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STRENGTH ANALYSIS OF THE MODEL 918 WAGON UNDER NON-TYPICAL BULK LOADS

Purpose. Highlighting the results of the analysis of the stress-deformed state of the wagon body of the 918 model under non-typical loads with bulk cargo. Such an analysis was carried out with the aim of investigating the possibility of transportation of various types of bulk cargo (for example, various types of raw materials, agricultural products, construction materials, etc.) in the existing design of the section of the refrigerated wagon.

Methodology. In order to ensure uninterrupted railway transportation in today’s difficult conditions, it is proposed to use scientific and applied approaches to develop the possibility of using existing models of wagons for types of transportation that are not typical for them. Namely, to consider the possibility of using refrigerated wagons for the transportation of bulk cargo. A systematic approach is used to conduct such research. This included: determination of the study of the specifics of the impact of bulk cargo on rolling stock structures; analysis of design and technological documentation to create a spatial 3D model of the wagon under investigation; creation of a calculation model using a modern software complex; checking the adequacy of the developed model and the accuracy of the data obtained with its help; application of non-typical design loads; obtaining and analyzing pictures of stress-strain states by the finite element method.

Findings. A 3D model of the body module of the model 918 wagon was developed. The results of the analysis of the equivalent stress plot according to the first mode proved that the greatest stresses are 800 MPa, that is, they significantly exceed the permissible ones. According to the third mode, the highest stresses are 320 MPa and also exceed the permissible ones. The results of the analysis of the plot of equivalent stresses, which occur during expansion, proved that the loads are excessive. The cladding, supported only by racks, cannot hold the load from the bulk cargo.

Originality. A strength analysis of the existing design of a refrigerated wagon section was conducted under non-typical bulk cargo loads.

Practical value. The obtained results of the analysis of the stressed-deformed state of the body of the model 918 wagon when loaded with bulk cargo made it possible to assess the potential possibilities of such transportation. It is expedient to use such results when carrying out research and development works on the improvement (modernization) of the existing sections of refrigerated wagons to ensure the possibility of transporting bulk cargo in them. This, in turn, will increase the efficiency of the domestic fleet of freight wagons.

Keywords: *mechanical engineering, freight wagons, strength calculations, bulk loads*

Introduction. Modern operating conditions of railway rolling stock of Ukraine are very complex. This is justified by the need to meet the requirements of railway freight transportation with the existing models of the wagon fleet. This requires their use in non-typical (not for the transportation of goods defined by the technical conditions) operating conditions. In particular, there is a need to use sections of refrigerated wagons for the transportation of various types of bulk cargo. The quality of such cargo can be, for example, various raw materials, agricultural products, construction and finishing materials, and others.

Literature review. In the paper [1], the authors describe the problems of the appearance of defects in the form of cracks on the vertical sheet of the backbone beam of dump trucks, the repair of which is not provided for in the documentation for current repairs. The scientific publication presents the results of the analysis of malfunctions of dump trucks, the results of control tests and strength studies in order to confirm the theory of the occurrence of cracks on the backbone beam using the calculation-experimental method in the SolidWorks Simulation software package.

The authors in the publication [2] consider modern methods for estimating the residual resource of the load-bearing structures of railway rolling stock. In the study, the authors also considered the change in the endurance limit in the structure under the action of multi-cycle loads, but the work does not describe how the endurance limit of modernized freight wagons changes.

In the scientific paper [3], the authors consider the issue aimed at the development of a modern methodology for assessing the fatigue life of new railway freight wagons. In order to evaluate the fatigue life, the authors propose to conduct accelerated bench tests simulating the conditions of real operation of freight wagons. However, the work does not describe the issue of estimating the fatigue life by computational and experimental methods of modernized freight wagon bodies.

In work [4], an analysis of the types of failures of elements of the rolling stock's undercarriage was performed and a structure based on their criticality was created. However, the analysis concerned only the running parts, failures of the load-bearing structures of the freight wagons were not considered. Freight railway wagons occupy a significant share in the total capital of a freight railway enterprise.

The authors of the work [5] consider the real problem of managing a fleet of freight wagons and propose a decomposition approach to optimize a heterogeneous fleet of platform wagons. The proposed approach includes four stages: generation of random container weight, optimal distribution of the container on the wagon, changing the position of the empty wagon, and optimal size of the wagon fleet. In the work, it would also be appropriate to consider the issue of modernization of the non-operated fleet of covered wagons into wagons for the transportation of bulk cargo.

