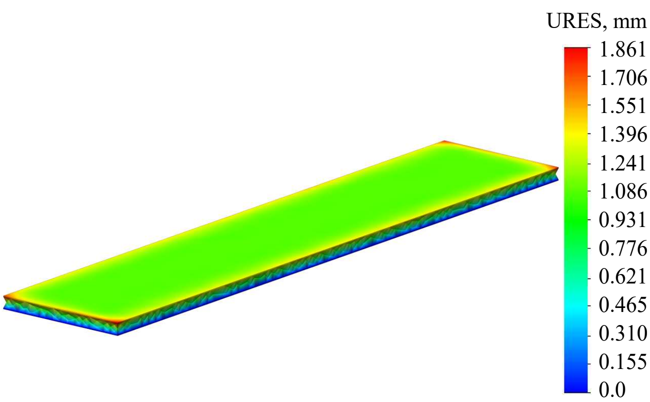

Fig. 7. Movement in the adapter design

5. 2. Determining the dynamic load of the supporting structure of an open wagon, taking into account the use of an intermediate adapter

To determine the dynamic loading of an open wagon body, taking into account the use of the adapter, modeling of its movements in the vertical plane during movement along the joint rail track was carried out (Fig. 8).

The movement of an open wagon is described by a system of second-order differential equations:

$$\begin{cases} M_1 \cdot \ddot{q}_1 + C_{1,1} \cdot q_1 + C_{1,2} \cdot q_2 + C_{1,3} \cdot q_3 = \\ = -F_{FR} \cdot \left(\text{sign}\left(\dot{\delta}_1\right) + \text{sign}\left(\dot{\delta}_2\right)\right) + F_z, \\ M_2 \cdot \ddot{q}_2 + C_{2,1} \cdot q_1 + C_{2,2} \cdot q_2 + B_{2,2} \cdot \dot{q}_2 = \\ = F_{FR} \cdot \text{sign}\left(\dot{\delta}_1\right) + k\left(\eta_1 + \eta_2\right), \\ M_3 \cdot \ddot{q}_3 + C_{3,1} \cdot q_1 + C_{3,3} \cdot q_3 + B_{3,3} \cdot \dot{q}_3 = \\ = F_{FR} \cdot \text{sign}\left(\dot{\delta}_2\right) + k\left(\eta_3 + \eta_4\right), \\ M_4 \cdot \ddot{q}_4 = F_z - M_4 \cdot g, \end{cases} \quad (2)$$

where M_1 – mass of the supporting structure of the open wagon; M_2, M_3 – mass, respectively, of the first and second bogie; C_{ij} are the elasticity characteristics of the oscillating system elements, which are determined by the stiffness coefficients of the springs of the spring suspension k_S; k – track stiffness; B_{ij} – dissipative coefficients; β – damping coefficient; F_{FR} – force of friction in the spring set of the bogie; δ_i – deformations of elastic elements of spring suspension; η_i – track unevenness; F_z is the force that occurs when the load is moved relative to the car body.

The solution of the system of differential equations was carried out in the Mathcad software package. The initial movement of the body is taken to be equal to 0.004 m, and the bogies to 0.003 m. The speeds of these movements are set to zero.

The results of our calculations are shown in Fig. 9–12.

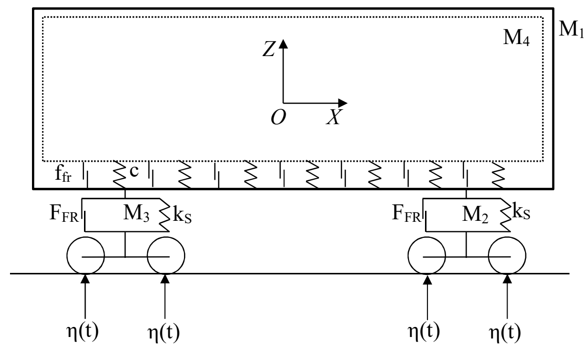

Fig. 8. Design diagram of open wagon

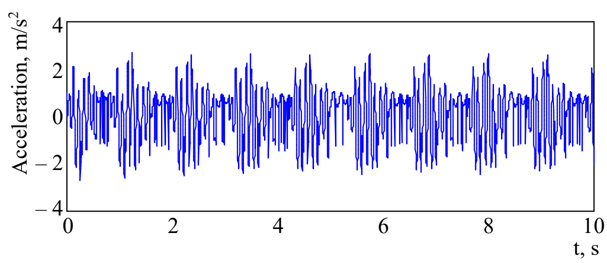

Fig. 9. Accelerations acting in the center of mass of the load-bearing structure of an open wagon

