

Інтенсифікація експлуатації вагонів зумовлює знос їх кузовів, як найбільш навантаженого елемента конструкції, та необхідність впровадження нових вагонів. Для скорочення витрат на виготовлення нових конструкцій вагонів пропонується продовження строку експлуатації кузовів універсальних напіввагонів понад 1,5 нормативного.

При проведенні розрахунків на міцність в умовах вагонобудівних підприємств до уваги приймаються нормативні величини навантажень, які не враховують можливі зноси елементів несучих конструкцій кузовів напіввагонів в експлуатації. Це може спричинити значну похибку при визначенні можливості продовження строку експлуатації кузовів напіввагонів, які вичерпали свій нормативний ресурс.

Тому при обґрунтуванні можливості продовження строку експлуатації вагонів важливим є урахуванням на стадії розрахунків на міцність уточнених величин динамічних навантажень, які діють на них в експлуатації.

Для дослідження динамічних навантажень, які діють на кузов напіввагону при маневровому співударянні, як випадку найбільшої навантаженості його конструкції у експлуатації, проведено математичне моделювання. Результати досліджень дозволили зробити висновок, що прискорення, яке діє на несучу конструкцію напіввагона з характерними для 1,5 строку експлуатації зносами при маневровому співударянні, складає близько 4g. Також дослідження динамічної навантаженості несучої конструкції кузова напіввагона при маневровому співударянні проведено шляхом комп'ютерного моделювання в програмному забезпеченні CosmosWorks. Результати досліджень показали, що максимальні прискорення кузова напіввагона складають близько 5g.

Для перевірки адекватності розроблених моделей використаний критерій Фішера. Результати розрахунків показали, що гіпотеза про адекватність не заперечується.

Отримані результати досліджень враховані при визначенні показників міцності кузова напіввагону з характерними для 1,5 строку експлуатації зносами. Для цього створено просторову комп'ютерну модель кузова базового напіввагона моделі 12-757, несучі елементи якої мають товщини, що відповідають мінімально визначеним. Розрахунок проведений за методом скінчених елементів. На підставі проведених розрахунків встановлено, що максимальні еквівалентні напруження не перевищують допустимих та складають близько 345 МПа, що дозволяє зробити висновок про можливість подальшої експлуатації вагона.

Проведені дослідження сприятимуть уточненому визначенню можливості продовження строку експлуатації напіввагонів, які вичерпали свій нормативний ресурс

Ключові слова: транспортна механіка, вантажні вагони, напіввагон, строк експлуатації, міцність конструкції, динамічна навантаженість

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RESEARCH INTO A POSSIBILITY TO PROLONG THE TIME OF OPERATION OF UNIVERSAL OPEN TOP WAGON BODIES THAT HAVE EXHAUSTED THEIR STANDARD RESOURCE

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1. Introduction

The accelerated pace of the integration of European countries into the system of international transport corri-

dors necessitates adaptation of the railroad rolling stock, being one of the leading transportation industries, to operation under market conditions. To improve the efficiency of a transportation process, it is required to ensure that transport

industry is equipped with functional fleet of railroad cars. According to DSTU 2860-94 "Reliability of equipment. Terms and definitions" (Norme Cei Internationale 1ec International 50(191) Standard), the designed service lifetime is the calendar prolongation of operation reaching which indicates that further operation must be stopped regardless of its technical condition. Among the most intensely used cars at railroads are the open top wagons; that is predetermined by the possibility of their transporting a wide range of cargoes. That explains why a given type of cars wears out faster compared to other railroad cars. In Ukraine, for example, the standard service time of open top wagons is 22 years, while about 18 % of open top wagons of the total fleet of cars are operated over lifetime prolonged by 1.5 times, and about 4.0 % – even longer [1].

Given an insufficient renewal of rolling stock by new designs of cars, there is a need for scientific research into the possibility of prolongation of operation period of the existing ones. At the same time, greater attention should be paid to the bearing design of the frame as the most loaded node of a railroad car under operation.

2. Literature review and problem statement

The issue of open top wagons frame bearing capacity has been investigated in detail up to now, which is explained by its relevance and economic justification. Thus, paper [2] reports results of research into bearing capacity of open top wagons of model 12-9745. However, the purpose of that research was to find structural reserves to reduce material consumption for a given model of cars. And, accordingly, the bearing capacity of a body design that would simulate the wear characteristic of 1.5 operation periods was not addressed.

