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DETERMINING THE LOAD ON THE BEARING STRUCTURE OF A FLAT WAGON FOR LONG CARGO IN RAIL-FERRY TRANSPORTATION

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This study's object is the processes of perception and redistribution of loads in the supporting structure of a flat wagon for long-length cargo during rail-ferry transportation. The task addressed is to adapt a universal flat wagon for transporting long-length cargo. In this case, it is proposed to improve the structure of a flat wagon by equipping it with frame-type side walls reinforced with sandwich panels.

The proposed technical advancement was substantiated by mathematical modeling of the dynamic loading of the flat wagon during transportation by rail ferry. The calculation results established that the proposed improvement contributes to a reduction in the dynamic loading of a flat wagon's supporting structure by 15% compared to the typical structure. The findings were confirmed by computer simulation. The results of calculating the strength of a flat wagon's supporting structure established that its strength is ensured.

A special feature of the technical advancement is that it does not require intervening in the basic concept of a flat wagon's supporting structure since the side walls are removable.

The scope of practical application of the research results is railroad transport. The practical use of the findings is subject to the absence of a natural degree of freedom of the side wall frame.

The results of this study will contribute to improving the efficiency of railroad transport operation, including international traffic. The results could also prove useful for designing modern car structures with improved technical and operational characteristics

Keywords: railroad transport, flat wagon, design improvement, structural loading, structural strength, railroad-ferry transportation

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1. Introduction

The transport industry is an integral part of the successful development of the European economy [1, 2]. It includes several separate types of transport that ensure its smooth functioning: rail transport, road transport, sea (river), aviation, and pipeline. Rail has been one of the most developed types of transport for a long time. Therefore, improving the efficiency of rail transport has been a relevant task over a long time [3–5].

Currently, a fairly wide segment of cargo is transported by rail, one of which is long-length cargo: forestry, construction, etc. For the transportation of long-length cargo by rail, flat wagons are most often used, which are equipped with vertical racks to hold the cargo. However, the fleet of such cars is limited.

In order to adapt universal flat wagons to the transportation of long-length cargo, they are being improved, for example, by installing wooden racks on the main longitudinal beams of the frame. Under operating load conditions, such a fastening scheme is not reliable and can contribute to the collapse of the cargo. This is a rather dangerous situation, especially along the train route. When transporting such trains on railroad ferries in international traffic, this can contribute to the violation of the stability of the car on the deck and the safety of sea transportation in general.

The lack of flat wagons for the transportation of long cargo has led to the use of gondolas for these purposes. To secure long cargo in a gondola, wooden racks and binding devices are used. However, under operating load conditions, damage to the supporting structures of gondolas occurs and unscheduled repairs are necessary. This is due to their unsuitability for such cargo transportation.

Therefore, it is important to devise solutions aimed at enabling the reliable transportation of long cargo by rail, including international traffic.

2. Literature review and problem statement

In work [6], the use of a removable module was proposed to adapt a flat wagon to the transportation of long-length cargo. This module is installed on the flat wagon and fixed through fitting stops. In addition, this module contains elastic-frictional connections in its structure, which helps reduce the dynamic loads acting on it during operation. Such a solution actually makes it possible to adapt the flat wagon to the transportation of long-length cargo but, at the same time, it requires the establishment of an appropriate base for its maintenance in operation. In addition, the authors did not study the possibility of transporting such a module on a railroad ferry. This may be due to the fact that this module is not adapted to such transportation.

Paper [7] highlights the features of the influence of operational loads on the strength indicators of a flat wagon for long-length cargo. The results of a modal analysis of a flat wagon's supporting structure are reported. The authors proposed adjustments to theoretical models that have been used in the study of flat wagon loading. As a drawback of the work, it can be noted that solutions aimed at improving the efficiency of transportation of long-length cargo on flat wagons were not proposed. Maybe this could be a further step to build on the work.

The design features of a long-wheelbase flat wagon, as well as research into its strength, are highlighted in work [8]. In this case, the authors conducted experimental studies using the method of electrical strain gage. It was established that the solutions adopted during the design of the flat wagon are appropriate. The authors proposed recommendations for the design of modern flat wagon structures. However, no attention was paid to the study of the loading of the flat wagon when transporting long-length cargo. This can be explained by the fact that the authors focused on the transportation of containers by flat wagons as the most common means of transport in international traffic.

