The object of research is the processes of emergence, perception, and redistribution of loads in the supporting structure of a flatcar with a floor made of sandwich panels.

To reduce the impact of dynamic loads on the supporting structure of a flatcar, as well as the safety of goods transported in it, it is proposed to manufacture floors from sandwich panels.

Within the framework of the study, mathematical modeling of the dynamic load on a flatcar when it runs in a loaded state was carried out. It was found that, taking into account the proposed solution, the accelerations acting on the supporting structure of a flatcar are reduced by 8.4 % compared to the typical one. At the same time, accelerations acting on cargo placed on a flatbed car are reduced by 11.7 %. The results of calculating the strength of sandwich panels, when arranged on a flatcar, proved the feasibility of the proposed improvement. The main indicators of dynamics of the improved flatcar structure operated in an empty state were determined. It was established that the flatcar movement is assessed as "good".

A feature of the results reported here is that the improved supporting structure of a flatcar contributes not only to reducing its dynamic load but also to improving the safety of transported cargoes.

The scope of practical application of the results is the engineering industry, in particular, railroad transport. The condition for the practical application of the research results is the use of energy-absorbing material in the structure of sandwich panels.

The study could contribute to devising recommendations regarding the design of modern structures of railroad vehicles and increasing the efficiency of the functioning of the transportation industry

Keywords: railroad car, sandwich panel, dynamic loading of the railroad car, strength of frame structure, safety of goods

UDC 629.463.62

DOI: 10.15587/1729-4061.2023.278267

DETERMINING LOADING PATTERNS IN THE BEARING STRUCTURE OF A RAILROAD FLATCAR WITH A FLOOR MADE FROM SANDWICH PANELS

Alyona Lovska
Corresponding author
Doctor of Technical Sciences, Associate Professor
Department of Wagon Engineering and Product Quality*
E-mail: alyonaLovskaya.vagons@gmail.com

Volodymyr Nerubatskyi
PhD, Associate Professor
Department of Electrical Power Engineering, Electrical Engineering and Electromechanics*

Andrii Okorokov
PhD, Associate Professor**

Roman Vernyhora
PhD, Associate Professor
Department of Transport Junctions***

Iryna Zhuravel
PhD, Associate Professor**

*Ukrainian State University of Railway Transport
Feuerbakh sq., 7, Kharkiv, Ukraine, 61050
Department of Management of Operational Work*
***Ukrainian State University of Science and Technologies
Lazaryana str., 2, Dnipro, Ukraine, 49010

Received date 03.03.2023
Accepted date 10.05.2023
Published date 30.06.2023

How to Cite: *Lovska, A., Nerubatskyi, V., Okorokov, A., Vernyhora, R., Zhuravel, I. (2023). Determining loading patterns in the bearing structure of a railroad flatcar with a floor made from sandwich panels. Eastern-European Journal of Enterprise Technologies, 3 (7 (123)), 6–13. doi: https://doi.org/10.15587/1729-4061.2023.278267*

1. Introduction

The development of a competitive environment in the transport market necessitates an increase in the efficiency of railroad transportation [1–3]. The key aspect of rail transportation of goods is to ensure their safety under operating loads.

Currently, one of the most used cars in international traffic are flatcars. This is due to the fact that the supporting structure of this type of car is represented by a frame that allows it to transport a fairly wide range of goods [4, 5]. At the same time, to ensure their stability, multi-rotating fastening means are used or additional fasteners (racks, sides, stops, etc.) are used.

When transporting goods by rail, they experience the effect of cyclic loads caused by rail irregularities, as well as transient modes of movement of cars as part of a train. As a result, there may be damage to the goods, especially in case of unreliable fastening. This circumstance necessitates compensation of relevant losses to cargo owners [6–8].

It is important to say that the loss of stability of goods also threatens the safety of train traffic. In the case of transportation of dangerous goods, the loss of their stability threatens the environmental safety of transportation.

In this regard, it is advisable to implement solutions aimed at reducing the dynamic load of goods during transportation by rail by improving the load-bearing structures of cars.

2. Literature review and problem statement

In [9], to reduce the load of the car body, the introduction into its design of a material with energy-absorbing properties – aluminum foam – is proposed. The calculation of strength is implemented with the main schemes of loads of the car body in operation, including shunting co-impact. It is proved that the use of aluminum foam could help reduce the dynamic loads on the body in comparison with its typical version.

To reduce the transverse dynamic loads that act on the body of freight cars in operation, works [10, 11] suggest the introduction of removable sandwich panels. The results of calculating the strength of the body, taking into account the proposed improvement, are given. In this case, the third calculated mode of operation of the car, that is, movement as part of the train, was taken into account. The calculation was carried out using the standard values of operating loads acting on the car body.

It must be said that in works [10, 11] the introduction of structural elements with pliable connections is proposed on the example of walls. Under conditions of jump fluctuations, which are among the most common in operation, it is advisable to consider reducing the dynamic loads that act directly in the vertical plane.

Paper [12] substantiates the introduction of functionally graduated honeycomb sandwich panels in the design of the car. The results of testing, taking into account the proposed improvement, gave a positive decision. It must be said that the purpose of this implementation was to reduce the tare of the car. The use of the proposed structure of sandwich panels does not contribute to reducing the dynamic load of its design.

