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DETERMINING THE STRENGTH OF A FRAME IN A RAILROAD OPEN WAGON WITH SLINGS IN ITS STRUCTURE TO IMPROVE ITS OPERATIONAL ENERGY EFFICIENCY

Alyona Lovska
Corresponding author
Doctor of Technical Sciences, Professor
Department of Wagon Engineering and Product Quality
Ukrainian State University of Railway Transport
Feuerbakh sq., 7, Kharkiv, Ukraine, 61050
E-mail: alyonaLovskaya.vagons@gmail.com
Iraida Stanovska
Doctor of Technical Sciences, Professor
Department of Advanced Mathematics and Systems Modelling
Odesa Polytechnic National University
Shevchenko ave., 1, Odesa, Ukraine, 65044
Yevhen Pelypenko
PhD, Associate Professor
Department of Car and Tractor Industry
National Technical University «Kharkiv Polytechnic Institute»
Kyrpychova str., 2, Kharkiv, Ukraine, 61002
Hanna Barsukova
PhD, Associate Professor*
Oleksandr Yurchenko
Senior Lecturer*
*Department of Energy and Electrical Systems
Sumy National Agrarian University
H. Kondratieva str., 160, Sumy, Ukraine, 40021

This study's object is the processes related to load acceptance and redistribution within the frame of a railroad open wagon with slings in the structure under operational loads. The task addressed in the study is to reduce the loading on the open wagon frame during operation by installing slings in its cantilever parts.

To substantiate this technological advancement, the strength of an open wagon frame was calculated under the basic load schemes in operation. The dynamic loads acting on the open wagon frame were determined by mathematical modeling. The strength calculations performed showed that the maximum stresses in the railroad open wagon frame occur under the first design mode. However, these stresses are 6% lower than those that occur in a typical frame structure.

In addition, within the framework of the study, the strength of a railroad open wagon frame was calculated while transported by railroad ferry. The calculation results showed that the strength of the open wagon frame is ensured. The estimated stresses are 4% lower than those in the typical structure of an open wagon frame.

A feature of the proposed technological advancement is that its implementation is feasible at the stage of wagon modernization, rather than only during the manufacture of new structures.

The area of practical use of the results is railroad transport.

A condition for the practical implementation of this study's results is to link the sling to the areas of arranging the front and rear stops of auto couplers.

The results of the research will contribute to improving the strength of the supporting structures in open wagons during operation and reducing the costs of their maintenance. The findings could also contribute to the design of freight wagons with improved technical and economic indicators

Keywords: railroad transport, railroad open wagon, open wagon frame, frame improvement, frame strength, structural energy efficiency

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1. Introduction

Ensuring a sustainable and uninterrupted transportation process of goods by rail necessitates the implementation of solutions to improve the technical and economic performance of vehicles [1, 2]. A wide variety of wagons with different structural features are used for the transportation of goods by rail. However, one of the most widely used among them is a railroad open wagon. This is due to its versatility and the ability to adapt to the transportation of a wide range of goods. That also predetermines different load patterns on the supporting structure of the open wagon during operation, which can be explained by the characteristics of goods transported in it. The most loaded unit of the supporting structure in the open wagon is the frame. During operation, it accepts significant loads that can cause damage. One of the most critical kinds of damage to the frame is its girdle beam damage as it is the main supporting element in the frame. Such damage along the route is quite dangerous and can cause an accident or catastrophe, contributing not only to the death of people but also to damage to vehicles. In addition, the specified damage is quite dangerous from the point of view of ecology [3]. This can be explained by the fact that hazardous substances are also transported by railroad quite often. Their release into the environment is quite dangerous. In the case of transporting such goods by sea on railroad ferries, the threat to the environment increases. After all, the loads acting on wagons during railroad-ferry transportation significantly exceed those that occur during operation on railroad tracks. In this regard, there is a need to devise and implement solutions that could help reduce the load on the open wagon frame.

Therefore, it is a relevant task to carry out studies to determine the strength of a open wagon frame with slings in the structure in order to improve the energy efficiency of its operation.