The authors of the work [6] investigate the longitudinal forces acting on a railway wagon for different loading conditions of the wagons in the train. Three different types of wagons are considered in the work, namely fully loaded, partially loaded and empty wagons. The purpose of this work is to determine the best place for their location in a freight train where the smallest longitudinal forces occur, regardless of the wagon loading scheme. However, the work does not assess the influence of horizontal forces on the railway wagon which significantly affect the safety of the movement of railway wagons.

In studies [7, 8], the author teams proposed approaches and methods regarding the possibility of calculating machine-building structures for non-typical loads. At the same time, appropriate mathematical models, graphical and analytical dependencies were obtained.

The article [9] presents a study of the descent of freight wagons in symmetrical turnouts No. 6. A dynamic model of a freight wagon and a model of a flexible turnout, which undergoes derailment when the wheel flange is lifted, were created. In addition, a full-scale wheel-rail interaction test was conducted to verify the dynamic model. As a result of the simulation of derailment during lifting, the wheels are consistent with the research data, and the safety of the cart depends on the condition of both the front and rear wheels.

In the article [10], the authors present the concept of a smart railway wagon modeled from smart components. This concept can meet the safety requirements of a complex railway system. Adding self-diagnostic features to a rail wagon reduces the risk of accidents. This paper also presents the concept and functional model of this railway wagon and illustrates the utility of this concept based on investigated railway accidents.

In work [11], the dynamic load of load-bearing structures of the main types of freight wagons with actual dimensions in the main operating conditions was determined. The work also takes into account two cases of load bearing structures of wagons – in the vertical and longitudinal planes. The results of the work make it possible to develop conceptual foundations for restoring the effective functioning of outdated freight wagons. Freight wagons mainly consist of welded steel structures subjected to time-varying loads.

Therefore, in [12], the authors proposed several technical codes for fatigue assessment of load-bearing structures. Also, in this article, a comparison of the studied codes for fatigue assessment of load-carrying structures of the freight wagon is carried out. The obtained results provide a comprehensive overview of the influence of the choice of a specific technical code for the evaluation and prediction of fatigue life.

Scientific publications [13, 14] are devoted to consideration of the features of the impact of loads on various types of structures. At the same time, more attention is paid to bulk cargoes and not bulk cargoes.

The authors of the paper [15] describe the calculation models of the 18–100 bogie built using modern information technologies and the developed software for predicting the influence of irregular cyclic loading and complex stresses on the growth of a surface fatigue crack in the side frame of the bogie, which significantly brings the problem closer to the real operating conditions.

The article [16] gives the results of an automated analysis of the strength of a modernized freight wagon using the finite element method. A CAD model of the considered freight wagon was created and its strength was analyzed in accordance with the norms describing the method for testing this type of freight wagons. Then, the model of the analyzed freight wagon was modernized by adding composite panels covering the inner surface of the wagon body. The strength analysis was performed again and the results obtained were compared. This work was carried out in order to check the effect of composite panels on the strength of the freight wagon body and evaluate the possibility of reducing the thickness of the steel shell of the body in order to reduce the weight of the freight wagon.

The article [17] examines the prospects for the implementation of the "smart freight wagon" concept. The concept of developing a system for monitoring the state of operation of rolling stock and transmitting telemetric data about the state of the infrastructure under the name "Smart Freight Wagon" is also being considered. The authors also offer their concept of improving this system based on the openHAB smart system model, which allows making a modular system in order to increase fault tolerance and flexible adaptation to the needs of specific customers.

The question of modernization of freight wagons using composite materials is discussed in [18]. The main direction with the use of composite materials is the body of a freight wagon. Such measures provide for the improvement of anti-corrosion characteristics. At the same time, it is believed that corrosion processes have the greatest effect on the body of a freight wagon, but this issue was not considered in the article.

In the paper [19], the authors presented a numerical study of the mechanical response of the freight wagon body to normal loads that occur during operation. The main goal of this study is to investigate the possibility of replacing the steel walls of the wagon with walls made of laminated composites. In this way, the total weight of the wagon can be reduced, leaving room for additional cargo loading. According to the results of the study, it was concluded that the proposed modernization does not change the strength indicators in the structure, and therefore, it is a good solution for reducing the total weight of the freight wagon.