To reduce the load of the vehicle, article [13] provides appropriate solutions for its improvement. At the same time, the manufacture of load-bearing structural elements from pipes, of round cross section, is proposed. The side walls of the vehicle consist of articulated shells that contain energy-absorbing material. However, the implementation of such a solution is quite complicated in practice and requires the creation of an appropriate maintenance system to maintain the car in working condition.

Solutions for the construction of multilayer structures of freight car bodies are proposed in [14]. Such improvement could help improve the moment of resistance of the car structure and, as a consequence, reduce its workload during operation. In this case, the authors proposed the use of panels in the form of "egg boxes". Examples of implementation of such a solution on different models of freight cars are given and further prospects of this direction are indicated. However, the studies have been conducted on the example of tank cars for the transportation of dangerous goods.

Paper [15] investigates the peculiarities of the loading of modern design of a railroad car with composite components under the most unfavorable loading conditions. The main disadvantages of using a fiber-reinforced composite as a material for the construction of a car are determined. The prospects for further research in this direction by changing the angle of placement of reinforced fibers in the material are given. However, the introduction of such material in the railroad car building industry requires additional investments and is possible at the stage of manufacturing, not modernization.

Paper [16] highlights the features of the use of panels made of composite material on freight cars. It is proposed to use panels on railroad cars in such a way that it is possible to modernize existing rolling stock, and not only in the manufacture of a new one. The results of endurance tests of composite panels are given. The methodology for testing panels is presented, as well as the expediency of their use on freight cars is substantiated. However, such modernization does not contribute to improving the strength of the car frame as the most loaded unit of the structure during operation.

Our review of literary sources [9–16] proves the feasibility of research into improving the structure of flatcars in order to ensure the safety of transported cargoes.

3. The aim and objectives of the study

The aim of this study is to determine the possibility of using sandwich panels as components of the floor of a flatcar. This could contribute to the safety of cargo transported by rail, as well as reduce the dynamic load of the supporting structure of the flatcar during operation.

To accomplish the aim, the following tasks have been set:

– to determine the dynamic load of the flatcar with a floor made of sandwich panels when it runs in a loaded state;

– to investigate the strength of sandwich panels forming the floor of the flatcar;

– to determine the dynamic load of the flatcar with a floor made of sandwich panels when it runs in a loaded state.

4. The study materials and methods

The object of research is the processes of emergence, perception, and redistribution of loads in the supporting structure of a flatcar with a floor made of sandwich panels.

The main hypothesis of the study assumes that reducing the dynamic load of the supporting structure of a flatcar could contribute to the safety of transported cargoes [17, 18].

To reduce the impact of dynamic loads on the supporting structure of a flatcar, as well as the safety of goods transported on it, it is proposed to manufacture floors from sandwich panels. The peculiarity of the sandwich panel is that it consists of two metal sheets, between which there is an energy-absorbing material with elastic-viscous characteristics (Fig. 1). The use of a sandwich panel as an intermediate adapter between the car frame and the load could help absorb dynamic loads that occur during jumping fluctuations and reduce their impact on the cargo.

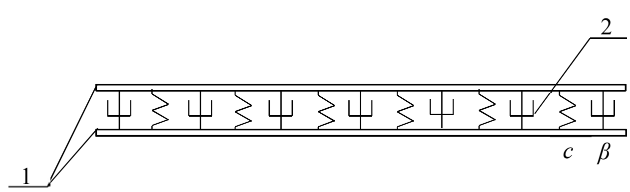

Fig. 1. Structural scheme of a sandwich panel: 1 – metal sheets; 2 – material with energy-absorbing properties

To substantiate the proposed solution, mathematical modeling of the dynamic load of the gondola car in the vertical plane is carried out, that is, jump fluctuations are taken into account as one of the most common types of oscillations that occur during operation.

The estimation scheme of a flatcar is shown in Fig. 2. As a prototype, the flatcar of model 13-401 was chosen. In this case, a flatcar is considered as a system formed by four bodies: a frame, two bogies (model 18-100), and a load placed on the frame. The cargo is considered as conditional using the full payload capacity of a flatcar.

It is assumed that the car moves along the butt rail track, which has elastic characteristics [19, 20].

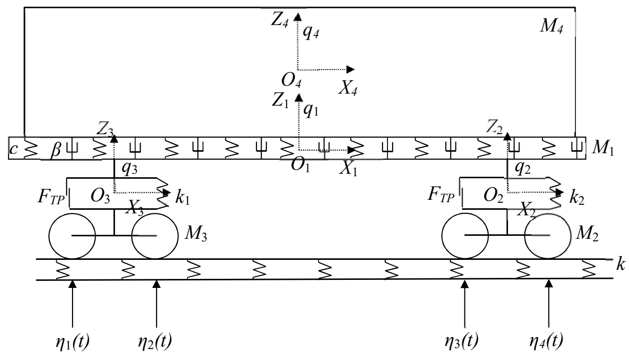

Fig. 2. Estimation scheme of a flatcar

The system of differential equations of movement of a flatcar takes the form:

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

where M_1 is the mass of the supporting structure of a flatcar; M_2, M_3 are the masses, respectively, of the first and second bogies; C_{ij} – elastic characteristics of the elements of the oscillatory system, which are determined by the values of the stiffness coefficients of the spring suspension springs k_T; k – track stiffness; B_{ij} – dissipative coefficients; F_{TR} – friction force in the spring set of the trolley; δ_i – deformations of elastic elements of spring suspension; η_i – track unevenness; F_z – force arising from the movement of cargo relative to the frame of a flatcar.