Article [3] outlines prospects for improving the designs of open top wagons, including a prolonged period of operation. However, an enhanced service period of open top wagons is proposed to be achieved by improving structural properties, for example through the introduction of materials with better characteristics.

An analysis of properties of structural materials of the new-generation car bodies is given in [4]. The paper described the benefits of using new advanced materials for separate elements of car designs. However, the task on extending the implementation of this direction while prolonging the term of operation of open top wagons was not paid attention to.

Measures to improve the bearing capacity of an open top wagon body in order to ensure the reliability of its attachment to the deck of a train ferry are described in [5]. The reported results of calculating the strength of a body considering fixing it relative to the deck using the proposed structural nodes under conditions of sea pitching allowed the authors to draw a conclusion on the feasibility of proposed solutions. In this case, construction and application of dynamic models that would take into consideration the wear of bearing system of open top wagons will make it possible to carry out research related to the appropriate designs of open top wagons.

Study of the dynamics of a railroad car with an open loading platform is described in [6]. The calculation was carried out in the MSC Adams programming environment. Stability of a wagon against overturning was investigat-

ed while it was positioned along a curve with a radius of 250 meters, taking into consideration different motion speed.

Estimation of accuracy of the throughput capacity of railroad networks, intended for transportation of raw materials and finished products of mining-metallurgical industry was described in [7].

The issue of designing rolling stock for the transportation of heavy cargoes was considered in [8]. The dynamics and durability were examined using the modern software ProMechanica and CosmosWorks. When designing a bearing structure of a transporter, the authors studied a possibility of its fabrication from materials of various types.

Structural features of a wagon for intermodal transportation were considered in [9]. The wagon has a lowered middle part, and the presence of a reverse part makes it possible to load/unload vehicles to/from it by gravity.

Paper [10] reports results of research into determining the character and level of influence of different freight cars on strength properties of bearing systems for cars. However, the tasks of a given study did not imply determining a respective effect on the bodies in operation beyond a standard service time.

Article [11] describes the impact of a bogie front rolling wheels profile on the overall dynamics of a rolling stock unit. In this case, the authors failed to consider the simulation of appropriate operational wear and to study dynamic properties for a given case.

Study [12] analyzed the patterns of motion and interaction between units of rolling stock with parameters that match new equipment. However, no research for units with parameters that reflect operational wear was conducted.

Work [13] highlights results of improvement in the dynamic properties of rolling stock when passing curved sections of track by improving respective structural elements. Along with this, the authors did not determine possibilities and effect of the implementation of such innovations on the worn-out rolling stock, including open top wagons.

Summing up the results, one can note that up to now the issues related to the possibility of prolonging the term of operation of bearing structures of car bodies taking into consideration the refined magnitudes of dynamic loads that act on them have not been resolved. When carrying out calculations for strength, typically considered are the regulated magnitudes of loads that do not take into consideration possible wear of elements in the bearing structures of open top wagon bodies at operation. This might result in a significant error when estimating the stressed state of open top wagon bodies that have exhausted their standard resource at the stage of substantiating a possibility to prolong their service period.

3. The aim and objectives of the study

The aim of present study is to substantiate a possibility to prolong a period of operation of bearing structures of the universal open top wagon bodies with the wear characteristic of 1.5 terms of operation regarding the refined magnitudes of dynamic loads that act on them.

To accomplish the aim, the following tasks have been set:
 – to explore dynamic loading of the bearing structure of an open top wagon body with the wear characteristic of 1.5 terms of operation using the methods of mathematical modelling;

- to explore dynamic loading of the bearing structure of a open top wagon body with the wear characteristic of 1.5 terms of operation using the methods of computer simulation;
- to verify the developed models of dynamic loading of a open top wagon body with the wear characteristic of 1.5 terms of operation;
- to investigate and analyze the stressed-strained state of the bearing structure of a open top wagon body with the wear characteristic of 1.5 terms of operation using the methods of computer simulation.

4. Study of dynamic loading of the bearing structure of a open top wagon body using the methods of mathematical modeling

To simulate the wear characteristic of 1.5 terms of operation, we constructed a spatial computer model of the open top wagon body whose bearing elements are of thickness that meets the minimally thickness defined experimentally.

Fig. 1 and 2 show elements of the examined design of open top wagons, as well as the appropriate thickness designated as N_k^m , where:

- N is the number of an element of the bearing component;
- m is the rated thickness of the component's element, mm;
- k is the determined minimum actual mean value, mm.