The study [20, 21] presented the results of research works on the influence of non-typical loads on the structures of freight wagons. At the same time, the loads that arise during the transportation of wagon structures on ferries were considered.

Article [22] is devoted to diagnostics of the technical condition of load-bearing transport modules. At the same time, the main attention was paid to driving forces and driving moments.

The study [23] presents the results of solving important scientific and practical issues for freight wagon constructions. It is these structures that take the main part in the transportation of bulk cargo. However, today the fleet of such wagons does not fully meet the needs of seasonal transportation. In addition, the fleet of freight wagons is characterized by high wear and tear and obsolescence.

Articles [24, 25] present the results of research and development work on modeling and determination of loads acting on transport structures made of composite materials. However, in this case, the structures are made of steel.

Unsolved aspects of the problem. The results of the analysis of various types of information sources proved that insufficient attention was paid to the issue of consideration of the possibility of transporting bulk cargo in sections of refrigerated wagons. At the same time, the relevance of researching and solving such a question is undeniable. This is explained by the presence of a significant share of refrigerated wagons that are idle and thus incur unjustified costs. Despite the fact that there is a demand for the transportation of bulk cargo, and for the full provision of which, accordingly, there is not enough fleet of wagons. Summarizing the above, it is possible to confidently conclude about the relevance and economically justified feasibility of deploying research and development works in order to ensure the involvement of a refrigerated fleet of freight wagons in the transportation of bulk cargo. And accordingly, the first important step on the way to solving this scientific and technical problem is to conduct an analysis of the strength (stress-strain state) of the typical model 918 refrigerated rolling stock under (non-typical) loads with bulk cargo.

The purpose of the article. The purpose of the article is to highlight the results of the analysis of the stress-deformation state of the body of the type-918 wagon under (non-typical) loads with bulk cargo. Such an analysis was conducted with the aim of investigating the possibility of transporting various types of bulk cargo (for example, various types of raw materials, agricultural products, construction materials, etc.) in the existing design of the section of the refrigerated wagon. To achieve the specified goal of the study, the following tasks were set:

- to analyze the features of the bearing structures of the wagons under consideration;
- to develop an adequate computational finite-element model of the load-bearing structures of the wagons under consideration;
- to determine the nature of the application and the magnitude of the current (non-typical) loads with bulk cargo on the bearing structures of the wagons under consideration;
- to carry out computer modeling in order to obtain pictures of the stress-strain state of the structure under investigation;
- to analyze the received pictures of the stress-strain state of the structure and draw conclusions.

Methods. Obtaining the results of the presented scientific and applied research included traditional, generally accepted research stages in accordance with the goal. Namely: a formalized presentation of the problem and tasks of the research (based on: the results of information-analytical and international patent search, a complete and systematic critical analysis of global and industry developments in this direction, a collection of expert-experienced assessments and proposals, a comprehensive and systematized review of modern scientific and technical departments on the profile of issues); analysis of design and technological documentation to create a spatial 3D model of the wagon under investigation; creation of a calculation model using a modern software complex; checking the adequacy of the developed model and the accuracy of the data obtained with its help; application of non-typical (corresponding to the action of bulk cargo) design loads; obtaining and analyzing pictures of stress-strain states by the finite element method; formulation of conclusions. When conducting the research, normative data from: interstate standards, DSTU, instructions, methods, regulations and projects were used, which correspond to the problems of research and implementation, and when creating a computer calculation model, software products: Mathcad, SolidWorks, CosmosWorks were used.

Results. The refrigerator wagon is a universal covered wagon designed for the transportation of perishable goods, most of which are food products. Refrigerated wagons are structurally isometric wagons with an all-metal body and a layer of thermal insulation to protect the interior of the wagon from external thermal influences. The refrigerated section consists of one diesel and four freight wagons. In order to assess the stress-strain state (strength calculation according to the Norms) of the load-bearing structures of the model 918 wagon using the finite element method, a corresponding 3D model was built in the SolidWorks computer package. The body of the model 918 wagon is an all-metal load-bearing structure and is made of a set of longitudinal and transverse stiffening elements covered with thin corrugated sheets. The 3D model of the wagon body of the 918 model was built according to the design documentation of the manufacturing plant and consists of more than 550 parts (Fig. 1).