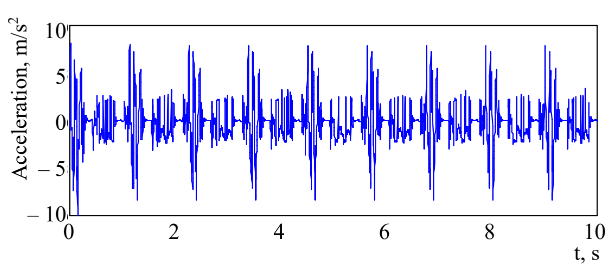

Fig. 10. Accelerations acting on the first bogie of an open wagon

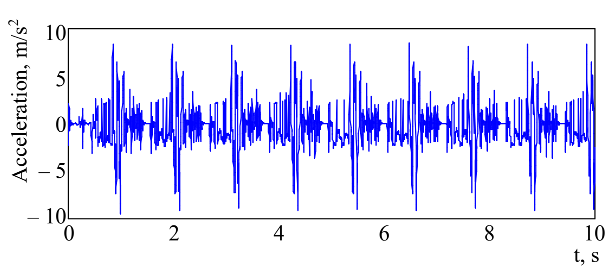

Fig. 11. Accelerations acting on the second bogie of the open wagon in the direction of travel

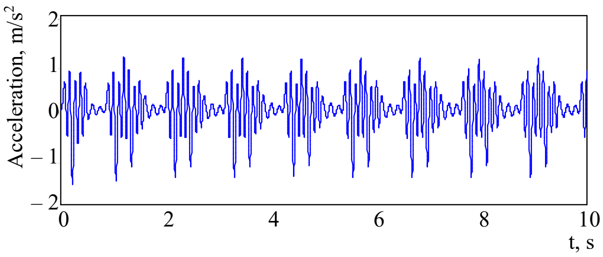

Fig. 12. Accelerations that act on cargo placed in an open wagon

Analyzing the obtained dependences, it can be concluded that the acceleration acting in the center of mass of the supporting structure of the open wagon is about 2.4 m/s^2 (Fig. 9). The resulting acceleration value is 4.2 % lower than that acting on the supporting structure of the open wagon without the use of an adapter. The acceleration acting on the first moving bogie is about 10 m/s^2 (Fig. 10). The same amount of acceleration acts on the second bogie (Fig. 11), but with some delay. The acceleration acting on the load was 1.7 m/s^2 (Fig. 12). The resulting acceleration is less than that acting on the load without using an intermediate adapter by 3.8 %.

5. 3. Determining the main strength indicators of the load-bearing structure of an open wagon

The results of dynamic loads are taken into account when calculating the strength of the supporting structure of an open wagon. To this end, its spatial model was built in SolidWorks and the strength calculation was carried out in SolidWorks Simulation.

The calculation diagram of the supporting structure of the open wagon is shown in Fig. 13. It is taken into account that it tests the vertical static load P_{st} caused by its natural weight, as well as the vertical dynamic P_d that occurs during oscillations. The finite element model of the supporting structure of the open wagon was built by 355568 with a maximum size of 100 mm and a minimum size of 20 mm. The number of model nodes is 117433.

Fixation of the 3-D model was carried out by hinges. The construction material is 09G2S steel.

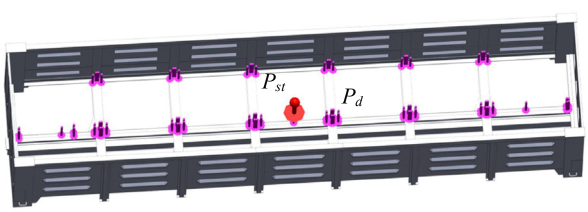

Fig. 13. Design diagram of open wagon

The results of our calculations are shown in Fig. 14, 15. The maximum stresses were 120.5 MPa (Fig. 14). They were recorded in the zones of interaction of the girder beam with the pivot beam. In Fig. 15, these zones are shown in blue. The resulting stresses are 6 % lower than those occurring in a typical open wagon construction.

The maximum displacements occur in the middle part of the girder beam and are 3.3 mm (Fig. 16).

This is due to the fact that the body is fixed by the heels, and the load is distributed along the length of the frame.

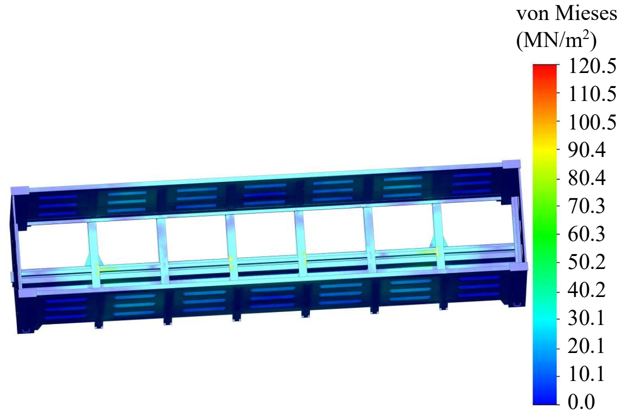

Fig. 14. Stressed state of the load-bearing structure of an open wagon

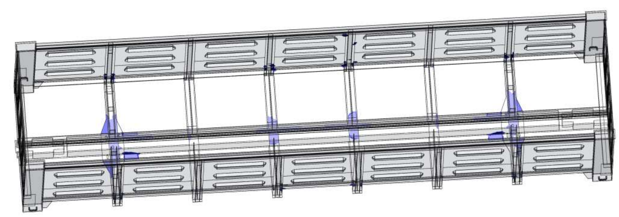

Fig. 15. Zones of concentration of the greatest stresses in the load-bearing structure of an open wagon