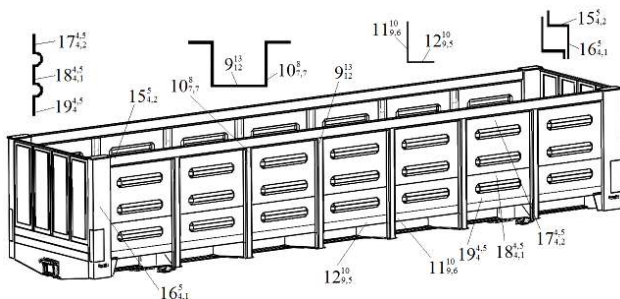


Fig. 1. Spatial schematic of a open top wagon body, model 12-757, with the designated rated and the determined minimum actual mean thickness of bearing components' elements

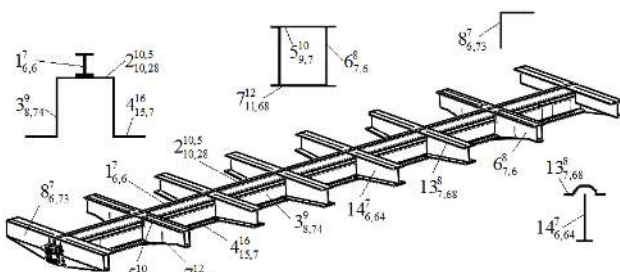


Fig. 2. Spatial schematic of a open top wagon frame, model 12-757, with the designated rated and the determined minimum actual mean thickness of bearing components' elements

To determine the dynamic loads that act on a open top wagon body in operation, we applied a mathematical model given in [14] that was constructed using the Lagrange method of second kind. In this case, we considered a case of the largest loading on a bearing structure in operation – impact at shunting. This model was built in order to determine

accelerations as a component of dynamic load that act on the car platform with containers-tanks during an impact at shunting. The model therefore was modified to determine accelerations that a open top wagon is exposed to under the influence of the longitudinal force of impact.

$$M'_w \cdot \ddot{x}_w + M' \cdot \ddot{\varphi}_w = S_a, \tag{1}$$

$$I_w \cdot \ddot{\varphi}_w + M' \cdot \ddot{x}_w - g \cdot \varphi_w \cdot M' = l \cdot F_{FR} (\text{sign} \dot{\Delta}_1 - \text{sign} \dot{\Delta}_2) + l(C_1 - C_2), \tag{2}$$

$$M_w \cdot \ddot{z}_w = C_1 + C_2 - F_{FR} (\text{sign} \dot{\Delta}_1 - \text{sign} \dot{\Delta}_2), \tag{3}$$

where

$$M'_w = M_w + 2 \cdot m_B + \frac{n \cdot I_{WL}}{r^2};$$

$$M' = M_w \cdot h; \quad C_1 = k_1 \cdot \Delta_1; \quad C_2 = k_2 \cdot \Delta_2;$$

$$\Delta_1 = z_w - l \cdot \varphi_w; \quad \Delta_2 = z_w + l \cdot \varphi_w,$$

where M_w is the mass of the bearing structure of a open top wagon; I_w is the moment of inertia of a open top wagon relative to the longitudinal axis; S_a is the magnitude of the longitudinal force of impact into automatic coupling; m_B is the mass of the bogie; I_{WL} is the moment of inertia of a wheelset; r is the radius of a medium-worn wheel; n is the number of axles in the bogie; l is the half-base of a open top wagon; F_{FR} is the absolute value of dry friction force in the spring set; k_1, k_2 is the spring rigidity of the spring suspension of open top wagon bogies; x_w, φ_w, z_w are coordinates that correspond, respectively, to longitudinal, angular around the transverse axle, and vertical displacement of a open top wagon.

We solved differential equations in the MathCad programming environment. In this case, they were reduced to the Cauchy standard form and integrated then using the Runge-Kutta method.

The initial displacements and velocity were taken to equal to zero. The input parameters of mathematical model are a open top wagons body technical characteristics with the wear characteristic of 1.5 terms of operation; parameters of spring suspension, as well as the value of force of a longitudinal impact at automatic coupling.

Research results have allowed us to conclude that the acceleration acting on the bearing structure of a open top wagon during an impact at shunting is about 40 m/s² (Fig. 3).