In this case:

$$F_z = c \cdot \left(q_1 - q_4\right) + \beta \cdot \left(\dot{q}_1 - \dot{q}_4\right), \tag{2}$$

where c is the coefficient of stiffness of energy-absorbing material; β – coefficient of viscous resistance of energy-absorbing material.

The unevenness of the track was described by a periodic function in the following form [19]:

$$\eta(t) = A \cdot (1 - \cos \omega t), \tag{3}$$

where A is the amplitude of the irregularity; ω is the oscillation frequency.

The system of differential equations of motion (1) is solved using the software package Mathcad (USA). To this end, it was reduced to Cauchy equations written in normal form, followed by integration by the Runge–Kutta step-by-step iteration method [21–24]. This method was chosen as an estimation method because it is quite common for solving the equations of car dynamics.

The initial conditions for solving the mathematical model are zero [25–28]. This is justified by the fact that the calculation was carried out with the nominal parameters of the components of the supporting structure of a flatcar.

At the next stage of the study, the thickness of the sheets forming the sandwich panel was determined. It is taken into account that the sandwich panel is represented by a plate having the width a and height b. Its fixing occurs around the perimeter. A uniformly distributed load P is applied to the horizontal plane of the sandwich panel (Fig. 3). To determine the thickness of sheets that form a sandwich panel, the Bubnov-Galerkin method was used [29].

In accordance with this method, the stresses acting in the plate are determined by the following formula:

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

$$\sigma_Y = P \cdot \frac{96}{\pi^4} \cdot \frac{\left(a^2 + \mu \cdot b^2\right) \cdot a^2 \cdot \delta^2}{\left(a^2 + b^2\right) \cdot \delta^2}. \tag{5}$$

Then, if the plate thickness is determined by stresses relative to the X axis, we have:

$$\delta = \sqrt{P \cdot \frac{96}{\pi^4} \cdot \frac{\left(b^2 + \mu \cdot a^2\right) \cdot a^2 \cdot \delta^2}{\sigma_X \left(a^2 + b^2\right)^2}}. \tag{6}$$

In the case of determining the thickness of the plate taking into account the stresses relative to the Y axis, formula (6) takes the form:

$$\delta = \sqrt{P \cdot \frac{96}{\pi^4} \cdot \frac{\left(a^2 + \mu \cdot b^2\right) \cdot a^2 \cdot b^2}{\sigma_Y \left(a^2 + b^2\right)^2}}. \tag{7}$$

According to the obtained values of sheet thickness, a spatial model of a sandwich panel was constructed (Fig. 4) and strength was calculated. Graphic work was carried out in the software package SolidWorks [30, 31].

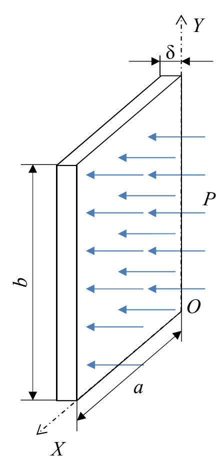

Fig. 3. Estimation scheme of a sandwich panel

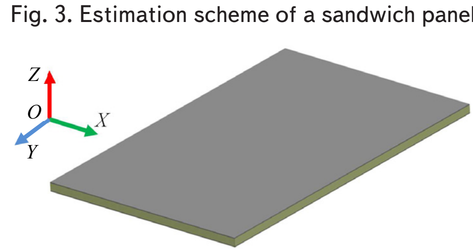

Fig. 4. Sandwich panel spatial model

Aluminum foam is used as an energy-absorbing material. The built models of sandwich panels were laid on the floor of the frame (Fig. 5). When carrying out the calculations, the nominal dimensions of the supporting structure of a flatcar were taken into account. Welds were not taken into account when building the model.

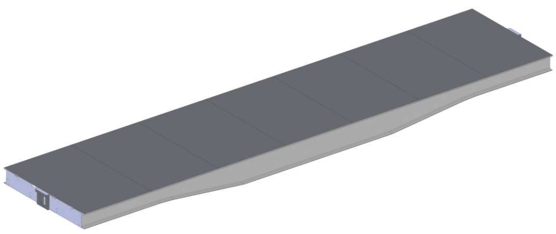

Fig. 5. Placement of sandwich panels on the frame of a flatcar

The calculation of strength was carried out using the finite element method, which is currently the most used one in calculating the strength of vehicles. We employed the software package SolidWorks Simulation (France).

To determine the main indicators of the dynamics of a flatcar, taking into account the fact that its tare increased, mathematical modeling of the vertical load was carried out. It was taken into account that the car travels over a butt irregularity. The estimation scheme of a flatcar is shown in Fig. 6.