2. Literature review and problem statement

To improve the strength of the frame in a railroad wagon, in work [4] it was proposed to use beams with corrugated walls as a profile for the girdle beam of the frame. The features of the selection of the parameters for such a beam were highlighted, as well as the results of frame calculation for strength. It was found that the proposed solution helps reduce the stresses in the frame of the wagon by 4.4% compared to its typical structure. However, the study was conducted on the example of a passenger wagon frame. That is, the authors did not pay attention to the feasibility of introducing such beams into the frame of a open wagon. This can be explained by the fact that the frame of a passenger wagon has a length of 23.6 m, which contributes to its cyclic loading in operation. Therefore, the authors paid attention to improving the frame of the passenger wagon itself.

The study reported in [5] also justifies the use of beams with corrugated walls as a profile for the girdle beam of a passenger wagon. The results of the calculation of the wagon body for strength, as well as its modal analysis, proved that such an implementation is justified. However, the work has similar shortcomings to [4].

The use of standard thin-walled steel profiles in the structures of railroad vehicles is substantiated in [6]. The work provides examples of the use of such profiles. The prospects for their application in mechanical engineering are indicated. However, the work does not provide solutions for improving the frame of an open wagon, which is the most common type of wagon in operation.

To improve the strength of the load-bearing structure of a freight wagon, in [7] it was proposed to introduce sandwich components into its design. The feasibility of the proposed improvement was confirmed by testing the wagon, which proved that the use of honeycomb panels helps improve the strength of the load-bearing structure of the body. However, such implementation does not help reduce the load on the wagon frame. Probably, the introduction of honeycomb panels as components of the wagon floor could help improve the strength of the frame. However, the authors did not conduct such studies.

To improve the strength of the freight wagon frame, in [8] it was proposed to design its structure in the form of "egg crates". The justification of the proposed solution and the prospects for its use in freight wagon designs are given. However, the authors did not consider the possibility of its use in open wagon frame structures. This can be explained by the fact that the authors chose a tank wagon as the object of their study. This choice is justified by the fact that the presence of a free cargo surface causes additional loading of the tank wagon boiler during operation. Therefore, the authors studied that specific type of wagon.

In work [9], in order to enhance the strength of freight wagons, it is proposed to introduce new materials with improved characteristics as the material of their structural components. The study was conducted on the example of magnesium alloys. It is proven that the use of such material contributes not only to reducing the wagon's packaging but also to improving its strength characteristics. But the authors did not consider the feasibility of introducing such materials for the manufacture of the wagon frame. This is explained by the fact that the use of magnesium alloys as body components can be carried out not only in the manufacture of new wagons but also during their modernization. This circumstance contributes to the simplification of the implementation of the proposed solution into operation.

A similar drawback is also found in [10], in which the use of extruded aluminum panels as components of the wagon body structure is proposed. Naturally, such a solution helps improve the strength of the body at operation. However, it is quite expensive and requires the establishment of an appropriate base for technical maintenance and repair of wagons. In addition, the authors did not study the possibility of using such panels to improve the strength of the wagon frame.

In order to improve the strength of the open wagon's supporting structure under operational loads, in work [11] it was proposed to use an intermediate adapter between it and the cargo. This adapter acts as a removable module that transfers a uniformly distributed load to the floor of the body from the transported cargo. The results of calculating the strength of the open wagon's supporting structure proved the correctness of the hypothesis put forward regarding improving the strength of the open wagon body. However, this solution does not help improve the strength of the open wagon frame, but only of the body.

Our review of the literature [4–11] demonstrates that existing technological advancements related to the issues of improving wagons mostly concern the introduction of new materials into their structure or changes in their manufacturing profiles. This requires significant capital investments at the stage of manufacturing and operation of wagons. Therefore, there is a need to conduct further research on improving the supporting structures of open wagons during operation.

3. The aim and objectives of the study

The purpose of our study is to determine the strength of a open wagon frame with slings in the structure to improve its operational energy efficiency. This will reduce damage to open wagon frames during operation and, accordingly, decrease the cost of their maintenance.

To achieve this goal, the following tasks have been set:

– to conduct mathematical modeling of the dynamic loading on an open wagon frame with slings in the structure;

– to calculate the strength of the open wagon frame under the basic operating load modes;

– to calculate the strength of the open wagon frame when transported by rail ferry.

4. The study materials and methods

The object of our study is the processes of load acceptance and redistribution in the frame of an open wagon with slings in the structure when accepting operational loads.