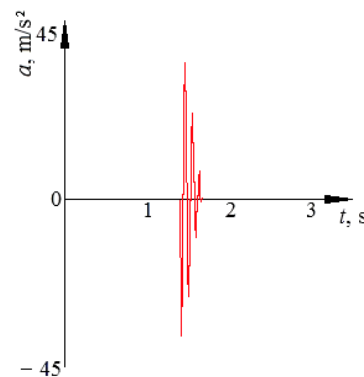


Fig. 3. Accelerations acting on the bearing structure of a open top wagon body during an impact at shunting

In this case, the longitudinal force of impact that acts on the vertical surface of the rear support of an automatic coupling was taken to be equal to 3.5 MN [2, 3].

5. Study of dynamic loading of the bearing structure of an open top wagon body using computer simulation methods

In order to verify the obtained magnitudes of accelerations, we performed computer simulation of dynamics of the bearing structure of an open top wagon body under the action of a longitudinal force of 3.5 MN on the rear support of an automatic coupling. The study was conducted using the CosmosWorks programming environment, version 2015.

We constructed the model based on the album of drawings of a universal open top wagon, model 12-757, produced at PAT “Kryukivsky wagon building plant” (Ukraine). When compiling the model, we considered elements of the bearing structure of the body, which are tightly connected by welding or by rivets; in other words, when constructing the model, we took disregarded the covers of openings.

A spatial model of the bearing structure of an open top wagon body with the wear characteristic of 1.5 terms of operation is shown in Fig. 4.

The calculation was performed using the method of finite elements.

When constructing a finite-element model (FEM), we employed spatial isoparametric tetrahedra. The number of elements in the grid in this case was 142,251; nodes – 45,742. The maximum size of a grid element equals 180 mm, minimum – 36 mm, the maximum ratio between the sides of the elements is 9103.2; the percentage of elements with the ratio of sides less than three is 6.02, larger than ten – 55.3.



Fig. 4. Spatial model of an open top wagon with the wear characteristic of 1.5 terms of operation: a – side view; b – bottom view

When building a model of strength (Fig. 5), we considered that the bearing structure of an open top wagon body, in addition to longitudinal load P_L , is exposed to vertical static loading P_V^{ST} and an effort from the bulk cargo expansion P_C (coal).

The material for the bearing structure of an open top wagon body was steel of grade 09G2S with a value of strength limit $\sigma_S=490$ MPa and a value of fluidity limit $\sigma_F= 345$ MPa [15].

When constructing a model of strength, we did not take into consideration a possible difference between the levels of cars’ automatic couplings that interact with each other.

Results of the calculation are shown in Fig. 6.

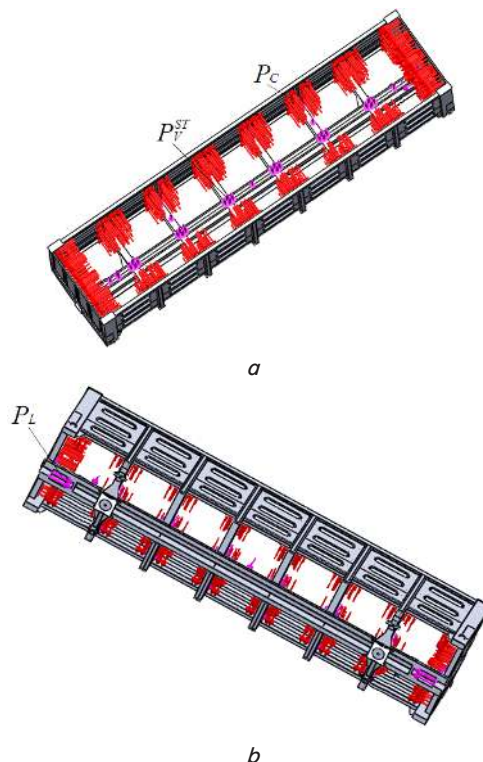


Fig. 5. Computer model of strength of the bearing structure of an open top wagon with the wear characteristic of 1.5 terms of operation: a – top view; b – bottom view (impact, compression), P_V^{ST} – vertical static loading; P_L – longitudinal loading; P_C – effort of the bulk cargo expansion