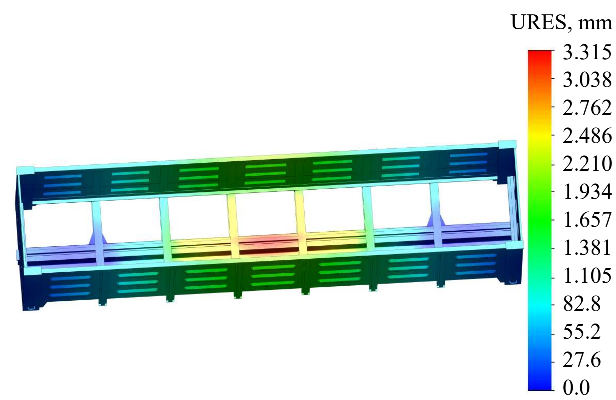

Fig. 16. Movement in the load-bearing structure of an open wagon

6. Discussion of results of studying the influence of the intermediate adapter on the load bearing structure of an open wagon

In order to reduce the dynamic load of the supporting structure of the car, as well as to ensure the safety of the cargo, it is proposed to use an intermediate adapter (Fig. 1). The reduction of dynamic loads is carried out due to the dissipative forces that arise in the adapter when the car bounces.

The design of the adapter includes two metal sheets, between which there is a layer of energy-absorbing material (Fig. 2). The thickness of the adapter sheets, which ensures its strength, is determined. The strength of the adapter was calculated using the finite element method. It was established that the maximum stresses in the adapter occur in its corner parts and amount to about 180 MPa (Fig. 6). The stress data is recorded in its upper sheet.

Mathematical modeling was carried out to determine the dynamic loads acting on the load-bearing structure of the open wagon, taking into account the use of an intermediate adapter. It is assumed that the rail track has elastic characteristics. At the same time, the adapter is considered as a component of the supporting structure of the open wagon, which completely repeats its movement trajectory. It is also assumed that the energy-absorbing material placed in the adapter has elastic-frictional properties. It was established that the acceleration acting in the center of mass of the supporting structure of the open wagon was about 2.4 m/s^2 (Fig. 9). It is important to say that the obtained acceleration value is 4.2 % lower than that acting on the supporting structure of the open wagon without the use of an adapter.

The results of dynamic loads are taken into account when calculating the strength of the supporting structure of the open wagon. The maximum stresses were 120.5 MPa (Fig. 14). They arise in the zones of interaction of the girder beam with the pivots.

The limitation of this study is that it was carried out for the case of using model 18-100 bogies with single-stage spring suspension under the car.

As a drawback of the research, it should be noted that at this stage we did not take into account the galloping oscillations of the open wagon when modeling its vertical load.

The advantage of this study in comparison with [4, 5, 7–9] is that we proposed solutions aimed at reducing the vertical load of the supporting structure of the car, as for the most common type of oscillations in operation. In contrast to work [6], in order to ensure the strength of the supporting structure of the car, we proposed not to strengthen it but to reduce the dynamic load. In comparison with works [10, 11], the proposed solution to reduce the dynamic load of the supporting structure of the car can be implemented without its improvement.

The further development of the research is the experimental modeling of the loading of an open wagon, taking into account the use of an intermediate adapter between its supporting structure and the load. This is planned to be carried out by the method of similarity under laboratory conditions.

Our research will contribute to devising recommendations on reducing the load on the load-bearing structures of cars, the costs of their unplanned repairs, and to increasing the efficiency of railroad transport operation.

7. Conclusions

1. The strength of the intermediate adapter when vertical loads are applied to it was determined. It was established that the maximum stresses in the adapter occur in its corner parts and amount to about 180 MPa. These stresses take place in its upper sheet. In the lower sheet, stresses have insignificant values. The maximum movements in the design of the adapter take place in its console parts and amount to 1.86 mm.

2. The dynamic load of the supporting structure of the open wagon was determined, taking into account the use of an intermediate adapter. At the same time, the acceleration acting in the center of mass of the supporting structure of the open wagon is about 2.4 m/s^2. The resulting acceleration value is 4.2 % lower than that acting on the supporting structure of the open wagon without the use of an adapter. The acceleration acting on the first moving bogie is about 10 m/s^2. The same amount of acceleration acts on the second bogie, but with some delay. The acceleration acting on the load was 1.7 m/s^2.

3. The main indicators of the strength of the supporting structure of the open wagon were determined. The maximum stresses were recorded in the zones of interaction of the girder beam with hinges and amounted to 120.5 MPa. It must be said that the resulting stresses are 6 % lower than those occurring in a typical design of an open wagon. The maximum displacements occur in the middle part of the girder beam and amount to 3.3 mm.

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.

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Use of artificial intelligence

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

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