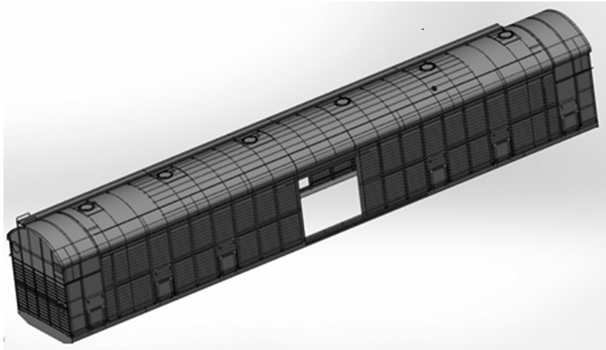


Fig. 1. 3D model of the wagon body

Table 1

Parameters of the finite-element model of the wagon body

Parameter	Value
The size of the element	5 and 50 mm
The number of elements	9,962,551
The number of nodes	3,769,747

For strength calculations, a finite-element model of the wagon body with the dimensions of the finite elements of 5 and 50 mm was developed.

The parameters of the finite-element model of the 918 wagon body are listed in Table 1.

The loading scheme for the wagon body of model 918 was developed according to [11, 23]. The calculations were performed for the most unfavorable possible combination of simultaneously acting standard forces in accordance with the established design modes.

The first – to take into account the maximum load on the end wall and the third – the maximum load on the side wall. The first design mode is a conditional safety mode. The operating conditions according to the first calculation mode for freight wagons correspond to the settling and shifting of heavy rolling stock from a place, collision of wagons during shunting, including when disbanding from humps, emergency braking in trains at low speeds or collision of wagons in emergency situations, as well as an emergency jerk (push).

The third design mode is the operational mode. Under the operating conditions of the Third design mode, the cases of movement of a fully loaded wagon as part of a train on straight and curved sections of track and switches of the corresponding design and condition at an acceptable speed, up to the design speed, during periodic service adjustment braking, periodic moderate jerks and periodic moderate jerks of the standard operation of the wagon mechanisms and units correspond.

Since the wagon will be used for the transportation of bulk cargo, it was decided to calculate the side walls for the bursting load.

The pressure of the bulk cargo per unit of pilgrimage of the walls of the body P_a, N/m^2 is determined by the formula

$$P_a = (1 + k_{vd}) \cdot \gamma \cdot g \cdot y \cdot \mathrm{tg}\left(\frac{\pi}{4} - \frac{\varphi}{2}\right), \quad (1)$$

where k_{vd} is the coefficient of vertical dynamics, it is taken when calculating according to the first mode $k_{vd} = 0.1$ and according to the third mode $k_{vd} = 0.353$; γ – the bulk density of the cargo (the density of the transported cargo) is determined by the nominal carrying capacity (50 t) and the volume of the body in the general case is determined (112 m^3) and is:

a) $\gamma = 800$ kg/m^3 loading height 1.2 m;

b) $\gamma = 500$ kg/m^3 loading height 2.2 m.

At the minimum density, the loading height is 2.2 m, and the maximum cargo weight is 39.2 tons.

At the maximum cargo density, the maximum loading height is 1.2 m, and the maximum cargo weight is 49 tons.

$g = 9.81$ m/s^2 – acceleration of free fall; y is the distance from the load to the point where the pressure is determined; φ is the angle of the natural slope of the load, formed by the surface of the loosely packed load with a horizontal surface. The angle φ is taken when calculating according to the I mode in accordance with [11, 23] (for sunflower we take 0.78 rad), and according to the III mode it is equal to 0.2 from the value [11, 23] ($0.78 \cdot 0.2 = 0.157$ rad).

Bulk cargo pressure according to the third load mode. We determine the active (static) pressure per unit thickness of the side wall, Pa

$$P_a = P_a = (1+0.353)\cdot 800\cdot 9.81\cdot y\cdot \mathrm{tg}\left(\frac{3.14}{4}-\frac{0.157}{2}\right) = 9.062;$$

$$P_a = (1+0.353)\cdot 500\cdot 9.81\cdot y\cdot \mathrm{tg}\left(\frac{3.14}{4}-\frac{0.157}{2}\right) = 5.664.$$

The calculated forces are given in Table 2.

The calculation scheme for the third mode is presented in Fig. 2. During the calculation, simulation was performed with different degrees of loading: $\gamma = 800$ kg/m^3 loading height 1.2 m; $\gamma = 500$ kg/m^3 loading height 2.2 m.