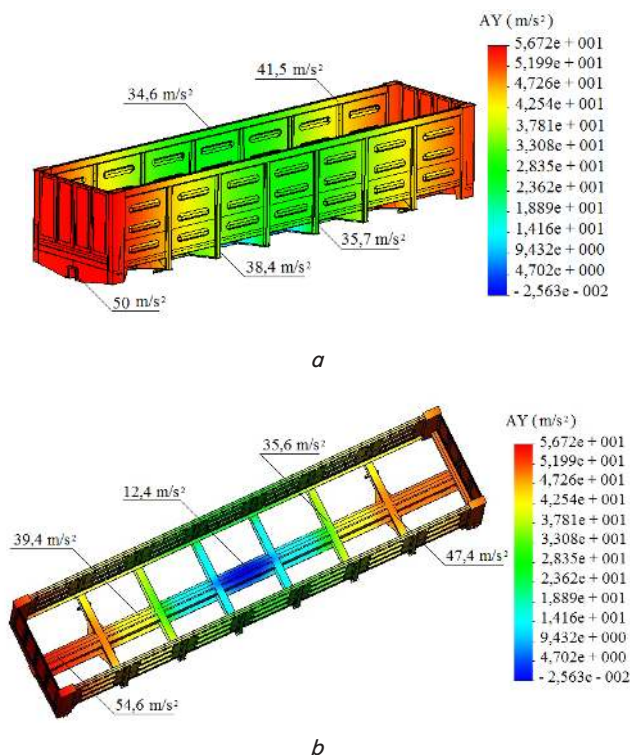


Fig. 6. Distribution of acceleration fields acting on the bearing structure of an open top wagon body: a – top view; b – bottom view

Based on the study, we can conclude that the maximum accelerations of a open top wagon body occur in a zone from the console part to the zone of interaction between a girder beam and a pivot beam and reach about 50 m/s^2 (5 g). In the region between a pivot beam and the middle part of a girder beam the magnitude of accelerations decreases and makes up about 15 m/s^2 (1.5 g).

6. Verification of the developed models of dynamic loading of a open top wagon body with the wear characteristic of 1.5 terms of operation

In order to test the adequacy of the developed computer model of a open top wagon body with the wear characteristic of 1.5 terms of operation, as well as the modified mathematical model, we applied a Fisher criterion. In this case, the input variable of the model is the force of shunting impact of the body ranging from 0.5 MN to 3.5 MN; the output variables are the accelerations that occur in the elements of the body's bearing structures. Results of determining the accelerations, obtained by mathematical modeling and computer simulation, are given in Table 1.

Table 1

Values of accelerations that act on a open top wagon body with the wear characteristic of 1.5 terms of operation

Impact force, MN	Acceleration magnitude, g	
	Mathematical model	Computer model
0.5	0.8	1.2
1.0	1.3	1.8
1.5	2.1	2.3
2.0	2.3	2.7
2.5	2.6	3.4
3.0	3.1	4.6
3.5	3.9	5

To determine the optimal number of experiments, we used a Student criterion. The required volume of static data was determined from formula [16]

$$n = \frac{t^2 \cdot \sigma^2}{\delta^2}, \tag{4}$$

where t is determined from ratio $\Phi(t) = \gamma / 2$; $\Phi(t)$ is a Laplace function, tabular value; σ is the standard deviation of a random magnitude that is examined; δ^2 is the absolute error of a measurement result.

At $N=7$, the value is $t=2.5$. Based on the calculations performed, it was revealed that the number of static measurements must be at least 6, therefore the number of experiments is sufficient.

It was found that the considered models are linear and characterize a change in the accelerations of the bearing structure of a open top wagon body due to the longitudinal force acting on the rear support of an automatic coupling (Fig. 7). In this case, the number of degrees of freedom at $N=7$ will make up $f_1=5$.

At a reproducibility variance of $S_r^2=0.93$ and an adequacy variance of $S_{Ad}^2=1.9$, the actual value of the Fisher criterion is $F_p=2.2$, which is smaller than the tabular value of

the criterion $F_t=3.97$. Thus, a hypothesis about the adequacy of the developed model is not contradicted.