A similar drawback is also found in [9], which highlights the features of experimental studies on the strength of a long-wheelbase flat wagon. The authors focused their attention on investigating the endurance and cyclic fatigue of a flat wagon's supporting structure. However, they did not study its loading during the transportation of long-length cargo, including on railroad ferries. This could be explained by the fact that the authors focused their attention on the vertical loading of a flat wagon's supporting structure as the most common in operation.

To increase the efficiency of the operation of flat wagons, a solution was proposed in [10] to improve them. It is proposed to install superstructure frames in the cantilever parts, which limit the movement of cargo in the longitudinal plane. The features of determining the profile of the superstructures are highlighted. A study of the dynamic loading and strength of the improved flat wagon structure was conducted. The results of the calculations confirmed the feasibility of the proposed improvement. However, the authors did not study the possibility of transporting long-length cargo on such a flat wagon. This can be explained by the fact that the proposed superstructures do not make it possible to use the full load capacity of the flat wagon when transporting long-length cargo on it. This situation causes the ineffective use of this improvement for the transportation of the specified range of cargo.

In paper [11], a structure of a flat wagon with improved technical and economic characteristics for intermodal cargo transportation is proposed. The authors highlight the design features of this car, as well as its strength calculations under the main operating load conditions. The most loaded zones of the structure were identified, and their stress state was analyzed. Along with a number of advantages of this flat wagon structure, it should be noted that it is not adapted to the transportation of long-length cargo. This limits the demand for this flat wagon in operation.

The prototype of an innovative flat wagon was proposed by the authors of paper [12]. Such a flat wagon has a rotating cargo platform, which allows it to be unloaded and loaded using the ACTS system. The features of the calculation of the strength of the components of the flat wagon under operational loads are reported. The prospects for using such a flat wagon are indicated. However, the design of this flat wagon is highly specialized and adapted to the transportation of vehicles.

In paper [13], in order to expand the range of goods transported on the flat wagon of model 13-7024, a solution is proposed for its situational adaptation. In this case, the use of a transition adapter in the form of a removable module is proposed, which forms a cargo platform for placing the corresponding types of cargo. The features of the selection of profiles for the removable module and the results of the calculation of its design for strength are reported. The proposed removable module could be supplemented with vertical racks, which would facilitate the possibility of transporting long-length cargo on a flat wagon of the specified model. However, the corresponding calculations are not given. The authors could have planned to conduct similar studies at the next stages of the development of their work.

To enable the transportation of long-length cargo on flat wagons or in gondola cars, paper [14] proposed the structure of a removable module. It is designed according to the overall dimensions of a universal container, which allows it to be transported not only in domestic but also in international traffic. The authors highlighted the features of designing the structure of the removable module, as well as its calculation under asymmetric loads. In this case, the design of the removable module allows for the transportation of cargo limited in length, which reduces its demand in operation.

Our review of the literature [6–14] proves that the issue of transportation of long-length cargoes by flat wagons on railroad ferries has not yet been given due attention. This may be due to the fact that this type of cargo has not been transported actively enough on railroad ferries. In this case, modern trends in the evolution of railroad-ferry transportation predetermine the need for research into this area.

3. The aim and objectives of the study

The purpose of our study was to identify the loading of a flat wagon's supporting structure for long-length cargo during rail-ferry transportation. This could make it possible not only to increase the efficiency of cargo transportation by rail in the domestic connection among European countries but also in international.

To achieve this aim, the following objectives were accomplished:

– to conduct mathematical modeling of the loading of a flat wagon's supporting structure during transportation by rail ferry;

– to conduct computer simulation of the loading of a flat wagon's supporting structure during transportation by rail ferry and verify the formed mathematical model;

– to calculate the strength of a flat wagon's supporting structure.

4. The study materials and methods

The object of our study is the processes of perception and redistribution of loads in the supporting structure of a flat wagon for long-length cargo during rail-ferry transportation.

The principal hypothesis of the study assumes that the use of removable walls on the supporting structure of a flat wagon could make it possible to adapt it to the transportation of long-length cargo not only by rail but also by rail ferries.