The principal hypothesis of the study assumes that the use of slings in the structure of an open wagon frame could contribute to reducing its loading during operation.

To reduce stresses in the most loaded areas of the open wagon frame, it is proposed to install slings in its cantilever parts (Fig. 1). These elements work on the principle of braces in the frame of a flat wagon, that is, they remove part of the loads from the girdle beam and transfer them to the pivot beam.

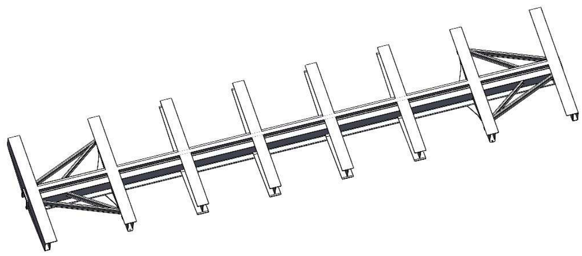

Fig. 1. Spatial model of an open wagon frame with slings in the end parts

The braces that form the sling connect the front stops with the pivot beam, as well as the rear stops with the pivot beam. The sling's profile is an I-beam No. 14, i.e., the same as the profile of the braces in a flat wagon frame.

To substantiate the introduction of slings as a structural element in the open wagon frame, we calculated its strength. Graphical work on designing the frame was performed using SolidWorks (France), and the calculation itself – SolidWorks Simulation, which implements finite element analysis [12, 13]. The Mises criterion was used as the calculation criterion [14–16]. This choice is justified by the fact that the frame construction material has linear isotropic properties. The calculation was performed using the example of a open wagon frame of model 12-757. The calculation scheme of the open wagon frame is shown in Fig. 2. It includes the following loads: vertical load P_v, which is a combination of static and dynamic loads, as well as longitudinal load P_l.

The vertical static load was taken into account for the case of the maximum permissible loading of the wagon, that is, when using the maximum load capacity.

The vertical dynamic load was determined for the movement of an open wagon over a rail unevenness. For this purpose, mathematical modeling of the dynamics of the open wagon was carried out. The bouncing oscillations, vertical movements of the wagon, were taken into account. It was taken into consideration that the calculation scheme is formed by three bodies – the supporting structure of the open wagon, as well as two bogies of model 18-100. The friction forces between the stops of the supporting structure of the open wagon and the bogie bearings were not taken into account [17, 18]. The movement of the wagon over a butt rail unevenness, which has elastic-dissipative characteristics, was studied.

The mathematical model was solved in the Mathcad software package (USA). For this purpose, the system of equations was reduced to the Cauchy normal form. After that, we solved it by using the Runge-Kutta method [19–21].

The longitudinal load was applied to the auto coupler stops (front or rear), depending on the studied design mode. On the opposite side of the frame, this load was balanced by the inertia forces of the bogie masses.

The model was fixed to the horizontal surfaces of the stop wheels. The frame material was 09G2S steel, which is typical for the manufacture of open wagon frames. This steel grade has permissible stresses for design mode I – 310.5 MPa, and for III – 210 MPa. These stress values were determined on the basis of the regulatory document DSTU 7598:2014. Freight wagons. General requirements for calculations and design of new and modernized 1520 mm gauge wagons (non-self-propelled). An analog of this document is the international standard: "EN 12663-2. Railroad applications – structural requirements of railroad vehicle bodies – Part 2: Freight wagons".

In addition, the study determined the strength of a open wagon frame of the improved design when transported by a railroad ferry. For this purpose, it is proposed to install nodes on the open wagon frame for securing chain ties (Fig. 3). The installation of these nodes is assumed on the pivot beams.

The calculation was carried out for the case of a side sway of a railroad ferry. This type of oscillation has the greatest impact on the stability of the wagon relative to the deck; therefore, it was chosen as the determining one. The calculation scheme of the frame is shown in Fig. 4.

It was taken into account that the frame accepts vertical load P_v. Load P_{ch} was applied to the nodes for fastening the chain ties. The features of determining this load and its application to the supporting structure in a open wagon are highlighted in work [22].