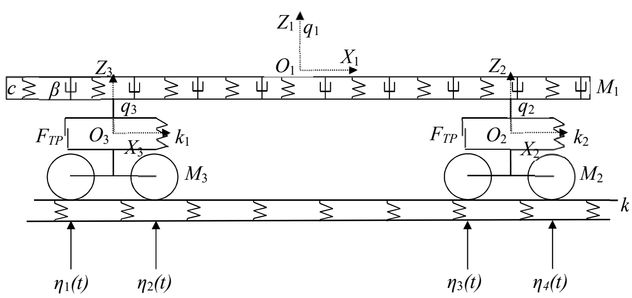

Fig. 6. Estimation scheme of an empty flatcar moving over a butt irregularity

The mathematical model describing the movement of a flatcar takes the following form:

$$\begin{cases} M_1 \cdot \ddot{q}_1 + C_{1,1} \cdot q_1 + C_{1,2} \cdot q_2 + C_{1,3} \cdot q_3 = \\ = -F_{TP} \cdot \left(\operatorname{sign}\left(\dot{\delta}_1\right) + \operatorname{sign}\left(\dot{\delta}_2\right) \right), \\ M_2 \cdot \ddot{q}_2 + C_{2,1} \cdot q_1 + C_{2,2} \cdot q_2 + B_{2,2} \cdot \dot{q}_2 = \\ = F_{TP} \cdot \operatorname{sign}\left(\dot{\delta}_1\right) + k\left(\eta_1 + \eta_2\right), \\ M_3 \cdot \ddot{q}_3 + C_{3,1} \cdot q_1 + C_{3,3} \cdot q_3 + B_{3,3} \cdot \dot{q}_3 = \\ = F_{TP} \cdot \operatorname{sign}\left(\dot{\delta}_2\right) + k\left(\eta_3 + \eta_4\right). \end{cases} \quad (8)$$

All components that are included in this mathematical model are identical to those inherent in model (1).

5. Results of identifying the features of the loading of the supporting structure of a flatcar with a floor made of sandwich panels

5. 1. Determining the dynamic load of a flatcar with a floor made of sandwich panels when it runs in a loaded state

The results of determining the main indicators of the dynamics of a flatcar under the condition of movement in the loaded state over a butt irregularity are shown in Fig. 7–9.

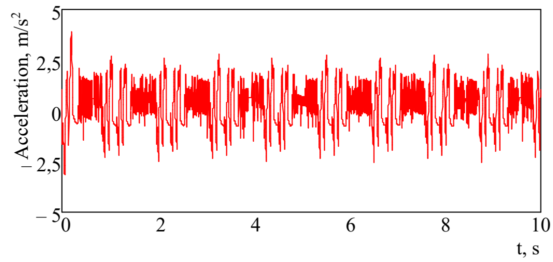

Fig. 7. Acceleration of a flatcar in the center of mass

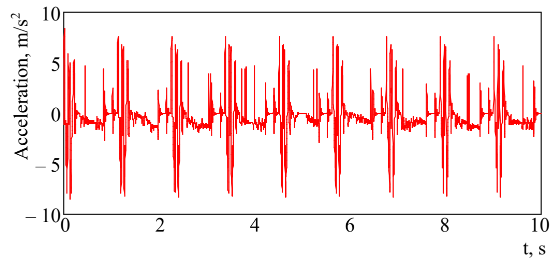

Fig. 8. Acceleration that acts on bogies

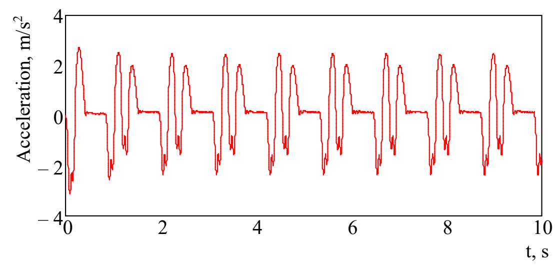

Fig. 9. Acceleration acting on the load

It is established that the maximum accelerations acting in the center of mass of the supporting structure of a flatcar occur at the moment of passing rail unevenness (joint) and are equal to 3.8 m/s^2 (Fig. 7). During the subsequent oscillatory process, the magnitude of acceleration decreases and amounts to 2.5 m/s^2. Consequently, taking into account the proposed solution, the accelerations acting on the supporting structure of a flatcar are reduced by 8.4 % compared to the typical one.

The acceleration that acts on the bogies, the first in the course of movement and the second, respectively, is shown in Fig. 8. The numerical value of acceleration is about 9.4 m/s^2.

The acceleration acting on the load placed on the frame of a flatcar was 2.8 m/s^2 (Fig. 9).

The obtained value of acceleration is 11.7 % lower than that acting on the cargo, taking into account the typical pattern of perception of loads.

5. 2. Investigation of the strength of sandwich panels forming the floor of a flatcar

To determine the thickness of the sheets that form the sandwich panel, appropriate calculations were performed. It was taken into account that the plate has the width a=1.914 m when using 7 sandwich panels on the frame, and the height b=3.0 m.

The material for the manufacture of metal sheets of sandwich panels is steel 09G2S. The tensile strength for this steel grade is 490 MPa, and the yield strength is 345 MPa. Taking into account the fact that a flatcar is loaded using full carrying capacity, the force acting on one plate will be P=98.1 kN.

Based on our calculations in accordance with formulas (6), (7), the value of the plate thickness was obtained, which is equal to 6 mm.