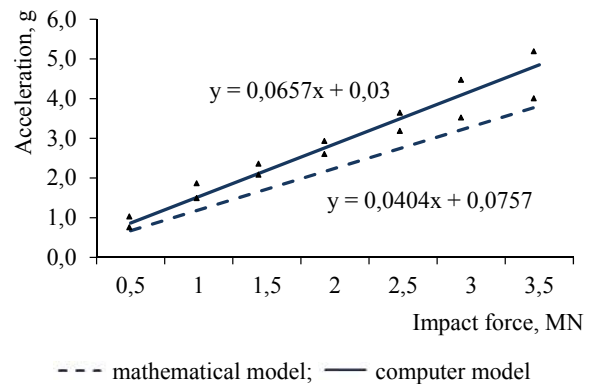


Fig. 7. Dependence of accelerations that act on a open top wagon body with the wear characteristic of 1.5 terms of operation on the impact force at shunting

7. Research and analysis of the stressed-strained state of the bearing structure of a open top wagon body

To study the strength of the bearing structure of a open top wagon body with the wear characteristic of 1.5 terms of operation, we constructed a computer model of its strength in the programming environment of Cosmos-Works software.

When building a model of strength (Fig. 8), we considered that the bearing structure of a open top wagon body is exposed to the longitudinal loading on the rear support of an automatic coupling P_L , whose numerical value was defined based on the results of modeling dynamic loading of a open top wagon body, the vertical static loading on the frame P_V^{ST} taking into consideration full utilization of the cargo capacity of the body and the effort of the bulk cargo expansion on the side and end walls of the body P_C , calculated by the procedure given in [17]. The model accounts for the vertical P_R^V reactions in supporting nodes to action P_V^{ST} and the horizontal P_R^C reactions caused by the action of lateral and longitudinal efforts on the bearing structure.

Calculation for strength was performed using a method of finite elements. The patterns of FEM for the bearing structure of a open top wagon body with the wear characteristic of 1.5 terms of operation were considered when modeling its dynamic loading.

Limitations of the model are the lack of difference in the levels of bodies of open top wagon automatic couplings that interact with each other. The model disregarded welded seams; in other words, it was considered to be a monolithic structure.

The model was fixed by heels and slips of pivot beams of the bearing structure of a car.

Based on the calculations performed, we determined that the structure meets the requirements for strength (Fig. 9).

Results of the analysis of patterns in the obtained stressed-strained state (Fig. 9) allowed us to find out that the maximum equivalent stresses in the bearing structure of a open top wagon body do not exceed the permissible stresses [15]. In this case, numerical values of stresses make up approximately 345 MPa. Maximum displacements are 4.68 mm and are concentrated in the middle of the girder

beam. The maximum equivalent stresses occur in the region between the rear support of an automatic coupling and the pivot beam and make up about $2.81 \cdot 10^{-3}$.

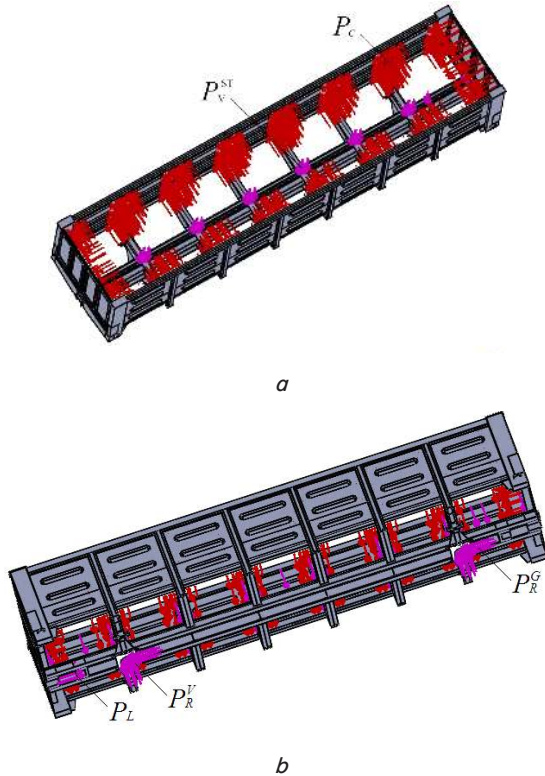


Fig. 8. Model of strength of the bearing structure of an open top wagon, model 12-757, under calculation mode I (impact): a – side view; b – bottom view