To enable the transportation of cargo on a universal flat wagon, its structure is proposed to be improved. It is assumed to use side walls that will ensure that the cargo is kept from tipping over. Each wall has a frame structure that includes vertical posts and horizontal belts. To reduce the load on a flat wagon's supporting structure when perceiving lateral loads, the walls are reinforced with sandwich panels (Fig. 1). The sandwich panel is formed by metal sheets, in the layer between which there is an energy-absorbing material. This solution helps reduce the impact of dynamic loads on a flat wagon's supporting structure, and, accordingly, the load during oscillations lateral sway.

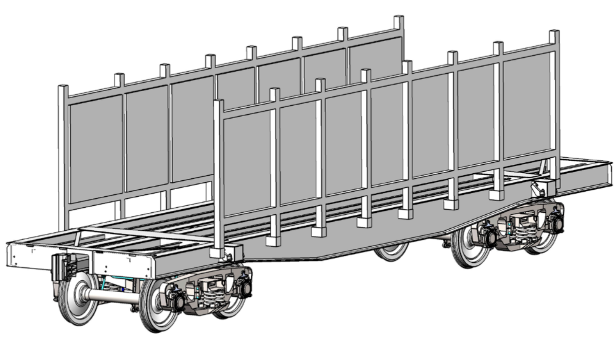

Fig. 1. Flat wagon for transporting long cargo

The walls are installed in scaffolding brackets welded to the longitudinal beams of the flat wagon frame using lifting and transport equipment.

The structure of a flat wagon is adapted to transportation on a railroad ferry. For this purpose, nodes for fastening chain ties are installed on its longitudinal beams of the frame (Fig. 2). These nodes are attached to special box-section superstructures. Such arrangement of nodes ensures compliance with the angles of placement of chain ties in space with regulatory values.

In the course of our study, the loading of a flat wagon's supporting structure during transportation by rail ferry was considered. Such operating conditions are the most unfavorable in terms of force impact on a flat wagon's supporting structure, so they were taken into account.

To identify the dynamic loading of a flat wagon's supporting structure during rail ferry transportation, mathematical modeling was performed. The side sway of the railroad ferry with cars on its decks was taken into account. The disturbing effect (action of a sea wave) on the railroad ferry is described by the trochoidal law.

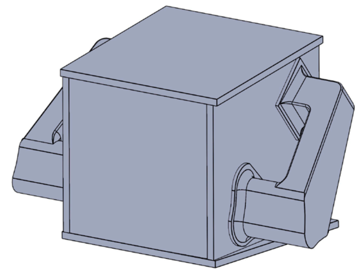

Fig. 2. Superstructure with nodes for securing a flat wagon to the deck of a railroad ferry

When building the model, the following assumptions were accepted:

– the cargo is considered as conditional;

– the carrying capacity of the flat wagon is fully utilized;

– the energy-absorbing material has viscous properties.

The mathematical model built was solved using the Mathcad software package (USA) [15–17]. The Runge-Kutta method [18, 19] was applied, which is one of the most common for solving such problems as "Dynamics of railroad cars". The starting conditions were taken equal to zero.

Our results were verified by computer simulation. In this case, the SolidWorks Simulation software package (France) was used, which implements the finite element method [20, 21]. Currently, this calculation method has found the greatest application in the mechanical engineering industry to determine the strength of vehicles. Therefore, it was used as a basic one in our study. The model was verified using the F-test [22].

At the next stage of the calculation, a study was carried out on the strength of a flat wagon's supporting structure during transportation by railroad ferry. The calculation was carried out using the Mises criterion [23, 24]. This is justified by the fact that the material of a flat wagon's supporting structure is steel 09G2S, which has isotropic properties.

5. Results of determining the loading of a flat wagon's supporting structure for long-length cargo during rail-ferry transportation

5. 1. Results of mathematical modeling of the loading of a flat wagon's supporting structure during transportation by rail ferry

To substantiate the proposed structural solutions for adapting the flat wagon to the transportation of long-length cargo, a study of its loading during transportation by rail ferry was conducted.

The design scheme of the flat wagon is shown in Fig. 3. In this case, coordinate θ_1 characterizes the movement of the railroad ferry under conditions of side sway, θ_2 – a flat wagon's supporting structure, θ_3 – the cargo fixed in the flat wagon.