Permissible stresses. When determining the properties of the material, which are required for strength calculations, some assumptions are made. First, the material from which this or that part is made is considered homogeneous. In addition, the actual characteristics of the real material from which any structure is made have certain deviations from the characteristics given in the handbooks.

Wagon bodies are made of St3 steel. The allowable stresses adopted in accordance with [11, 23] when calculating the strength of the load-bearing elements of the frame are given in Table 3.

Table 2

Static and kinematic boundary conditions

Load conditions	Mode I	Mode III
Longitudinal load (applied to the rear stops of the auto coupling)	2.5 MN	2.0 MN
Vertical load: - gross gravity; - vertical dynamic load (applied as the acceleration of a rigid body); - the vertical component of the longitudinal inertia force of the body (applied as the acceleration of a rigid body)	72.6 t (36.3 t for half of the body) Not taken into account 13.45 t (50 % $g + a$ = = 11.6 m/s^2)	72.6 t (36.3 t for half of the body) 25.6 t ($K_d = 0.353$ $g + a = 9.81 + 3.46 =$ $= 13.27$ m/s^2) Not taken into account
Lateral load: - centrifugal force (applied to the pivot and compensated by the inertia of the body in the lateral direction); - the transverse component of the longitudinal quasi-static force (applied to the pivot and on the rear stop)	Not taken into account 263 kN 224 kN	72.6 kN (0.98 m/s^2) Not taken into account
Self-balanced loads: - resistance forces Side wall End wall	Y·3,600 N/m 61.250 kN	Y·9,060 N/m Not taken into account

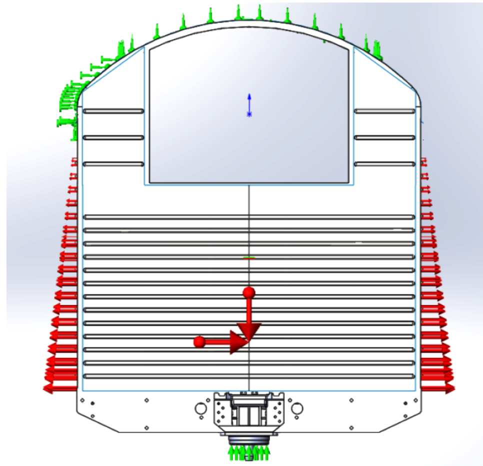


Fig. 2. Calculation scheme for mode III with bulk cargo

Calculation results of the type-918 wagon body without side wall reinforcements

Fig. 3 shows the graph of the equivalent stresses arising in the frame of the wagon body from the action of the standard load according to the first mode for a finite-element model with dimensions of 5 and 50 mm.

The most stressed zones of the wagon body frame according to the first mode are presented in Figs. 3–4.

The sheet of the side wall near the end wall of the body, which is not supported by anything, cannot withstand loads. The stress in this area is 800 MPa.

Stresses in the body frame do not exceed 250 MPa.

Fig. 5 shows the graph of the equivalent stresses arising in the frame of the wagon body from the action of the standard

Table 3

Permissible stresses

Material	Mode I			Mode III		
	$[\sigma]$, MPa	$[\tau_{cut}]$, MPa	$[\sigma_{crum}]$, MPa	$[\sigma]$, MPa	$[\tau_{cut}]$, MPa	$[\sigma_{crum}]$, MPa
St3	$0.95\ \sigma_т$	$0.6\ \sigma_т$	$1.2\ \sigma_т$	155	95	215