To determine the strength of sandwich panels, subject to placement on the frame of a flatcar, an estimation scheme was built (Fig. 10). It was taken into account that the sandwich panel is affected by the vertical load P_v, due to vertical static and dynamic loads.

The model of the supporting structure of a flatcar is fixed to the horizontal surfaces of the frame heels. When building a finite-element model, tetrahedra were used [32–34]. The model has 373651 elements and 127073 nodes. The maximum size of the element is 180 mm, and the minimum is 36 mm. Steel grade 09G2S is intended as the material of the supporting structure. This steel grade is typical for the manufacture of load-bearing structures of cars.

The results of the strength calculation showed that the maximum stresses in the frame of a flatcar are 131.7 MPa (Fig. 11). These stresses occur in the girder beam – in the zones of its interaction with the pin beam and are due to the fact that the model was fastened to the heels. The maximum stresses in sandwich panels are about 94.5 MPa, that is, almost twice lower than permissible. In this case, the stress is 210 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). The foreign analog of this standard is EN 12663–2. Railroad applications – structural requirements of railroad vehicle bodies – Part 2: Freight cars.

Maximum displacements occur in the middle part of the frame of a flatcar and are 4.35 mm (Fig. 12).

Our studies prove that the introduction of sandwich panels in the supporting structure of a flatcar is expedient.

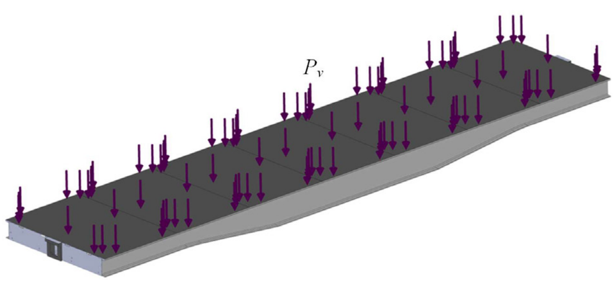

Fig. 10. Estimation scheme of a flatcar

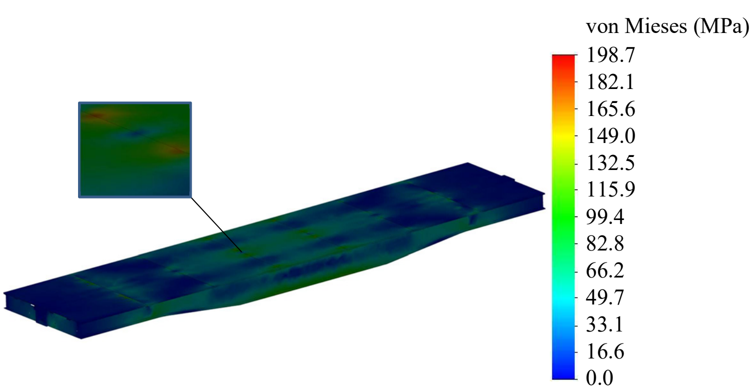

Fig. 11. Stressed state of the supporting structure of a flatcar

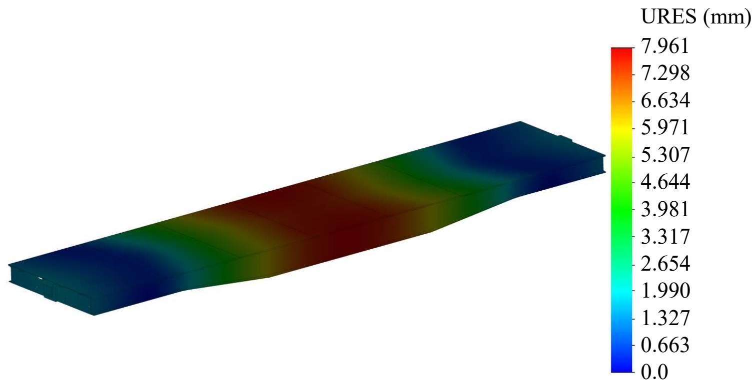

Fig. 12. Displacement in the nodes of the supporting structure of a flatcar

5. 3. Determination of the dynamic load of a flatcar with a floor made of sandwich panels when it runs in a loaded state

Due to the fact that the use of sandwich panels contributes to an increase in the tare of a flatcar by 12 %, the main indicators of dynamics during its movement in an empty state were determined.

The results of our calculations are shown in Fig. 13, 14.

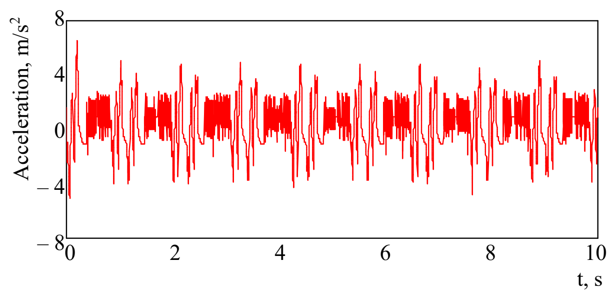

Fig. 13. Acceleration of a flatcar in the center of mass

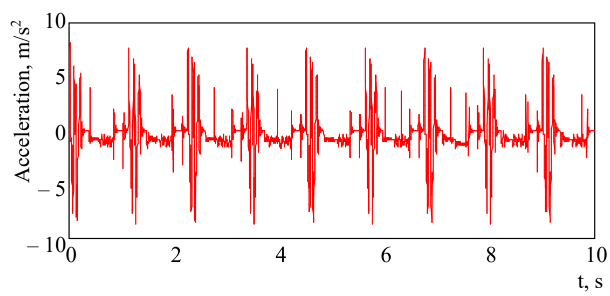

Fig. 14. Acceleration that acts on bogies

The maximum acceleration of a flatcar in the center of mass was about 6 m/s^2 (0.6 g), and the acceleration of the bogies – about 8.5 m/s^2. The obtained dynamics indicators correspond to the "good" run of the car.