The mathematical model that characterizes the movement in the system "railroad ferry – flat wagon – cargo" takes the following form

$$\begin{cases} \left(\frac{D}{12\cdot g}\left(B^2+4z_g^2\right)\right)\ddot{q}_1+\left(\Lambda_\theta\cdot\left(\frac{B}{2}\right)^2\right)\dot{q}_1= \\ =\left(\left(p'+F(t)\right)\cdot\left(\frac{B}{2}\right)^2\right), \\ I_{FW}^\theta\cdot\ddot{q}_2=p'_{FW}\cdot\frac{h_{FW}}{2}+M_{FW}^D+M_{FW}^C, \\ I_C^\theta\cdot\ddot{q}_3=M_C^{FW}-\beta\cdot h_C\cdot\dot{q}_3, \end{cases} \quad (1)$$

where $q_1=\theta_1$, $q_2=\theta_2$, $q_3=\theta_3$.

Railroad ferry:

– D – displacement of the railroad ferry;

– B – width of the railroad ferry hull;

– h – height of the railroad ferry side;

– Λ_θ – coefficient characterizing the resistance to oscillations of the railroad ferry;

– z_g – coordinate of the center of gravity of the railroad ferry;

– p' – wind load on the surface projection of the railroad ferry;

– $F(t)$ – law of action of the force that disturbs the motion of the system "railroad ferry – flat wagon – cargo".

Flat wagon:

– I_{FW}^θ – inertia coefficient of the flat wagon;

– h_{FW} – height of the lateral projection of the flat wagon;

– p'_{FW} – wind load on the lateral projection of the flat wagon;

– M_{FW}^D – moment of forces arising between the flat wagon and the deck of the railroad ferry;

– M_{FW}^C – moment of forces arising between the flat wagon and the cargo;

– β – coefficient of viscous resistance of the energy-absorbing material.

Cargo:

– I_C^θ – inertia coefficient of the cargo;

– h_C – height of the lateral projection of the cargo;

– M_C^{FW} – moment of forces arising between the cargo and the flat wagon.

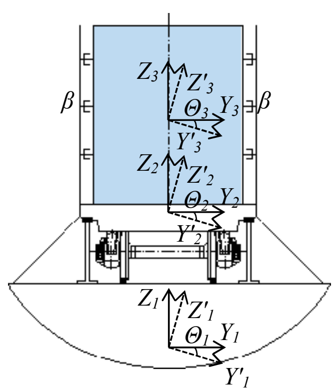

Fig. 3. Calculation scheme of a flat wagon during oscillations of a railroad ferry

The calculation was carried out using an example of a ferry of the "Heroes of Plevna" type for the Black Sea water area. It was established that the maximum acceleration acting on a flat wagon's supporting structure, which is placed on the track farthest from the bulwark (Fig. 4) of the upper deck of the railroad ferry, is 0.18 g. This acceleration value is given taking into account the horizontal component of the acceleration of free fall, which is calculated for a heel angle of 12.2°. The specified heel angle was determined for the case of static wind action on the lateral projection of the railroad ferry [25].

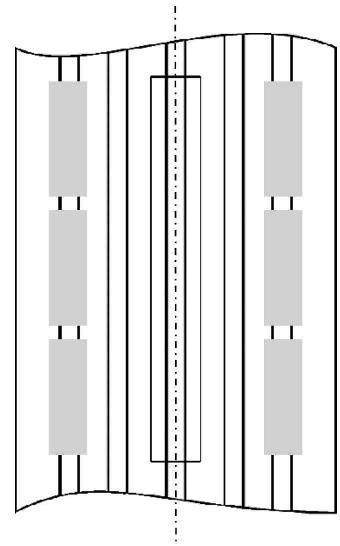

Fig. 4. Layout of carriages on the outermost tracks of a railroad ferry from the bulwark

We must note that the obtained acceleration value is 15% lower than that acting on a flat wagon of a typical design when transported by rail ferry.