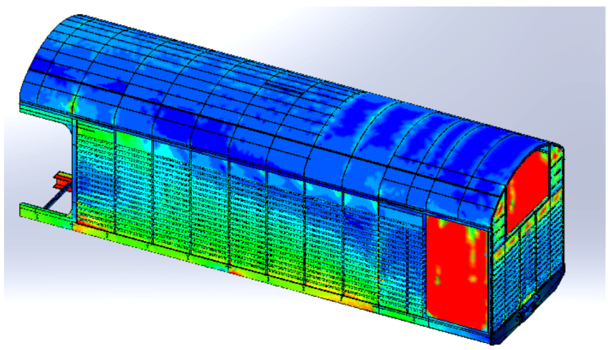


Fig. 3. Diagram of body stress distribution in the I mode

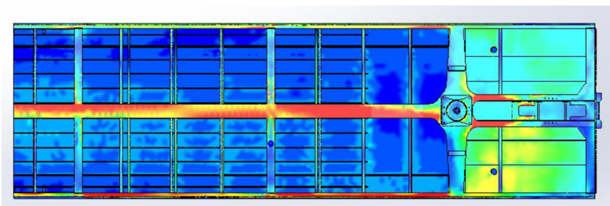
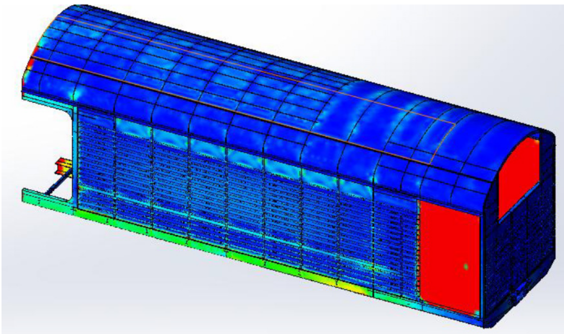
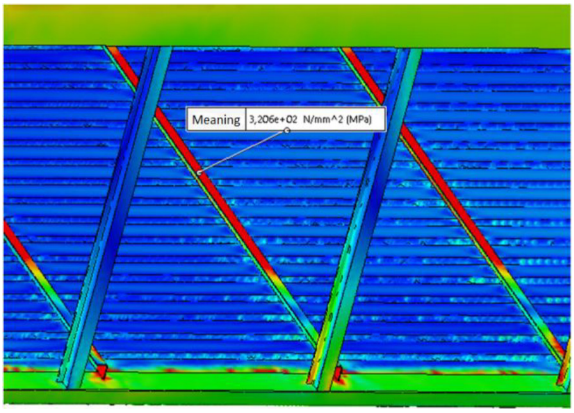


Fig. 4. Diagram of equivalent stresses in the body frame in the I mode

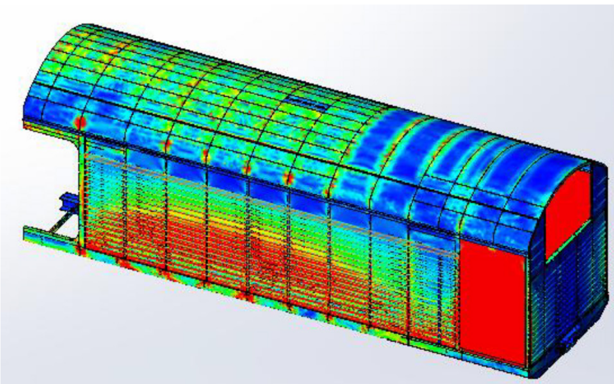


a

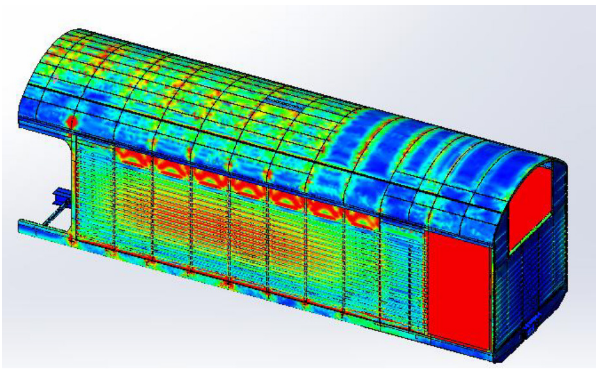


b

Fig. 5. Diagram of stress distribution III mode:
a — isometry; b — enlarged fragment of the side wall



a



b

Fig. 6. The diagram of stress distribution according to the third mode:
a — γ = 800 kg/m^3 *loading height* 1.2; *b* — γ = 500 kg/m^3 *loading height* 2.2

load according to the third mode for a finite-element model with dimensions of 5 and 50 mm.

Fig. 5, *b* shows the beams on the side walls, the stress in which is 320 MPa, which exceeds the permissible values. The allowable stresses are 155 MPa, so the sidewall racks and cladding cannot withstand these loads.

Fig. 6 shows the equivalent stresses when calculating the side walls for bursting loads.