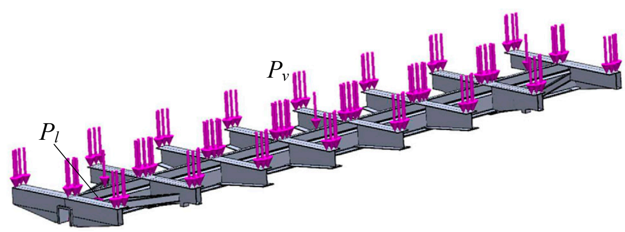

Fig. 2. Calculation diagram of the open wagon frame

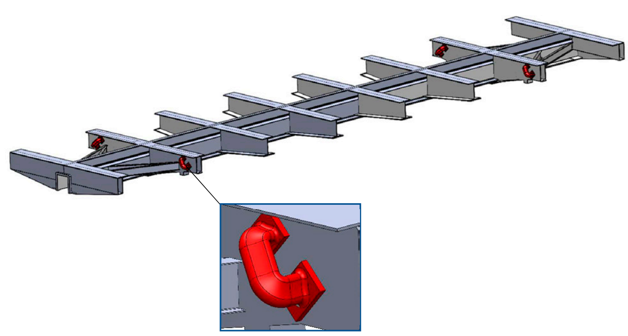

Fig. 3. Spatial model of the open wagon frame with nodes for securing chain ties

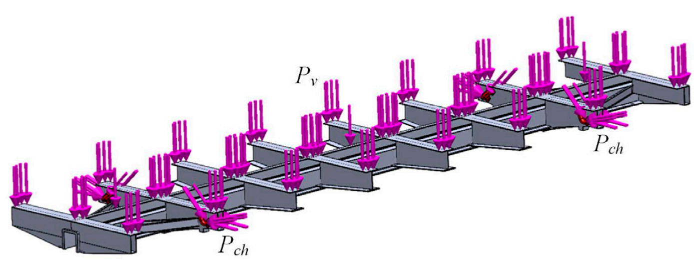

Fig. 4. Calculation diagram of the open wagon frame with nodes for fastening chain ties

5. Results of analyzing the loading on the frame of a open wagon with slings in the structure when accepting operational loads

5. 1. Results of the mathematical modeling of dynamic loading on the frame of a open wagon with slings in its structure

To determine the dynamic loads acting on the frame of a open wagon with slings in its structure, we mathematically modeled its dynamics when moving over a joint unevenness. The calculation scheme of the open wagon is shown in Fig. 5.

The equations of motion of the open wagon take the form

$$\begin{cases} M_1 \cdot \frac{d^2}{dt^2} q_1 + C_{1,1} \cdot q_1 + C_{1,2} \cdot q_2 + C_{1,3} \cdot q_3 = \\ = -F_{FR} \cdot \left(\text{sign}\left(\frac{d}{dt} \delta_1 \right) + \text{sign}\left(\frac{d}{dt} \delta_2 \right) \right), \\ M_2 \cdot \frac{d^2}{dt^2} q_2 + C_{2,1} \cdot q_1 + C_{2,2} \cdot q_2 + B_{2,2} \cdot \frac{d}{dt} q_2 = \\ = F_{FR} \cdot \text{sign}\left(\frac{d}{dt} \delta_1 \right) + k_1(\eta) + \beta_1 \left(\frac{d}{dt} \eta \right), \\ M_3 \cdot \frac{d^2}{dt^2} q_3 + C_{3,1} \cdot q_1 + C_{3,3} \cdot q_3 + B_{3,3} \cdot \frac{d}{dt} q_3 = \\ = F_{FR} \cdot \text{sign}\left(\frac{d}{dt} \delta_2 \right) + k_1(\eta) + \beta_1 \left(\frac{d}{dt} \eta \right), \end{cases} \quad (1)$$

where M_1, M_2, M_3 are inertia coefficients that characterize, respectively, the mass of the supporting structure of the open wagon, as well as the masses of the first and second bogies; C_{ij} is the elasticity characteristic of the elements that form the vibration system and is determined by the stiffness of the spring suspension of the bogies; B_{ij} is the dissipation function (energy dissipation); β_1 is the damping coefficient; k_1 is the track stiffness; F_{FR} is the friction force that occurs in the spring suspension of the bogies during vibration; η is the joint unevenness; q_i is the generalized coordinates corresponding to the displacements of the elements of the vibration system in the vertical plane.