5. 2. Results of computer simulation of the load on a flat wagon's supporting structure during transportation by rail ferry

To verify the mathematical model (1), a simulation of the dynamic load on a flat wagon's supporting structure during transportation by rail ferry was carried out. The calculated model of a flat wagon's supporting structure is shown in Fig. 5. It was taken into account that a flat wagon's supporting structure is subjected to vertical load P_v, caused by its own weight and the weight of the cargo. The model also takes into account lateral load P_l on the walls, which includes the wind load and the horizontal component of the gross weight of the flat wagon. Load P_c was applied to the nodes for fastening the chain ties. This load was decomposed into three components: longitudinal, vertical, and transverse. These components are determined by the angles of placement of the tie in space: YZ – 30°; XY – 60°; XZ – 60°. It is taken into account that the ties are symmetrically placed relative to the flat wagon.

On the side of the car tilt during the oscillations of the railroad ferry, the load from the chain ties takes into account the dynamic component; on the opposite side, only the load from the tension of the chain tie is taken into account – 50 kN.

The model was fixed to the supporting surfaces of the pivot beams, i.e., the zones of their interaction with the stop jacks. In this case, a rigid connection was used. Friction forces were neglected.

The finite-element model of a flat wagon's supporting structure is formed by tetrahedra (Fig. 6). The graph-analytical method was used to determine the optimal number of model elements. The model has 792589 elements and 267606 nodes. The maximum size of the model element is 100 mm, the minimum is 20 mm.

The material of a flat wagon's supporting structure is 09G2S steel. Permissible stresses are taken equal to 310.5 MPa in accordance with DSTU 7598:2014. Freight cars. General requirements for calculations and design of new and modernized 1520 mm gauge cars (non-self-propelled). Foreign analog of this standard: "EN 12663-2. Railroad applications – structural requirements of railroad vehicle bodies – Part 2: Freight cars".

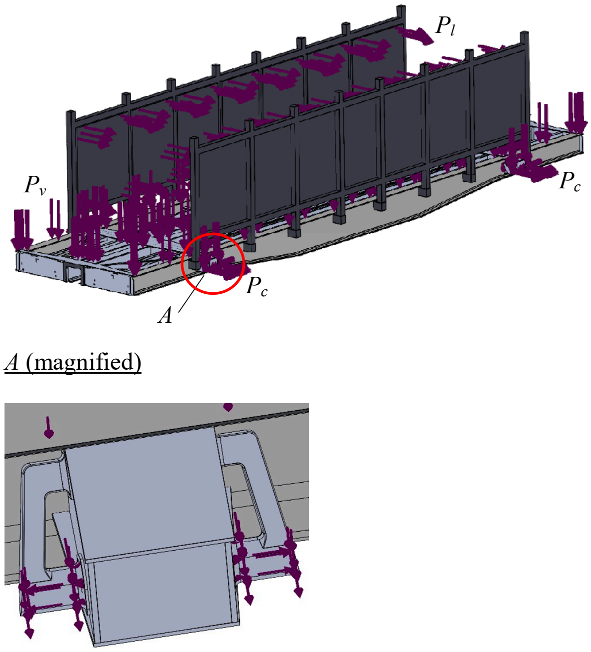

Fig. 5. Calculation diagram of a flat wagon's supporting structure

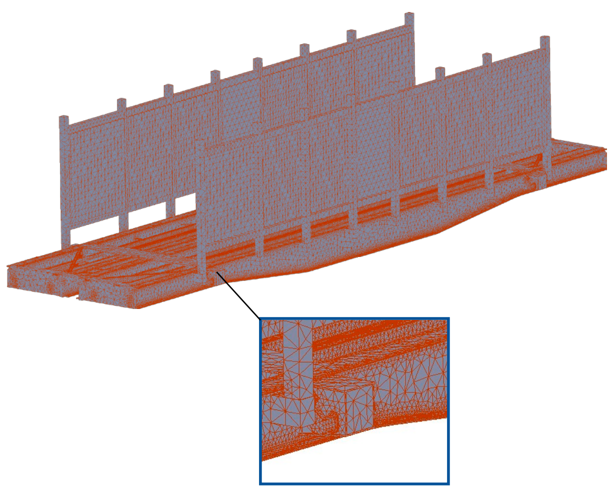

Fig. 6. Finite element model of the supporting structure of a flat wagon

Based on our calculations, the acceleration distribution fields relative to a flat wagon's supporting structure were obtained (Fig. 7). The maximum acceleration acting on a flat wagon's supporting structure was concentrated behind the center of the upper part of the side wall and was 2.62 m/s^2 (0.26 g).