6. Discussion of results of identifying the peculiarities of the loading features of the supporting structure of a flatcar with a floor made of sandwich panels

To ensure the safety of transported goods by rail, it is proposed to improve the design of a flatcar by introducing sandwich panels. This solution could help reduce the dynamic loads that act on the supporting structure of a flatcar, and, accordingly, on the cargo placed on it.

The results of mathematical modeling of the dynamic load of the improved design of a flatcar showed that the accelerations acting on it are reduced by 8.4 % compared to the typical one (Fig. 7). This is due to the use of an intermediate adapter in the form of a sandwich panel with malleable connections between the frame of a flatcar and the cargo. The accelerations acting on the load placed on a flatcar are reduced by 11.7 % (Fig. 9). The magnitude of accelerations is given for the case of movement of a flatcar in a loaded state over a butt irregularity.

The obtained accelerations were taken into account when calculating the strength of sandwich panels, taking into account their placement on a flatcar. It was established that the maximum stresses in sandwich panels are about 94.5 MPa (Fig. 11), that is, almost twice lower than permissible. This is due to the fact that the accelerations that act on the supporting structure of a flatcar, taking into account the proposed improvement, are reduced compared to those that act on a typical structure. Maximum displacements occur in the middle part of the frame of a flatcar and are 4.35 mm (Fig. 12).

It is important to say that the use of sandwich panels as components of the construction of a flatcar increases its tare by 12 % compared to the prototype. In this regard, in order to ensure the safety of movement of a flatcar, the main indicators of its dynamics when it runs in a loaded state were determined. It was established that the maximum acceleration of a flatcar in the center of mass is about 6 m/s^2 (Fig. 13), and the acceleration of bogies is about 8.5 m/s^2 (Fig. 14). Consequently, the run of movement of a flatcar can be assessed as "good".

The advantage of our study in comparison with [9–11] is that we proposed solutions aimed at reducing the dynamic load, which may be appropriate for different types of cars. In comparison with work [12], the advantage of the results obtained is that they contribute to improving the strength indicators of the car structure by reducing the dynamic load, rather than strengthening the structure. It must be said that the proposed improvement is appropriate at the stage of modernization of cars, in contrast to the solution considered in [13]. The solution proposed in this work is implemented on the most common type of car in international traffic, which could contribute to its profitability, in contrast to the solutions reported in works [14, 15]. In contrast to the results of work [16], the proposed improvement contributes to improving the strength of the car frame as the most loaded structural unit during operation.

It is important to say that the solutions proposed in this article are also relevant in relation to other sectors of transport.

The limitation of the study is that we took into account the movement of a flatcar on an elastic track, that is, the dissipative components that occur during its oscillations were not taken into account.

The disadvantage of this study is that we investigated the efficiency of sandwich panels with fluctuations in the jumping of a flatcar. That is, galloping fluctuations, which are also characterized by vertical displacements of a flatcar, but angular ones, were not taken into account.

Further development of this study is to determine the feasibility of using sandwich panels as components of structures of other types of cars. It is necessary to analyze the prospects for the use of more optimal materials for the execution of sandwich panels. The issues of experimental confirmation of the feasibility of introducing sandwich panels require attention. These issues will be addressed in further research by our prolific team.

7. Conclusions

1. The dynamic load of a flatcar with a floor made of sandwich panels when it runs in a loaded state has been determined. The maximum accelerations that act in the center of mass of the supporting structure of a flatcar occur at the time of its run over a rail unevenness and are equal to 3.8 m/s^2. During the subsequent oscillatory process, the acceleration value decreases and amounts to 2.5 m/s^2. Consequently, taking into account the proposed solution, the accelerations acting on the supporting structure of a flatcar are reduced by 8.4 % compared to the typical one. The acceleration that acts on the load placed on a flatcar amounted to 2.8 m/s^2, which is 11.7 % lower than that acting on the cargo, taking into account the typical pattern of perception of loads.

2. The strength of sandwich panels forming the floor of a flatcar was investigated. The maximum stresses in sandwich panels are about 94.5 MPa, that is, almost twice lower than permissible. In this case, the permissible stress is 210 MPa. Maximum displacements occur in the middle part of the frame of a flatcar and are 4.35 mm.

The peculiarity of our results is that the improvement of the strength of the supporting structure of a flatcar is achieved by reducing the dynamic loads that act on it. That is, a distinctive feature of the research results is not the strengthening of the supporting structure of a flatcar but the reduction of the impact of dynamic loads on it. By reducing dynamic loads, the safety of goods transported by a flatcar also improves.

