This study investigates processes related to the occurrence, acceptance, and redistribution of loads in the supporting structure of a railroad flat wagon. The task addressed is to improve the technical and economic indicators of the modernized flat wagon for container transportation by reducing its tare.

To this end, the stress distribution fields in the modernized railroad flat wagon structure were determined. It was established that the main longitudinal beams of the frame have a strength reserve, which is due to the underutilization of railroad flat wagon bearing capacity. This leads to an excess sprung mass of its supporting structure. Therefore, it is proposed to introduce perforation in the walls of the main longitudinal beams of a railroad flat wagon. To substantiate this solution, the strength of the bearing structure of a railroad flat wagon was calculated. It was established that the maximum stresses in the bearing structure are 13.6% lower than the permissible ones.

The design service life of a railroad flat wagon is at least 32 years. The biaxiality calculation of the bearing structure showed that its greatest values are reached in the middle parts of girdle beams.

A special feature of the proposed solution is that it makes it possible to improve the technical and economic indicators of the modernized railroad flat wagon with minor capital investments.

The scope of practical application of the results is railroad transport.

A condition for practical use of the results is symmetrical loading of the bearing structure of a railroad flat wagon with cargo.

The results of the research could contribute to improving the efficiency of container cargo transportation along international routes. In addition, the results might prove useful for designing and fabricating new structures of railroad flat wagons, as well as for modernizing existing ones

Keywords: railroad transport, railroad flat wagon, modernization of the structure, stressed state of the structure, container transportation

UDC 629.45

DOI: 10.15587/1729-4061.2025.344818

SCIENTIFIC RATIONALE FOR THE USE OF PERFORATION BEAMS IN THE BEARING STRUCTURE OF A MODERNIZED RAILROAD FLAT WAGON FOR CONTAINER TRANSPORTATION

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Received 28.08.2025
Received in revised form 28.10.2025
Accepted 06.11.2025
Published 30.12.2025

How to Cite: *Panchenko, S., Lovska, A., Zhuravel, I., Naumenko, Y., Zharova, O. (2025). Scientific rationale for the use of perforation beams in the bearing structure of a modernized railroad flat wagon for container transportation. Eastern-European Journal of Enterprise Technologies, 6 (7 (138)), 45–52. https://doi.org/10.15587/1729-4061.2025.344818*

1. Introduction

Ensuring a stable freight transportation process is one of the most important tasks in the development of the European economy [1]. The largest share of freight requiring transportation falls on railroad transport. This is explained by a number of its advantages in comparison with other types of transport: transportation safety, cost, delivery time, etc. [2, 3].

Currently, one of the most common types of railroad wagons operated along international routes is a railroad flat wagon. This can be explained by the fact that modular vehicles, in particular containers, are quite widely used along international routes [4]. They are most often transported by rail on railroad flat wagons. Therefore, this type of a railroad wagon is quite in demand.

The increase in the intensification of freight transportation along international routes has caused a shortage of specialized railroad flat wagons for container transportation. Therefore, for a sustainable process of freight transportation along international routes, it is necessary to ensure that existing fleet of railroad flat wagons is reasonable. This situation can be resolved by introducing new designs of railroad flat wagons into operation, which requires significant capital investments. This complicates their widespread implementation. An option for solving the problem of the shortage of railroad flat wagons for international routes is their retrofitting by installing fitting stops. This could make it possible, at low costs, to allow for the transportation process by vehicles.

Therefore, the issue of retrofitting railroad flat wagons for container transportation along international routes is an urgent task.

2. Literature review and problem statement

The design features of a modern railroad flat wagon structure for container transportation are described in work [5]. The bending moments in the railroad flat wagon design were determined by reducing it to a rod system. The results were used to determine the frame profiles. The results of the strength calculation of the railroad flat wagon were reported, which confirmed the proper choice of frame profiles. However, the authors did not optimize the railroad flat wagon design in order to reduce its material consumption. A likely reason is that they planned to conduct similar studies in subsequent works.

In [6], in order to enable the universal railroad flat wagon to be used for container transportation, it was proposed to install fitting stops and end superstructures on it. These superstructures limit the movement of containers in the longitudinal plane. The proposed structural improvement was justified by theoretical calculations of the dynamics and strength of the supporting structure of a railroad flat wagon. At the same time, the authors did not pay attention to the issue of reducing the tare of the railroad flat wagon structure, which is due to the underutilization of its usable carrying capacity. This can be explained by the fact that in the absence of the need to transport containers on it, the railroad flat wagon design can be returned to its original form.