To obtain a sample of accelerations acting on a flat wagon's supporting structure during transportation by rail ferry, variational calculations were performed. The variation was performed by the roll angle. The results of the calculations are given in Table 1.

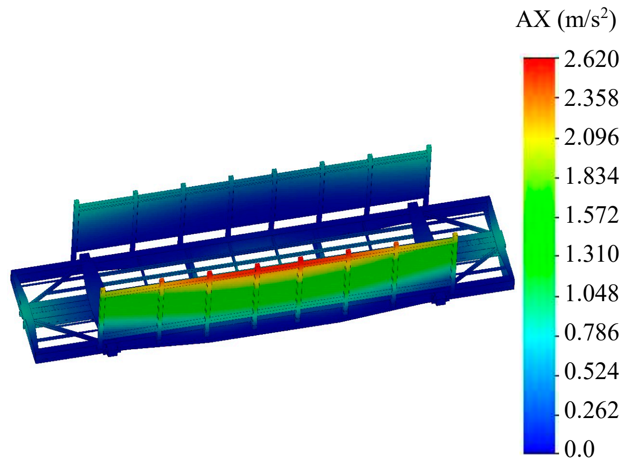

Fig. 7. Acceleration distribution fields relative to a flat wagon's supporting structure

Using the results of these two samples with the F-test, it was found that the hypothesis of the adequacy of the constructed model is not rejected. In this case, the calculated value of the criterion was $F_c = 1.29$, which is less than the tabulated value – $F_t = 3.29$.

Table 1

Accelerations acting on a flat wagon's supporting structure at different angles of roll of the railroad ferry

Model	Angle of roll, degree								
	5	7,5	10	12.5	15	17.5	20	22.5	25
Mathematical	1.42	1.65	1.8	2.1	2.32	2.46	2.62	2.95	3.18
Computer	1.84	1.98	2.3	2.6	2.71	2.86	3.05	3.33	3.54

5. 3. Results of calculating the strength of a flat wagon's supporting structure

The acceleration calculated by the mathematical model (1) was taken into account when calculating the strength of a flat wagon's supporting structure. The calculation was carried out in accordance with the scheme shown in Fig. 5.

The results of our calculation showed that the most loaded areas of the flat wagon structure are the nodes for fastening the chain ties from their tension side (Fig. 8). The stresses in them were 238.5 MPa (Fig. 9), which is lower than the permissible ones.

Also, stress concentration was recorded in the zone of interaction of the extreme vertical post of the side wall with the scaffolding bracket. Here, the stress was 225.4 MPa (Fig. 10), which also does not exceed the permissible value.

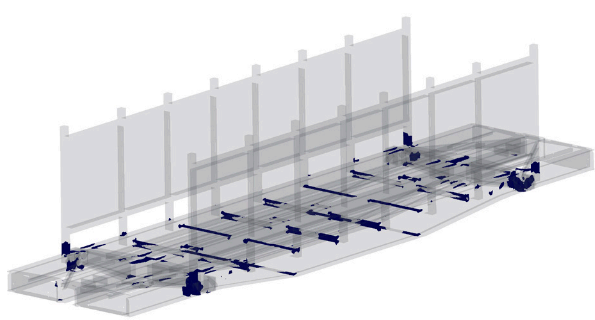

Fig. 8. The most loaded areas of a flat wagon's supporting structure

The maximum displacements were recorded in the upper part of the side wall behind its center – 3.34 mm (Fig. 11).

Fig. 12 shows the distribution of displacements along the upper belt of the side wall.

Therefore, at the end parts of the upper belt, the displacements take a minimum value and are about 1.6 mm. To the center, these displacements increase and have a maximum value. This distribution of displacements is explained by the scheme of fastening the wall to the frame of the flat wagon and the loads applied to it.