The starting conditions are as follows:

– the initial displacement of the supporting structure in a open wagon body is 0.004 m, and of the bogies – 0.003 m [23];

– the initial velocities of the elements in the vibration system are taken to be zero.

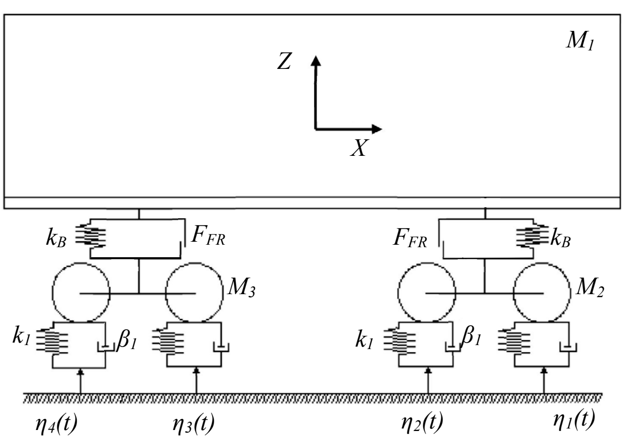

Fig. 5. Calculation scheme of an open wagon

The accelerations acting on the supporting structure of the open wagon were calculated in array $ddq_{j,i}$:

$$ddq_{j,1} = \frac{-F_{FR} \cdot \left(\text{sign}\left(\frac{d}{dt} \delta_1 \right) + \text{sign}\left(\frac{d}{dt} \delta_2 \right) \right) - C_{1,1} \cdot y_1 - C_{1,2} \cdot y_2 - C_{1,3} \cdot y_3}{M_1}, \quad (2)$$

$$ddq_{j,2} = \frac{F_{FR} \cdot \text{sign}\left(\frac{d}{dt} \delta_1 \right) + k_1(\eta) + \beta_1 \left(\frac{d}{dt} \eta \right) - C_{2,1} \cdot y_1 - C_{2,2} \cdot y_2 - B_{2,2} \cdot y_5}{M_2}, \quad (3)$$

$$ddq_{j,3} = \frac{F_{FR} \cdot \text{sign}\left(\frac{d}{dt} \delta_2 \right) + k_1(\eta) + \beta_1 \left(\frac{d}{dt} \eta \right) - C_{3,1} \cdot y_1 - C_{3,3} \cdot y_3 - B_{3,3} \cdot y_6}{M_3}. \quad (4)$$

Here, $y_1 = q_1, y_2 = q_2, y_3 = q_3, y_4 = \frac{d}{dt} y_1, y_5 = \frac{d}{dt} y_2, y_6 = \frac{d}{dt} y_3$.

The calculation was carried out at a open wagon speed of 85 km/h. It was established that the acceleration acting at the center of mass of the open wagon's supporting structure when moving in a loaded state at the moment of passing the junction is about 1.8 m/s^2 (Fig. 6).

The obtained acceleration value corresponds to the "perfect" movement of the open wagon along the rail track.

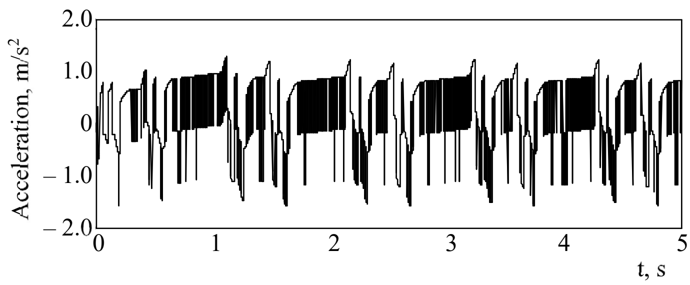

Fig. 6. Acceleration at the center of mass of an open wagon when moving in a loaded state

5. 2. Results of calculating the strength of a open wagon frame under the main operating load conditions

The calculated acceleration value was taken into account when calculating the strength of the open wagon frame.

The finite element model of the frame is shown in Fig. 7. It is formed by tetrahedra [24, 25]. This type of element was chosen due to the fact that the mesh was constructed on a solid body [26, 27].