The authors of work [7] proposed a new structure of a long-wheelbase railroad flat wagon for container transportation. The peculiarity of the railroad flat wagon is the presence of perforations on the main longitudinal beams of the frame. The features of studying the strength of the supporting structure of the railroad flat wagon under some operational load schemes were highlighted. The feasibility of the solutions proposed at the design stage regarding the structure of a railroad flat wagon was proven. The disadvantage of such a railroad flat wagon is its significant cost. Therefore, it is more rational to adapt the existing fleet of railroad wagons to container transportation. A similar drawback can be noted for the design of a railroad flat wagon described in [8]. The railroad flat wagon is designed for intermodal transportation and has an adjustable loading flat wagon. This allows it to transport a wide range of cargoes.

To engage a universal railroad flat wagon for container transportation, work [9] proposed installing fitting stops on it. The features of experimental studies of the strength of the supporting structure of the railroad flat wagon were highlighted. One of the most unfavorable loading modes of its structure was taken into account – shunting impact. During the research, the railroad wagon was subjected to longitudinal loads. The test results established that the modernization is possible from the point of view of ensuring the strength of the railroad wagon during operation. However, the authors did not study the issue of reducing the tare of the supporting structure of a railroad flat wagon, which is caused by the underutilization of its usable carrying capacity. Apparently, this can be explained by the fact that the retrofitting is proposed in connection with the shortage of specialized railroad flat wagons for container transportation. If necessary, this upgrade can be easily abandoned for the structure of the railroad flat wagon to return to the original variant.

The authors of [10] analyzed existing designs of long-wheelbase flat wagons. Their structural shortcomings were identified. The main damage to the structural elements of flat wagons during operation was indicated. The work also highlights the features of experimental studies on the strength of flat wagon frames. However, the authors do not propose solutions to improve their technical and economic indicators. Perhaps this can be explained by the fact that at a certain stage of the research, the authors set the goal of identifying the most damaged structural elements of flat wagons with the possibility of their subsequent improvement.

A similar shortcoming is noted in [11]. The work highlights the features of experimental studies on the strength of a long-wheelbase flat wagon by vibration tests. The most loaded components of the flat wagon structure were identified and the reasons for their occurrence were analyzed. The need to improve the supporting structure of the flat wagon to ensure durability during operation was indicated.

In [12], the features in the experimental determination of the strength of the supporting structure of a flat wagon were highlighted. The purpose of studies was to establish the most loaded zones of the supporting structure of a flat wagon. The reasons for the concentration of stresses in the identified zones were analyzed. However, the authors did not propose solutions aimed at improving the technical and economic indicators of the flat wagon.

Our review of the literature [5–12] proves that not enough attention has been paid to improving the technical and economic indicators of modernized flat wagons. This necessitates further research in this area.

3. The aim and objectives of the study

The purpose of our study is to scientifically substantiate the use of perforated beams in the supporting structure of a modernized flat wagon for container transportation. This will make it possible to reduce the tare of the flat wagon and, accordingly, its sprung mass.

To achieve this aim, the following objectives were accomplished:

– to calculate the strength of the modernized flat wagon structure under the condition of movement as part of a train;

– to calculate the strength of the supporting structure of the flat wagon with perforation in the main longitudinal beams.

4. The study materials and methods

The object of our study is the processes of occurrence, acceptance, and redistribution of loads in the supporting structure of a flat wagon.

The principal hypothesis of the study assumes that the use of perforation in the main longitudinal beams of the frame of the flat wagon could contribute to the reduction of its tare while ensuring operational strength conditions.

The basic assumption in conducting the study is that the vertical load acting on the supporting structure of the flat wagon is evenly distributed. There is no wear of the components of the supporting structure of the flat wagon.

The simplification adopted in the study is that the structure of the flat wagon is considered monolithic. That is, welds were not taken into account.

To determine the strength reserve of the components of the supporting structure of the modernized flat wagon, its calculation was carried out. The modernization involves placing fitting stops on the main longitudinal beams of the frame. This allows the use of a flat wagon for container transportation. The flat wagon model 13-401 was chosen as a prototype. The strength calculation was carried out in the SolidWorks Simulation software package (France) using the finite element method. The work on constructing a spatial model of the flat wagon was reproduced in SolidWorks (France) (Fig. 1).