As a result of the calculation, the load on the side wall is excessive. The cladding, supported only by racks, cannot hold the load from the bulk cargo. It is necessary to strengthen the side walls by creating a lattice frame.

Results.

1. A 3D model of the load-bearing module of the wagon body of the 918 model was developed, which is an all-metal load-bearing structure made of a set of longitudinal and transverse stiffening elements covered with thin corrugated sheets.
2. The 3D model of the 918 wagon body is built according to the design and operational documentation of the manufacturing plant and consists of more than 550 parts.
3. According to the available current norms regarding calculations, robustness studies were carried out in the licensed software complex.
4. The results of the analysis of the plot of the equivalent stresses arising in the frame of the wagon body from the action of the standard load according to the first mode in the finite-element model with dimensions of 5 and 50 mm showed that the highest stress zones of the frame of the wagon body are located in the sheet of the side wall near the end wall body, which is not supported by anything. At the same time, the stress in that place is 800 MPa, that is, they significantly exceed the permissible level. Stresses in the body frame, in the specified calculation case, do not exceed 250 MPa.
5. The results of the analysis of the plot of the equivalent stresses arising in the frame of the wagon body from the action of the standard load according to the third mode in the case of a finite-element model with dimensions of 5 and 50 mm showed that the highest stress zones of the frame of the wagon body are located in the beam on the side walls, and their level is 320 MPa, which exceeds the permissible values. The allowable stresses are 155 MPa, so the sidewall racks and cladding cannot withstand these loads.
6. The results of the analysis of the plot of equivalent stresses, which occur when the load is stretched, proved that the loads are excessive. The cladding, supported only by racks, cannot hold the load from the bulk cargo. It is necessary to strengthen the side walls by creating a lattice frame.

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Аналіз міцності вагону моделі 918 при нетипових навантаженнях сипучим вантажем

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Мета. Висвітлення результатів проведеного аналізу напружено-деформованого стану кузова вагону моделі 918 при нетипових навантаженнях сипучим вантажем. Такий аналіз проводився з метою обґрунтування можливості перевезення різних видів насипних вантажів (наприклад різного роду сировини, сільськогосподарської продукції, будівельних матеріалів та інших) у існуючій конструкції секції рефрижераторного вагону.

Методика. З метою забезпечення безперебійності залізничних перевезень у сучасних складних умовах, пропонується за допомогою науково-прикладних підходів опрацювати можливість використання існуючих моделей вагонів для нетипових, для них, видів перевезень. А саме розглянути можливість застосування рефрижераторних вагонів для перевезення насипних вантажів. Для проведення таких досліджень застосовано системний підхід. Який включав: визначення дослідження особливостей впливу насипних вантажів на конструкції рухомого складу; аналіз конструкторської та технологічної документації для створення просторової 3D моделі вагону, що досліджується; створення за допомогою сучасного програмного комплексу розрахункової моделі; перевірка адекватності розробленої моделі й точності отриманих за її допомогою даних; прикладання нетипових розрахункових навантажень; отримання та аналіз картин напружено-деформованих станів методом скінчених елементів.

Результати. Розроблена 3D модель модуля кузова вагону моделі 918. Результати аналізу епюри еквівалентних напружень за першим режимом засвідчили, що найбільші напруження становлять 800 МПа, тобто значно перевищують допустимі. А за третім режимом найбільші напруження становлять 320 МПа, і також перевищують допустимі. Результати аналізу епюри еквівалентних напружень, які виникають при розпиранні, засвідчили що навантаження є надмірними. Обшивка, підкріплена тільки стійками, не може утримати навантаження від насипного вантажу.

Наукова новизна. Проведено міцнісний аналіз існуючої конструкції секції рефрижераторного вагона при нетипових навантаженнях сипучим вантажем.

Практична значимість. Отримані результати аналізу напружено-деформованого стану кузова вагону моделі 918 при навантаженнях сипучим вантажем дозволили оцінити потенційні можливості таких перевезень. Такі результати доцільно використовувати при проведенні науково-дослідних і дослідно-конструкторських робіт з удосконалення (модернізацій) існуючих секцій рефрижераторних вагонів для забезпечення можливості перевезення в них насипних вантажів. Що, у свою чергу, дозволить підвищити ефективність функціонування вітчизняного парку вантажних вагонів.

Ключові слова: *механічна інженерія, машинобудування, вантажні вагони, міцністні розрахунки, сипучі вантажі*

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