The finite element model is formed by 356016 elements, the maximum size of which is 75 mm, and the minimum – 15 mm, and 115345 nodes.

The calculation results showed that the maximum stresses under the main loading modes of the frame during operation do not exceed the permissible values. The highest stresses in the frame occur under design mode I (impact). At the same time, the maximum stresses in the frame were 287.4 MPa (Fig. 8) and arise in the zone of interaction between the girdle beam and the pivots (Fig. 9). These stresses are 6% lower than those that occur in a typical frame structure and 7.4% higher than the permissible ones.

The maximum displacements in the frame are concentrated in its middle part and amounted to about 3.5 mm (Fig. 10).

With other operational load schemes, the stresses in the frame also do not exceed the permissible values (Table 1).

Thus, the proposed solution to improve the open wagon frame helps reduce its load compared to the typical structure by 3.5–6%.

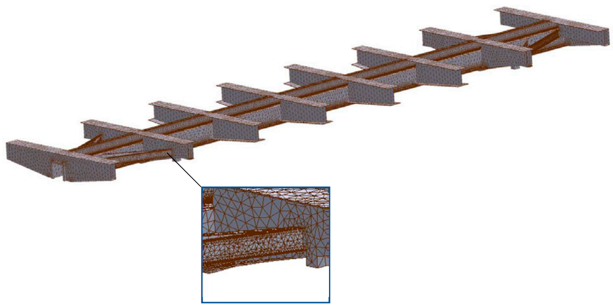

Fig. 7. Finite element model of an open wagon frame

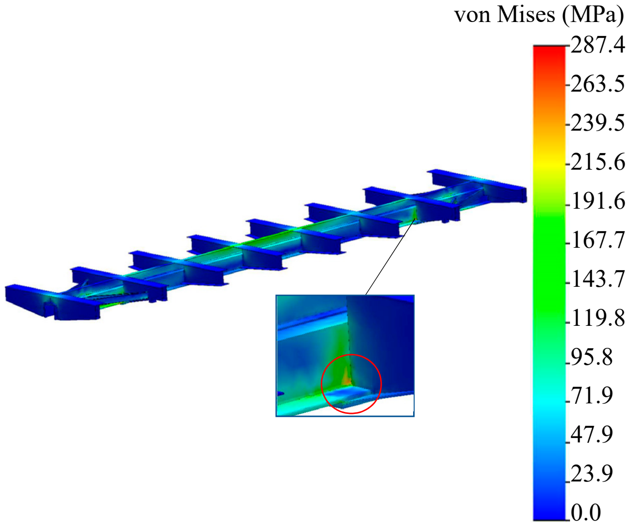

Fig. 8. Stressed state of the open wagon frame

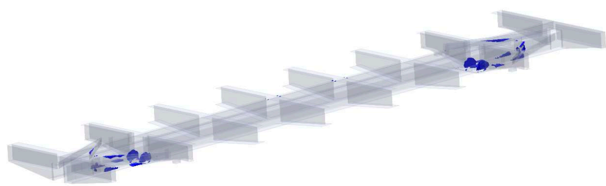

Fig. 9. The most loaded areas of the open wagon frame

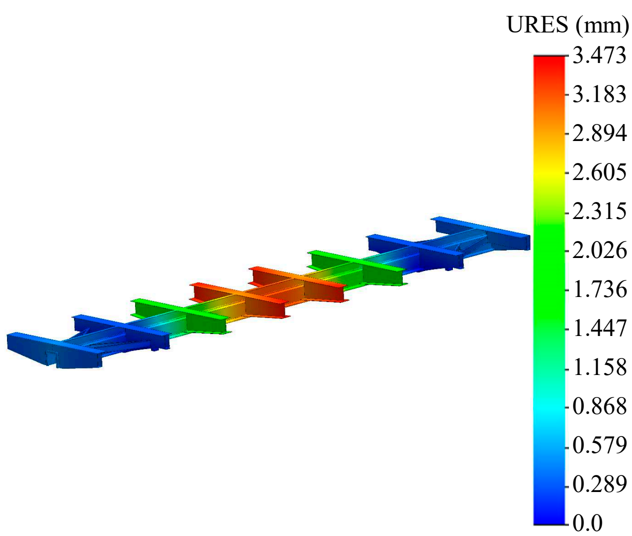

Fig. 10. Movement in the nodes of the open wagon frame

Table 1

Results of calculating the strength of a open wagon frame

Estimation mode	Loading scheme		
	Impact	Compression	Pulling-stretching
I	Stress, MPa		
	287.4	272.3	264.5
	Node displacement, mm		
	3.5	3.45	3.43
III	Stress, MPa		
	198.5	198.5	187.6
	Node displacement, mm		
	3.42	3.42	3.4