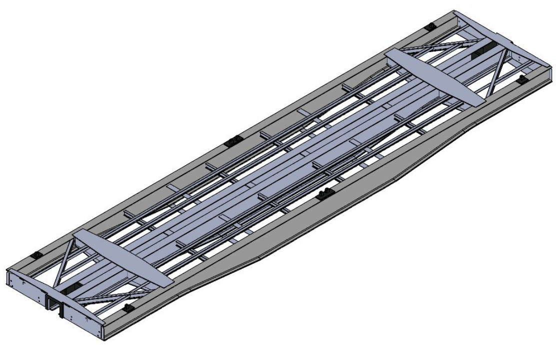

Fig. 1. Spatial model of the supporting structure of a flat wagon with fitting stops

The calculation is implemented for the case of the wagon moving as part of a train. The calculation diagram of the supporting structure of the flat wagonriage is shown in Fig. 2. It is taken into account that the flat wagon is loaded with two containers with a gross weight of 24 tons. The limitation of the model is that the friction force between the container fittings and the fitting stops of the flat wagon is greater than the dynamic load acting on them. Under this assumption, there are no horizontal reactions to the fitting stops. It is taken into account that the plates of the fitting stops are subject to vertical load P_v, which is caused by the gross weight of the containers, as well as a dynamic load arising from track irregularities. The rear stop of the automatic coupler is subject to longitudinal force P_l, which arises when the flat wagon is “compressed”. On the opposite side of the flat wagon, this force is balanced by the inertia forces of the mass of the wagon P_i.

The magnitude of the vertical dynamic load acting on the supporting structure of a flat wagon was determined by mathematical modeling. The mathematical model given in [13] was used. The model characterizes the movement of the wagon by the joint unevenness, which is described by the harmonic law. The calculation was carried out under the condition of the movement of the flat wagon at a speed of 80 km/h under initial conditions close to zero [14, 15].

The modeling of the support of the flat wagon on bogies was carried out by installing rigid connections on the horizontal surfaces of top pivot bearings [16–18]. The material of the structure was designated as steel of grade 09G2S, which has permissible stresses for design mode I – 310.5 MPa, and for III – 210 MPa. These stress values are required by the regulatory document DSTU 7598:2014. Freight wagons. General requirements for calculations and design of new and modernized 1520 mm gauge railroad wagons (non-self-propelled). The foreign analog of this document is “EN 12663-2. Railroad applications – structural requirements of railroad vehicle bodies – Part 2: Freight railroad wagons”.

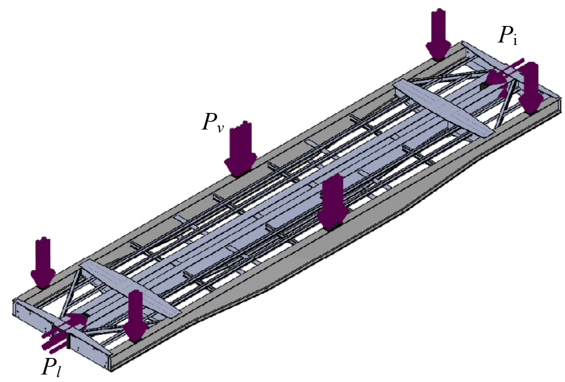

Fig. 2. Calculation diagram of the supporting structure in a flat wagon

The finite element model was formed by tetrahedra [19–21]. Their number was determined graph-analytically [22, 23] and amounted to 755630 units with a number of nodes of 1517358. The largest size of the model element was 100 mm, and the smallest – 20 mm.

5. Results of investigating the possibility of using beams with perforation in the supporting structure of the modernized flat wagon

5. 1. Results of calculating the strength of the modernized flat wagon structure under the condition of movement as part of a train

The results of our mathematical modeling of dynamic loading on the supporting structure of a flat wagon when moving as part of a train established that the acceleration at the center of mass is 1.6 m/s^2 (Fig. 3). This acceleration was taken into account in the calculations of the strength of the flat wagon, as a component of the dynamic load acting on it.