3. The dynamic load of a flatcar with a floor made of sandwich panels when it runs in a loaded state has been determined. The maximum acceleration of the supporting structure of a flatcar in the center of mass was about 6 m/s^2 (0.6 g). The acceleration of the bogies is about 8.5 m/s^2. The obtained dynamics indicators correspond to the "good" run of the car.

Our research could contribute to the preparation of recommendations for the design of modern structures of railroad vehicles and increase the efficiency of the functioning of the transportation industry.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

Funding

The study was conducted without financial support.

Data availability

All data are available in the main text of the manuscript.

References

1. Nerubatskyi, V., Plakhtii, O., Hordiienko, D. (2022). Adaptive Modulation Frequency Selection System in Power Active Filter. 2022 IEEE 8th International Conference on Energy Smart Systems (ESS). doi: https://doi.org/10.1109/ess57819.2022.9969261
2. Nerubatskyi, V., Plakhtii, O., Hordiienko, D. (2022). Improving the energy efficiency of traction power supply systems by means the implementation of alternative power sources. Transport Means 2022. Part I. Proceedings of the 26th International Scientific Conference, 459–464. Available at: https://www.ebooks.ktu.lt/eb/1610/transport-means-2022-part-i-proceedings-of-the-26th-international-scientific-conference/
3. Nerubatskyi, V., Plakhtii, O., Hordiienko, D. (2022). Efficiency Analysis of DC-DC Converter with Pulse-Width and Pulse-Frequency Modulation. 2022 IEEE 41st International Conference on Electronics and Nanotechnology (ELNANO). doi: https://doi.org/10.1109/elnano54667.2022.9926762
4. Lewandowski, K. (2006). Nadwozia wymienne (swap body) w bezterminalowym systemie transportu szynowego. Sistemy transportowe, 6, 53–55. Available at: https://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-article-BGPK-1398-5437/c/Lewandowski.pdf
5. Chuan-jin, O., Bing-tao, L. (2020). Research and application of new multimodal transport equipment-swap bodies in China. E3S Web of Conferences, 145, 02001. doi: https://doi.org/10.1051/e3sconf/202014502001
6. Šťastniak, P., Kurčík, P., Pavlík, A. (2018). Design of a new railway wagon for intermodal transport with the adaptable loading platform. MATEC Web of Conferences, 235, 00030. doi: https://doi.org/10.1051/matecconf/201823500030
7. Dižo, J., Blatnický, M., Steišūnas, S., Skočilasová, B. (2018). Assessment of a rail vehicle running with the damaged wheel on a ride comfort for passengers. MATEC Web of Conferences, 157, 03004. doi: https://doi.org/10.1051/matecconf/201815703004
8. Harak, S. S., Sharma, S. C., Harsha, S. P. (2014). Structural Dynamic Analysis of Freight Railway Wagon Using Finite Element Method. Procedia Materials Science, 6, 1891–1898. doi: https://doi.org/10.1016/j.mspro.2014.07.221
9. Fomin, O., Gorbunov, M., Lovska, A., Gerlici, J., Kravchenko, K. (2021). Dynamics and Strength of Circular Tube Open Wagons with Aluminum Foam Filled Center Sills. Materials, 14 (8), 1915. doi: https://doi.org/10.3390/ma14081915
10. Płaczek, M., Wróbel, A., Buchacz, A. (2016). A concept of technology for freight wagons modernization. IOP Conference Series: Materials Science and Engineering, 161, 012107. doi: https://doi.org/10.1088/1757-899x/161/1/012107
11. Lee, H.-A., Jung, S.-B., Jang, H.-H., Shin, D.-H., Lee, J. U., Kim, K. W., Park, G.-J. (2015). Structural-optimization-based design process for the body of a railway vehicle made from extruded aluminum panels. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 230 (4), 1283–1296. doi: https://doi.org/10.1177/0954409715593971
12. Al-Sukhon, A., ElSayed, M. S. (2021). Design optimization of hopper cars employing functionally graded honeycomb sandwich panels. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 236 (8), 920–935. doi: https://doi.org/10.1177/09544097211049640
13. Fomin, O., Gorbunov, M., Gerlici, J., Vatulia, G., Lovska, A., Kravchenko, K. (2021). Research into the Strength of an Open Wagon with Double Sidewalls Filled with Aluminium Foam. Materials, 14 (12), 3420. doi: https://doi.org/10.3390/ma14123420
14. Jeong, D. Y., Tyrell, D. C., Carolan, M. E., Perlman, A. B. (2009). Improved Tank Car Design Development: Ongoing Studies on Sandwich Structures. 2009 Joint Rail Conference. doi: https://doi.org/10.1115/jrc2009-63025
15. Street, G. E., Mistry, P. J., Johnson, M. S. (2021). Impact Resistance of Fibre Reinforced Composite Railway Freight Tank Wagons. Journal of Composites Science, 5 (6), 152. doi: https://doi.org/10.3390/jcs5060152
16. Wróbel, A., Płaczek, M., Buchacz, A. (2017). An Endurance Test of Composite Panels. Solid State Phenomena, 260, 241–248. doi: https://doi.org/10.4028/www.scientific.net/ssp.260.241
17. Fomin, O., Gerlici, J., Vatulia, G., Lovska, A., Kravchenko, K. (2021). Determination of the Loading of a Flat Rack Container during Operating Modes. Applied Sciences, 11 (16), 7623. doi: https://doi.org/10.3390/app11167623
18. Panchenko, S., Vatulia, G., Lovska, A., Ravlyuk, V., Elyazov, I., Huseynov, I. (2022). Influence of structural solutions of an improved brake cylinder of a freight car of railway transport on its load in operation. EUREKA: Physics and Engineering, 6, 45–55. doi: https://doi.org/10.21303/2461-4262.2022.002638
19. Domin, Yu. V., Cherniak, H. Yu. (2003). Osnovy dynamiky vahoniv. Kyiv: KUETT, 269.
20. Panchenko, S., Gerlici, J., Vatulia, G., Lovska, A., Pavliuchenkov, M., Kravchenko, K. (2022). The Analysis of the Loading and the Strength of the FLAT RACK Removable Module with Viscoelastic Bonds in the Fittings. Applied Sciences, 13 (1), 79. doi: https://doi.org/10.3390/app13010079
21. Zadachyn, V. M., Koniushenko, I. H. (2014). Chyselni metody. Kharkiv, 180. Available at: http://kist.ntu.edu.ua/textPhD/CHM_Zadachin.pdf
22. Hoi, T. P., Makhnei, O. V. (2012). Dyferentsialni rivniannia. Ivano-Frankivsk, 352. Available at: https://kdrpm.pnu.edu.ua/wp-content/uploads/sites/55/2018/03/deinf_el.pdf
23. Siasiev, A. V. (2004). Vstup do systemy MathCad. Dnipropetrovsk, 108. Available at: https://library_donetsk19.donetskedu.com/uk/library/vstup-do-sistemi-mathcad-navchalnii-posibnik.html