5. 3. Results of calculating the strength of a open wagon frame during transportation by rail ferry

To determine the strength of a open wagon frame during transportation by rail ferry, its calculation was carried out. The finite element model of the frame is formed by 1341431 elements, the maximum size of which is 75 mm, and the minimum is 3.75 mm, and 2395959 nodes (Fig. 11).

The model is fixed to the horizontal surfaces of body center plates, as well as to the supporting surfaces of pivot beams. That is, those areas under which mechanical jacks are installed to unload the spring suspension of the bogies when transporting wagons on railroad ferries [22].

The calculation results are shown in Fig. 12, 13. The maximum stresses in the frame occur in the fastening node and are 304.9 MPa (Fig. 12). In the pivot beam, the stresses in the fastening zone of the node are 282.4 MPa, which is 4% lower than those operating in a typical open wagon frame structure.

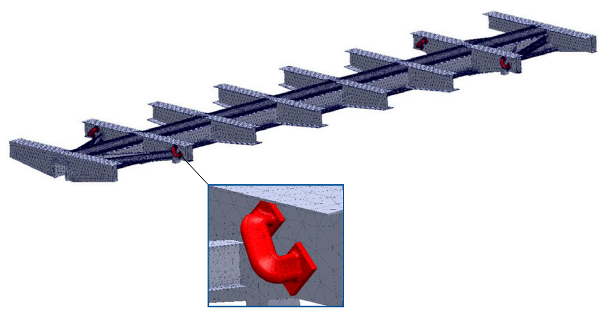

Fig. 11. Finite element model of an open wagon frame with nodes for securing chain ties

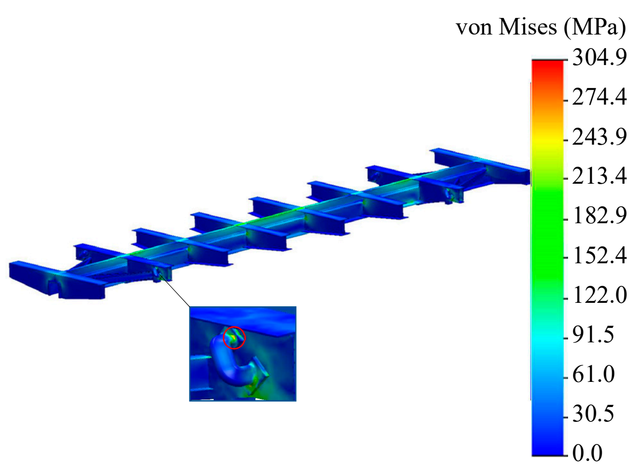

Fig. 12. Stressed state of the open wagon frame with nodes for securing chain ties

The maximum displacements occur in the middle part of the girdle beam. They amounted to 3.8 mm (Fig. 13).

Therefore, the strength of the open wagon frame is ensured under this loading regime.

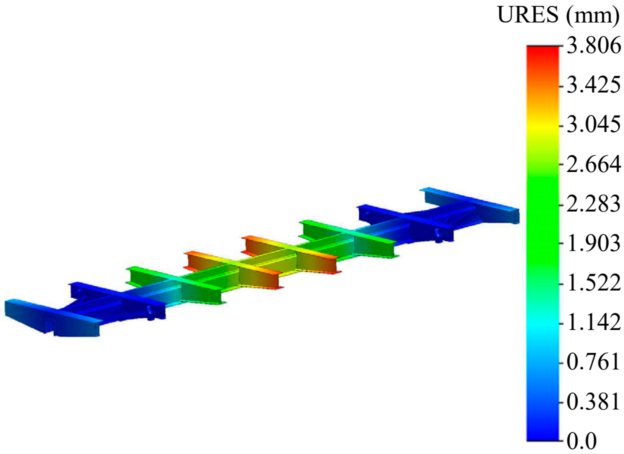

Fig. 13. Displacements in the nodes of the open wagon frame with nodes for securing chain ties