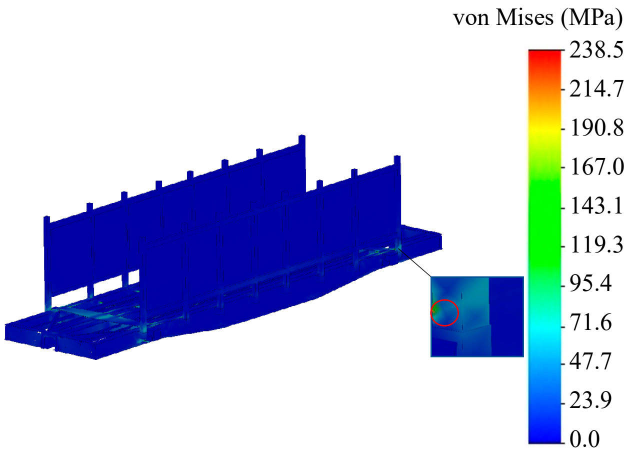

Fig. 9. Stressed state of a flat wagon's supporting structure

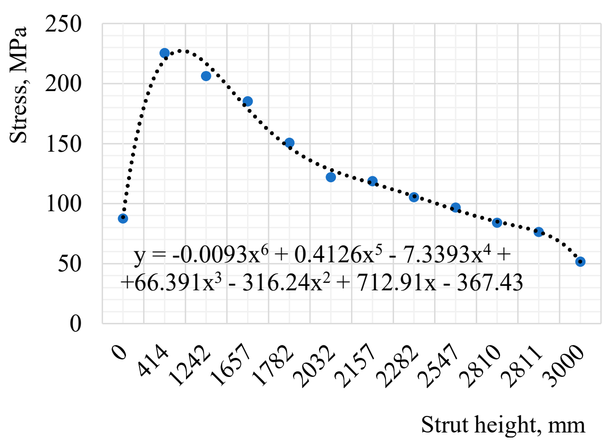

Fig. 10. Stress distribution along the height of the extreme vertical strut

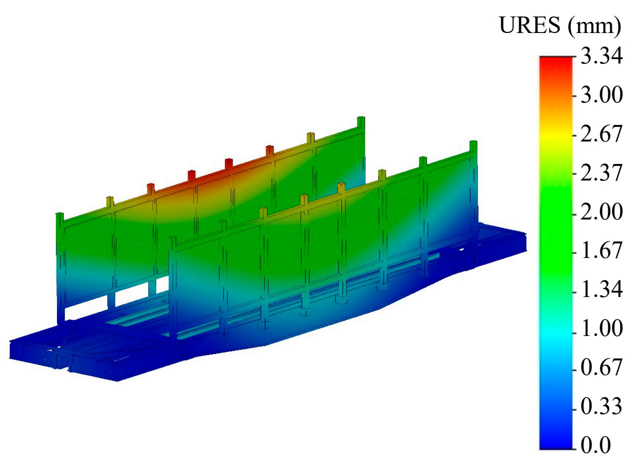

Fig. 11. Movement in the nodes of a flat wagon's supporting structure

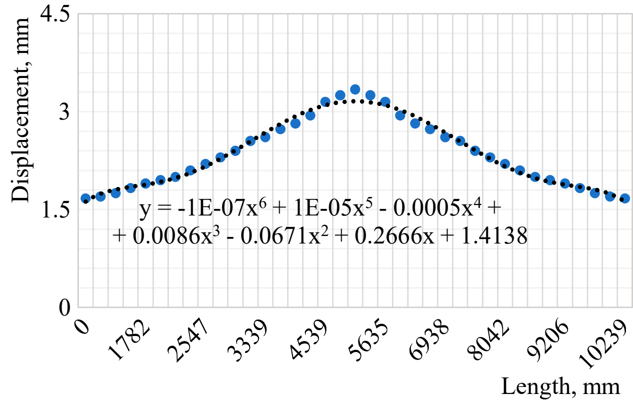

Fig. 12. Distribution of displacements along the upper belt of the side wall

6. Discussion of results based on determining the load of the supporting structure of a flat wagon for long-length cargo

To adapt the flat wagon to the transportation of long-length cargo, it is proposed to install removable frame-type walls on it, which are additionally equipped with sandwich panels (Fig. 1). Such a solution will not only facilitate the possibility of transporting long-length cargo on a flat wagon but also reduce its load, including during rail-ferry transportation. To enable the fastening of the flat wagon on a railroad ferry, superstructures with nodes for fastening chain ties were installed on its longitudinal frame beams (Fig. 2).