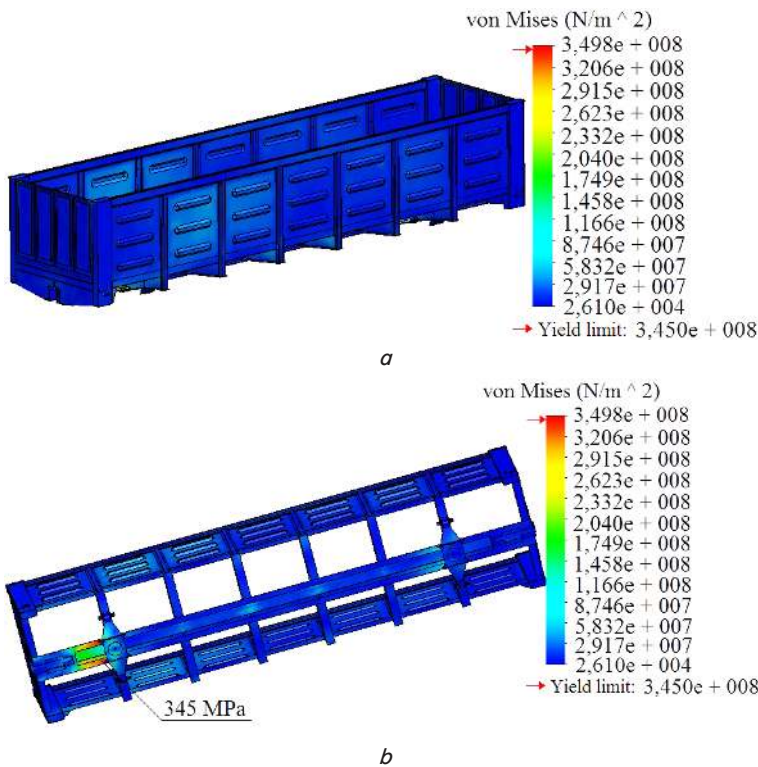


Fig. 9. Stressed state of the bearing structure of an open top wagon, model 12-757, under calculation mode I (impact): a – side view; b – bottom view

8. Discussion of results of studying the strength of an open top wagon body with the wear characteristic of 1.5 terms of operation

Typically, when investigating a possibility of further exploitation of railroad cars that have exhausted their term of service, the normative values of loads are applied that act on them during operation. It is important to note that in order to obtain a more accurate estimate of a open top wagon body loading during operation, we proposed a mathematical modeling of the dynamic loading of a bearing structure of a open top wagon body with the wear characteristic of 1.5 terms of operation. The research was carried out for the most loaded mode – impact at shunting. Results of the modeling allowed us to obtain a refined magnitude of the dynamic loading, which acts on a open top wagon body. It was found that the resulting magnitude of dynamic loading exceeds the standard one [15], which is predetermined by the presence of wear in the components of a body bearing structure. Calculation for strength of a body open top wagon taking into consideration the derived magnitude of dynamic loading allowed us to draw a conclusion about the possibility of further operation of the car. In the further development of the issues related to the possibility of prolongation of operation cycle of cars that have exhausted their standard resource it is required to conduct a physical experiment in order to refine the proposed models.

The study conducted will contribute to the possibility to prolong the term of operation of bodies of universal open top wagons that have exhausted their standard resource. The present research could be useful when prolonging the term of operation of other types of railroad cars.

9. Conclusions

1. We have investigated dynamic loading of the bearing structure of a open top wagon body with the wear characteristic of 1.5 terms of operation using the methods of mathematical modeling. To determine the accelerations as components of the dynamic loading that act on a open top wagon body under the most loaded mode of operation we employed a Lagrange method of the second kind. It was found that the acceleration acting on the bearing structure of a open top wagon is about 4 g.

2. We have examined dynamic loading of the bearing structure of a open top wagon body with the wear characteristic of 1.5 terms of operation applying the methods of computer modeling. The calculation was carried out in the software programming environment CosmosWorks. The maximum accelerations of a open top wagon body occur in a zone from the console part to the zone of interaction between the girder beam and the pivot beam and make up about 5 g.

3. We have verified the developed models of the dynamic loading of a open top wagon body with the wear characteristic of 1.5 terms of operation. A calculation criterion was the Fisher criterion. It was found that at a reproducibility variance of $S_r^2 = 0,93$ and an adequacy variance of $S_{AD}^2 = 1,9$, the actual value of the Fisher

criterion is less than the tabular one. This proves that the hypothesis of adequacy is not contradicted.

4. We have examined and analyzed the stressed-strained state of the bearing structure of a open top wagon body with the wear characteristic of 1.5 terms of operation using the

methods of computer simulation. Numerical values of the maximum equivalent stresses in this case amounted to about 345 MPa, which does not exceed the permissible values [15], and this makes it possible to draw a conclusion about the possibility of further operation of the car.

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