24. Bohach, I. V., Krakovetskyi, O. Yu., Kylyk, L. V. (2020). Chyselni metody rozviazannia dyferentsialnykh rivnian zasobamy MathCad. Vinnytsia, 106. Available at: http://pdf.lib.vntu.edu.ua/books/IRVC/Bogach_2020_106.pdf
25. Koshlan, A., Salnikova, O., Chekhovska, M., Zhyvotovskyi, R., Prokopenko, Y., Hurskyi, T. et al. (2019). Development of an algorithm for complex processing of geospatial data in the special-purpose geoinformation system in conditions of diversity and uncertainty of data. Eastern-European Journal of Enterprise Technologies, 5 (9 (101)), 35–45. doi: https://doi.org/10.15587/1729-4061.2019.180197
26. Dudnyk, V., Sinenko, Y., Matsyk, M., Demchenko, Y., Zhyvotovskyi, R., Repilo, I. et al. (2020). Development of a method for training artificial neural networks for intelligent decision support systems. Eastern-European Journal of Enterprise Technologies, 3 (2 (105)), 37–47. doi: https://doi.org/10.15587/1729-4061.2020.203301
27. Iwnicki, S. D., Stichel, S., Orlova, A., Hecht, M. (2015). Dynamics of railway freight vehicles. Vehicle System Dynamics, 53 (7), 995–1033. doi: https://doi.org/10.1080/00423114.2015.1037773
28. Yang, C., Li, F., Huang, Y., Wang, K., He, B. (2013). Comparative study on wheel–rail dynamic interactions of side-frame cross-bracing bogie and sub-frame radial bogie. Journal of Modern Transportation, 21 (1), 1–8. doi: https://doi.org/10.1007/s40534-013-0001-3
29. Bezukhov, N. I. (1957). Sbornik zadach po teorii upru gosti i plastichnosti. Moscow: Gosudartvennoe izdatel'stvo tekhniko-teoreticheskoy literatury, 286.
30. Lovska, A. (2014). Assessment of dynamic efforts to bodies of wagons at transportation with railway ferries. Eastern-European Journal of Enterprise Technologies, 3 (4 (69)), 36–41. doi: https://doi.org/10.15587/1729-4061.2014.24997
31. Fomin, O., Lovska, A., Khara, M., Nikolaienko, I., Lytvynenko, A., Sova, S. (2022). Adapting the load-bearing structure of a gondola car for transporting high-temperature cargoes. Eastern-European Journal of Enterprise Technologies, 2 (7 (116)), 6–13. doi: https://doi.org/10.15587/1729-4061.2022.253770
32. Stoilov, V., Simić, G., Purgić, S., Milković, D., Slavchev, S., Radulović, S., Maznichki, V. (2019). Comparative analysis of the results of theoretical and experimental studies of freight wagon Sdggmrss-twin. IOP Conference Series: Materials Science and Engineering, 664 (1), 012026. doi: https://doi.org/10.1088/1757-899x/664/1/012026
33. Kondratiev, A. V., Gaidachuk, V. E. (2021). Mathematical Analysis of Technological Parameters for Producing Superfine Prepregs by Flattening Carbon Fibers. Mechanics of Composite Materials, 57 (1), 91–100. doi: https://doi.org/10.1007/s11029-021-09936-3
34. Vambol, O., Kondratiev, A., Purhina, S., Shevtsova, M. (2021). Determining the parameters for a 3D-printing process using the fused deposition modeling in order to manufacture an article with the required structural parameters. Eastern-European Journal of Enterprise Technologies, 2 (1 (110)), 70–80. doi: https://doi.org/10.15587/1729-4061.2021.227075