The feasibility of the proposed structural solutions was substantiated by mathematical modeling of the dynamic loading of the flat wagon during transportation by rail ferry. This operating mode was chosen not only due to the fact that it provides access to international traffic of European countries. This is also justified by the fact that the flat wagon is subjected to increased loads compared to operation on main tracks.

A mathematical model (1) has been built that characterizes the movement in the system "railroad ferry – flat wagon – cargo". The solution to the mathematical model has made it possible to derive the acceleration acting on a flat wagon's supporting structure and to establish that the resulting acceleration value is 15% lower than that acting on a typical flat wagon structure during rail-ferry transportation.

Verification of the constructed model was carried out using the F-test. For this purpose, computer simulation of the dynamic loading of the flat wagon was performed (Fig. 7). The results were used to verify the model. Our calculation results showed that the hypothesis of adequacy is not rejected.

Also, as part of the study, a calculation was carried out on the strength of a flat wagon's supporting structure during rail-ferry transportation. It was established that the greatest stresses arise in the nodes for fastening the chain ties from the side of their tension – 238.5 MPa (Fig. 8, 9). However, these stresses are lower than permissible. The maximum displacements in a flat wagon's supporting structure were recorded in the upper part of the side wall behind its center and amounted to 3.34 mm (Fig. 11).

Design solutions for adapting the flat wagon to the transportation of long cargo have certain advantages compared to known ones. For example, unlike work [6], the proposed improvement is appropriate not only for the operation of cars on main tracks but also for rail-ferry transportation. Unlike work [7], we proposed an improvement in the design of the flat wagon, which could contribute to improving the efficiency of transportation of long-length cargo by rail. Compared with the results of works [8–12], the advantage of this study is that the proposed design of the flat wagon can be used not only for the transportation of a certain type of cargo, for example, long-length cargo, but also containers. Unlike works [13, 14], the proposed improvement is justified not only by the features of operation on main tracks but also in rail-ferry transportation.

It is important to note that the specified improvement does not require intervening in the basic concept of a flat wagon's supporting structure since the side walls are removable. Therefore, in the absence of the need to transport long-length cargo, they can be dismantled.

The conditions for the practical use of the results are the absence of a natural degree of freedom of the side wall frame.

The limitation of this study is that when constructing the model of the loading of the flat wagon during transportation by rail ferry, the disturbing effect was applied in the form of a trochoidal law.

The disadvantage of our study is that we have considered only one type of vibration process of the railroad ferry – side sway. But this can be explained by the fact that the most unfavorable type of railroad ferry oscillations from the point of view of ensuring the stability of the wagon on the deck was taken into account.

This study in the future will be complemented by the experimental determination of the loading of a flat wagon's supporting structure during rail ferry transportation. This can be carried out under laboratory conditions on a reduced model of a flat wagon using the similarity method.

The results of this study will contribute to improving the efficiency of rail transport operation, including international traffic. Our results might also prove useful for designing modern car structures with improved technical and operational characteristics.

7. Conclusions

1. A mathematical simulation of the loading of the supporting structure of a flat wagon during transportation by a railroad ferry has been carried out. It was established that the maximum acceleration acting on the supporting structure of a flat wagon, which is placed on the track of the upper deck of the railroad ferry, farthest from the bulwark, is 0.18g. The obtained acceleration value is 15% lower than that acting on a flat wagon of a typical design during transportation by a railroad ferry.

2. Computer simulation of the loading of a flat wagon's supporting structure during transportation by rail ferry has been carried out. The maximum acceleration acting on a flat wagon's supporting structure was concentrated behind the center of the upper part of the side wall and was 0.26g. To verify the model built, variational calculations were carried out. Using the F-test, it was established that the hypothesis of adequacy is not rejected. In this case, the calculated value of the criterion was $F_p = 1.29$, which is less than the tabular value – $F_m = 3.29$.

3. The calculation of the strength of a flat wagon's supporting structure has been carried out. It turned out that the most loaded zones of a flat wagon's supporting structure are the nodes for fastening chain ties. It is here that the greatest concentration of stresses occurs, which are 238.5 MPa. However, these stresses are lower than the permissible ones. The maximum displacements in a flat wagon's supporting structure were recorded in the upper part of the side wall behind its center and amounted to 3.34 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.

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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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