6. Discussion of results based on analyzing the loading on a open wagon frame with slings in its structure when accepting operational loads

In order to reduce the stresses in the most loaded areas of the open wagon frame, it is proposed to install slings in its cantilever parts (Fig. 1). Due to this, partial unloading of the girdle beam from longitudinal loads is carried out. To substantiate the introduction of slings as a structural element of the open wagon frame, its finite element analysis was carried out. The loading of the open wagon frame was taken into account under the modes characteristic of its operation on main tracks, as well as during transportation by railroad ferry.

We have determined the dynamic loads acting on the open wagon frame when moving along the main track with joints by mathematical modeling (Fig. 5). The accelerations obtained were taken into account in the calculations of the strength of the frame. It was established that the maximum stresses in the open wagon frame occur under the first design mode of the wagon, which correspond to the "impact" (Table 1). These stresses were recorded in the zone of interaction of the girdle beam with the pivot beams (Fig. 8, 9) and are 287.4 MPa. The maximum displacements in the frame were about 3.5 mm and are concentrated in its middle part (Fig. 10). Therefore, the introduction of slings contributes to a decrease in the stresses in the open wagon frame by 6% compared to those that occur in the typical frame structure and by 7.4% below the permissible ones.

The calculation of the strength of the open wagon frame during transportation on a railroad ferry showed that the maximum stresses in the pivot beam are 282.4 MPa (Fig. 12). The stresses obtained are 4% lower than those that occur in the typical frame structure of the open wagon.

Our research has certain advantages compared to known ones. For example, unlike works [4–6], within the framework of our research solutions were proposed that would help improve the strength of a open wagon frame during operation. At the same time, the implementation of these solutions is possible not only at the manufacturing stage but also during modernization of open wagons. Unlike papers [7, 8], the proposed implementation will not cause difficulties in carrying out technical maintenance and repair of the wagon. Compared with studies [9, 10], the improvement of the open wagon does not require significant capital investments. Unlike work [11], the proposed solution helps improve the strength of the open wagon frame under the most loaded operating modes.

A condition for the practical implementation of our research results is the connection of the sling with the areas of placement of the front and rear stops of auto couplers.

At the same time, this study has a certain limitation implying that the constructed calculation schemes of the open wagon frame do not take into account the asymmetric application of longitudinal load to it.

The disadvantage of the present study is that model 12-757 was considered as the base model of a open wagon. This model has unloading hatch covers. The presence of slings, as well as nodes for fastening chain ties, will prevent the opening of hatch covers in the cantilever parts. That is why, at the subsequent stages of our future studies, it is planned to change the body structure in its cantilever parts. This will advance current work.

The results of our study will contribute to improving the strength of the supporting structures in open wagons during operation and reducing the cost of their maintenance. The study could also contribute to new technological advancements in the design of freight wagons with improved technical and economic indicators.

7. Conclusions

1. We have established that the acceleration acting on the center of mass of the supporting structure in an open wagon when moving in a loaded state at the moment of passing the joint is about 1.8 m/s^2. The resulting acceleration value corresponds to the "excellent" movement of the open wagon along the rail track.

2. It was found that the greatest stresses in the open wagon frame under the main operating modes occur under mode I (impact) and amount to 287.4 MPa. They are concentrated in the zone of interaction of the girdle beam with the pivots. It is important to say that the obtained stresses are 6% lower than those that occur in the typical frame structure and 7.4% lower than the permissible ones. The maximum displacements in the frame are concentrated in its middle part and amount to about 3.5 mm. With other calculation schemes of frame loads, the stresses in it are also less than those that occur in the typical structure.

3. The maximum stresses in the open wagon frame during transportation by rail ferry occur in the node for fastening the chain ties and are 304.9 MPa. In the pivot beam, the stresses in the area of fastening the node are 282.4 MPa. These stresses are 4% lower than those acting in a typical open wagon frame structure. The maximum displacements occur in the middle part of the girdle beam and are 3.8 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, as well as the results reported in this paper.

Funding

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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.

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