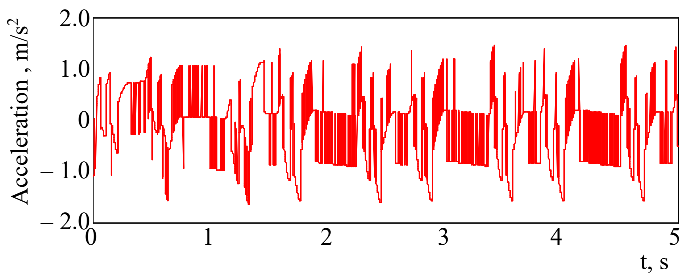

Fig. 3. Acceleration at the center of mass of the flat wagon

The results of strength calculation established that the maximum stresses in the supporting structure of a flat wagon arise in the zones of interaction of the girdle beam with pivot beams (Fig. 4). This distribution of stresses can be explained by the scheme of fastening and applying loads to the supporting structure of a flat wagon. These stresses amounted to about 176 MPa (Fig. 5) and are 16% lower than the permissible ones. In the main longitudinal beams of the frame, the maximum stresses amounted to about 128 MPa (Fig. 6). That is, they have a corresponding strength reserve. This is especially true for the middle part of the longitudinal beam, because its most loaded zones are the cantilever parts, namely the zones located closer to the pivot beams.

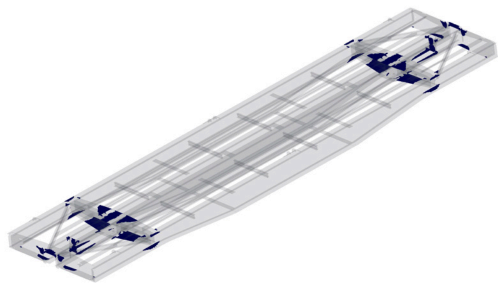

Fig. 4. Areas of greatest stress concentration in the supporting structure of a flat wagon

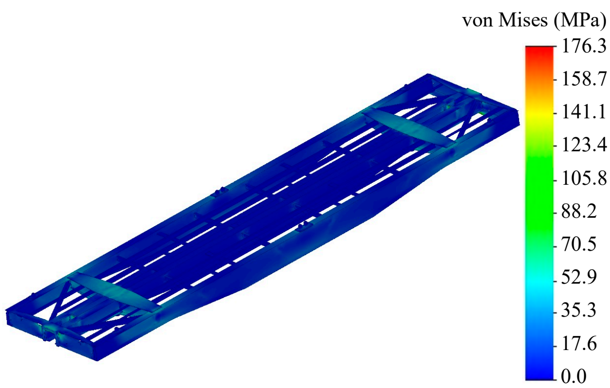

Fig. 5. Stressed state of the supporting structure of a flat wagon

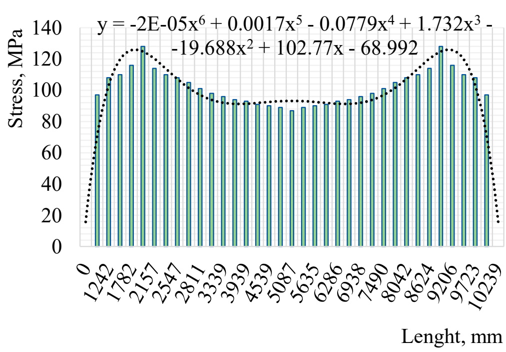

Fig. 6. Stress distribution along the main longitudinal frame beam

The maximum displacements are observed in the main longitudinal beams of the frame and are equal to 2.1 mm (Fig. 7).

This distribution of displacement fields is explained by the loading scheme of the main longitudinal beams.

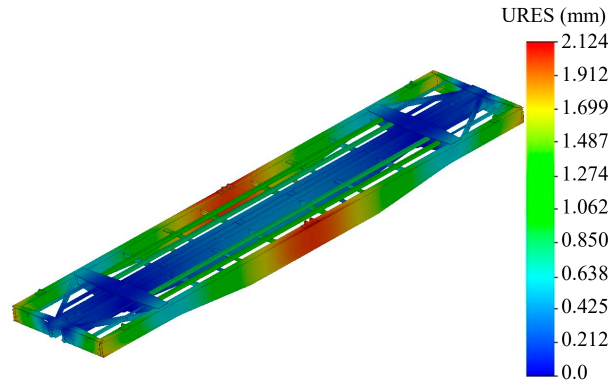

Fig. 7. Movement in the nodes of the supporting structure of a flat wagon

5. 2. Results of calculating the strength of the supporting structure of a flat wagon with perforation in the main longitudinal beams

The results of our calculation of the supporting structure of a flat wagon for strength showed that there is a reserve of strength in the middle parts of the main longitudinal beams. This causes an increased tare of the flat wagon's own structure. Therefore, it is proposed to introduce perforation in the walls of the main longitudinal beams of the flat wagon (Fig. 8). The placement of holes along the length of the main longitudinal beams is selected according to the stress distribution fields in it (Fig. 5). Taking into account the proposed solution, it is possible to reduce the tare of the supporting structure of a flat wagon by almost 2% compared to the typical design.

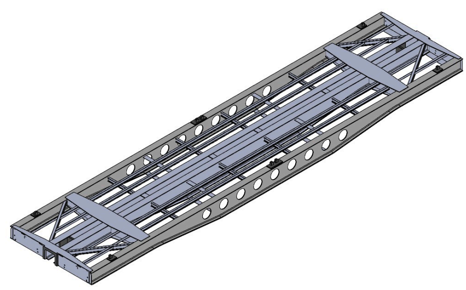

Fig. 8. Spatial model of the supporting structure of a railroad flat wagon with perforation in the walls of main longitudinal beams

A calculation was performed to study the strength of the supporting structure of a perforated flat wagon. The finite element model was formed by tetrahedra and had 75883 elements with a maximum size of 100 mm and a minimum size of 20 mm. The number of nodes in the model was 1527195 (Fig. 9).

The estimation scheme of the supporting structure of a flat wagon, the fastening scheme, as well as the material of the structure, are identical to those used in the calculation of a typical structure.

The calculation results are shown in Fig. 10–12. The most loaded zones of the supporting structure of a flat wagon are concentrated in the places of interaction between the girdle beam and the pivot beams (Fig. 10). In these zones, the maximum stresses were 181.5 MPa (Fig. 11). That is, the resulting stresses are 13.6% lower than the permissible ones and almost 3% higher than in the typical structure of the flat wagon.

The maximum displacements in the nodes of the supporting structure of a flat wagon were 2.7 mm and were concentrated behind the middle parts of the main longitudinal beams of the frame (Fig. 12). These displacements are 22.2% greater than those that occurred in a typical frame structure. However, it is important to note that the strength of the supporting structure of a flat wagon is ensured.

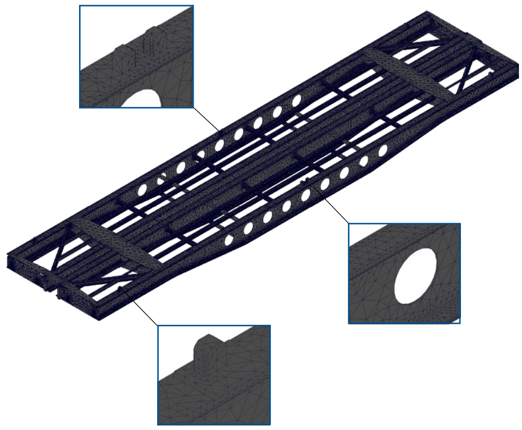

Fig. 9. Finite element model of the supporting structure of a flat wagon with perforation

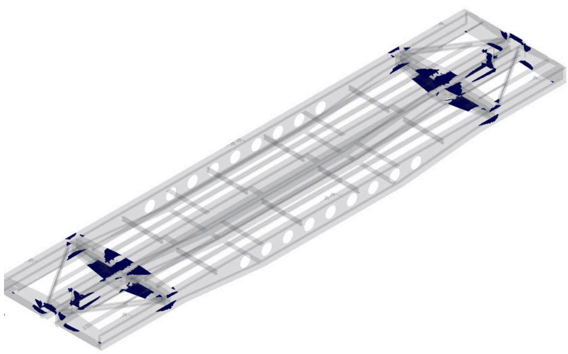

Fig. 10. Areas of greatest stress concentration in the supporting structure of a perforated railroad flat wagon

As part of our study, the design service life of the supporting structure of a flat wagon was determined. For this purpose, the following classical formula was applied

$$T_n = \frac{\left(\sigma_{-1L} / [n]^m \cdot N_0\right)}{B \cdot f_e \cdot \sigma_{ae}^m}, \quad (1)$$

where σ_{-1L} – average value of endurance limit, MPa; n – value of permissible safety factor; m – degree index of fatigue curve; N_0 – number of load cycles; B – coefficient that determines the time of continuous operation; f_e – effective frequency of dynamic stresses; σ_{ae} – amplitude of equivalent stresses (dynamic).

The coefficient, which characterizes the time of continuous operation, is determined from the following formula

$$B = \frac{365 \cdot 10^3 \cdot L_c}{\vartheta(1+0.34)}, \quad (2)$$

where L_c – average daily mileage of the wagon; ϑ – average speed of the wagon.

The calculation was carried out with the following input parameters: $\sigma_{-1L} = 245$ MPa; $n = 1.8$; $m = 4$; $N_0 = 10^7$; $B = 6514.4$ s; $f_e = 2.7$ Hz; $\sigma_{ae} = 57.4$ MPa.

Our calculations showed that the design service life of the supporting structure of a flat wagon is at least 32 years.

According to the calculation scheme shown in Fig. 3, the biaxiality of the supporting structure of a flat wagon was also determined. Biaxiality is understood as the ratio of the minimum stress value to the maximum one. The calculation results are shown in Fig. 13.

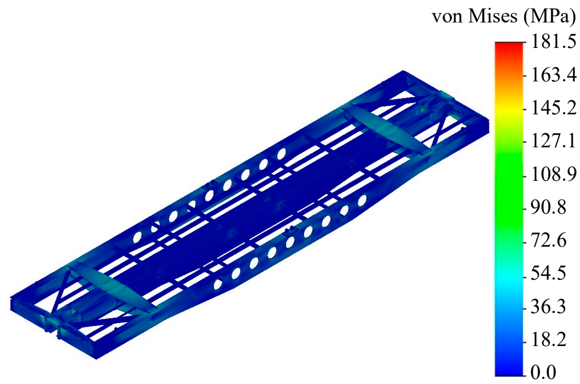

Fig. 11. Stressed state of the supporting structure of a flat wagon with perforation

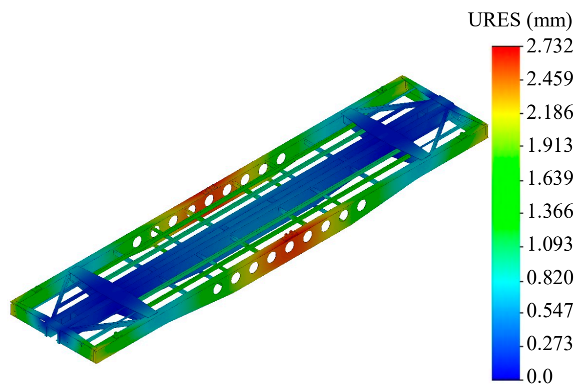

Fig. 12. Movement in the nodes of the supporting structure of a flat wagon with perforation

Analyzing Fig. 13, we can conclude that in the cantilever parts of the main longitudinal beams, as well as in the end beams, the discrepancy between the minimum and maximum stress values is quite insignificant. In the middle part of the girdle beam, it takes larger values.

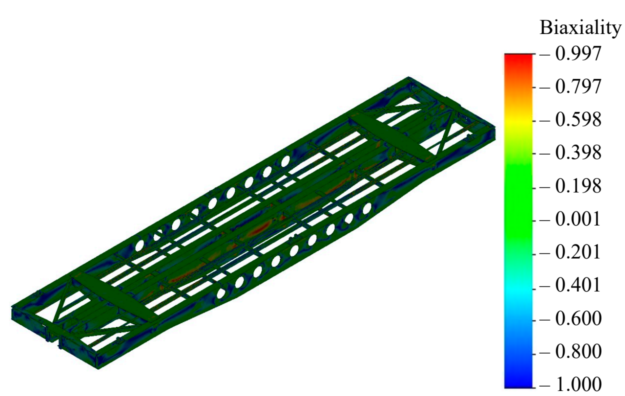

Fig. 13. Biaxiality of the supporting structure of a railroad flat wagon with perforation

6. Discussion of the results of investigating the possibility of using beams with perforation in the supporting structure of a flat wagon

To improve the technical and economic indicators of a flat wagon, modernized for the transportation of containers, its strength calculation was carried out. It was established that the main longitudinal beams have a strength reserve, which is due to the underutilization of the carrying capacity of the flat wagon (Fig. 5). Therefore, it was proposed to introduce perforation into the vertical walls of the main longitudinal beams (Fig. 8). To substantiate this solution, a calculation was performed on the strength of the supporting structure of a flat wagon. It was established that the proposed improvement is appropriate since the maximum stresses in the supporting structure of a flat wagon are 13.6% lower than the permissible ones and are 181.5 MPa (Fig. 11). The maximum displacements are concentrated in the middle parts of the main longitudinal beams and are equal to 2.7 mm (Fig. 12).

The calculation of the design service life of the flat wagon showed that it is at least 32 years. However, it must be said that this indicator is calculated at the nominal parameters of the structural components and does not take into account its possible operational wear.

The results of our calculation of the biaxiality of the supporting structure of a flat wagon indicate the need for further research to strengthen the middle part of the girdle beam (Fig. 13). It is here that the greatest biaxiality in the structure was found. This can lead to the accumulation of stresses in this area. Therefore, it is possible to implement structural solutions that will allow it to be partially unloaded.

Thus, the solutions proposed in the framework of our study are rational. It is important to note that the flat wagon could be used not only for the transportation of containers of standard size 1CC (Fig. 14) but also 1AA. For this purpose, it can be equipped with folding fitting stops. Such stops have a hinged fastening and, in the absence of the need for their use, are folded into a non-working position. This increases the efficiency of using the flat wagon during operation.

The results of our work have certain advantages compared to known studies. Unlike [5, 6], within the framework of our study, solutions have been proposed aimed at improving the technical and economic indicators of the modernized flat wagon. Unlike the results reported in [7, 8], the introduction of perforations into the vertical walls of the main longitudinal beams of the flat wagon has a lower cost than manufacturing a new flat wagon structure. The results of our work make it possible to improve the technical and economic indicators of the flat wagon by reducing its sprung mass, in contrast to [9–11]. Compared with the results from [12], our study not only identified the most loaded areas of the flat wagon structure but also proposed a solution to improve its technical and economic indicators.

The main condition for the practical use of the research results is the symmetrical loading of the supporting structure of a flat wagon with cargo. However, this condition is observed in practice since it affects the safety of transportation.

A limitation of our study is that the strength of the supporting structure of a flat wagon was calculated at its nominal parameters. In reality, in practice, there will be a deviation of the geometric parameters of the components of the flat wagon structure from the nominal ones. This is due to its wear during operation.

The disadvantage of our study is that for the time being we have limited ourselves to the mode of movement of a flat wagon as part of a train and have not taken into account other load schemes. This choice is due to the fact that this mode of movement is the main one. In further research in this area, it is planned to consider other modes of loading of the flat wagon.

The results of our study could contribute to increasing the efficiency of containerized cargo transportation along international routes. The results might also prove useful for designing and constructing new flat wagon structures, as well as for modernizing existing ones.

7. Conclusions

1. The strength of the modernized flat wagon structure has been calculated under the condition of movement as part of a train. It was established that the maximum stresses in the supporting structure of a flat wagon arise in the areas of interaction of the girdle beam with the pivots and are about 176 MPa. These stresses are 16% lower than the permissible ones. In the main longitudinal beams of the frame, the maximum stresses were about 128 MPa, which determines their strength reserve because of the underutilized flat wagon's load-bearing capacity. The maximum displacements are observed in the main longitudinal beams of the frame and are equal to 2.1 mm.

2. The strength of the supporting structure of a flat wagon with perforation in the main longitudinal beams has been calculated. In this case, the most loaded zones of the supporting structure of a flat wagon are concentrated in the areas of interaction of the girdle beam with the pivots. The maximum stresses in these zones were 181.5 MPa and were 13.6% lower than the permissible ones and almost 3% more than in the typical design of the flat wagon.

The maximum displacements in the nodes of the supporting structure of a flat wagon are concentrated in the middle parts of the main longitudinal beams of the frame and are equal to 2.7 mm. The obtained displacements are 22.2% greater than those that occurred in the typical design of the frame. Therefore, the results of our calculations prove that the strength of the supporting structure of a flat wagon is maintained.

The results of calculating the design service life of the flat wagon established that it is not less than 32 years.

The biaxiality of the supporting structure of a flat wagon was calculated. Its largest values are reached in the middle parts of the girdle beams. This creates prerequisites for further research in this area.

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

The study was conducted without financial support.

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.

Authors contribution

Sergii Panchenko: Conceptualization, Data curation, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing; **Alyona Lovska:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, resources, Software, Supervision, Visualization, Writing – review & editing; **Iryna Zhuravel:** Formal analysis, Funding acquisition, Investigation, Validation, Visualization; **Yevheniia Naumenko:** Data curation, Funding acquisition, Investigation, Writing – original draft; **Oksana Zharova:** Investigation, Methodology, Resources, Writing – review & editing.

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