

The dynamic loading and strength of the frame of the “East-West” type covered wagon were determined. To increase the efficiency of operation of covered wagons in international traffic, it is proposed to improve their frames. This improvement consists in using a sectional partition in the body in order to divide it into two separate sections. This allows the transportation of different goods in one wagon, and therefore decreasing empty mileage.

The longitudinal loading of the covered wagon frame was determined. The case of shunting impact was considered. The studies were carried out in a flat coordinate system. The loading mode of the frame of the covered wagon in the empty and loaded states was considered. The acceleration acting on the covered wagon frame in the loaded state was 0.37g, empty – 0.42g, which does not exceed the standard values. The wagon motion is rated “excellent”.

The main strength indicators of the covered wagon frame were determined. The calculation was made by the finite element method. It was found that the maximum equivalent stresses are concentrated in the area of interaction of the center sill with the bolster beam and amounted to 340 MPa, which is lower than the yield stress of the material. Maximum displacements occur in the middle of the frame beams and are about 12 mm. The natural vibration frequencies of the covered wagon frame were calculated.

The research will help to increase the efficiency of using covered wagons in international traffic. Also, the research results can be useful developments in the creation of innovative rolling stock structures

Keywords: transport mechanics, covered wagon, frame, dynamic loading, stress state, East-West wagon

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IMPROVEMENT OF COVERED WAGONS OF THE “EAST-WEST” TYPE BY SECTIONING WITH A PARTITION

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1. Introduction

The competitiveness of railway transport in the transport services market significantly depends on the technical and operational characteristics of the rolling stock used for transportation. The experience of developing a freight car fleet in the UIC member states indicates a steady trend towards improving speed characteristics, increasing traffic safety and ensuring the operational reliability of rolling stock.

One of the most important factors of transport competitiveness is transport capacity and cost.

Analysis of statistical data on freight traffic through international transport corridors in recent years suggests that a significant percentage of it is transported in covered wagons.

Insufficient replenishment of the car fleet in recent years necessitates the introduction of new technical solutions to improve car frames to meet the needs of transportation of the specified goods.

Therefore, in order to ensure the efficiency of the transportation process, it is necessary to create new-generation “East-West” type covered wagons to be operated in international transport corridors.

As an example, we can cite an ordinary four-axle 03-VM size “East-West” type covered wagon (model 11-950)

developed by the Stakhanov Railway Car Building Works, PJSC (Ukraine, Stakhanov) (Fig. 1).

The design of the wagon allows carrying out international freight transport in European countries by trains following a network of railways with a gauge of 1,520 mm and 1,435 mm [1, 2].

In early 2000, the Kryukiv Railway Car Building Works, PJSC (Ukraine, Kremenchuk) also developed the design of a covered wagon for operation in the East-West direction. A feature of the wagon is the presence of discharge hoppers in the middle part of the body, which allows the transportation of bulk cargo. The space of the body between the corner posts and the vertical walls of the central section has a sliding door for loading bulk cargo [2]. The disadvantage of this wagon is narrow specialization, so it is not widely used on railway networks.

Therefore, to ensure efficient international cargo transportation by rail, it is necessary to develop and put into operation modern wagon designs. At the same time, such rolling stock should have high technical and economic indicators. Also, to reduce empty mileage, it is advisable to create the possibility of transporting different goods in one car. This will help reduce the maintenance cost, as well as increase the operation efficiency of rolling stock in international traffic. This improvement can be implemented not only on new

wagons, but also on already operated ones by upgrading. For example, upgrading can be carried out during uncoupling repairs. The proposed solution will significantly decrease the cost of manufacturing new rolling stock and increase its demand. This will reduce the need for additional vehicles in the formation of railway trains. Therefore, conducting research on improving covered wagons to expand the range of goods transported in them is very relevant.

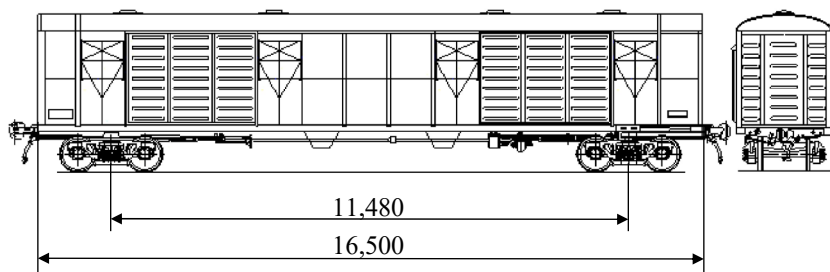


Fig. 1. "East-West" type covered wagon

2. Literature review and problem statement

In order to promote the use of ordinary wagons, the work [3] proposed to upgrade them. Substantiation of measures for upgrading wagons was carried out. Computer modeling methods were used and a field experiment was performed. However, the proposed measures are effective for open rolling stock. That is, they are not suitable for wagons transporting goods that need protection from precipitation.

Possible ways to improve the technical and economic indicators of railway cars are identified in [4]. The task is implemented by increasing the axial loading of the car. The substantiation of this solution is given. The BCNHL freight car was chosen as a prototype.

In [5], the prospects for using innovative materials to reduce the lightweight of wagons were investigated. The use of magnesium alloys as a material for wagon frames was substantiated. The results of calculating the expediency of using this material in metal structures of bodies are given. It is important to say that no attention is paid to the justification of the proposed solutions in the design of covered wagons.

A promising concept of upgrading freight cars is considered in [6]. To increase the service life of wagon frames, it is proposed to use composite materials. This solution can be implemented using fiberglass and epoxy resin panels. The results of calculating this solution confirmed its feasibility. However, the paper does not consider the possibility of such upgrading of covered wagons.

Design and optimization features of wagon frames made of aluminum panels are given in [7]. The characteristic function of finding the optimal combination is determined by maximum stresses and displacements. It was found that the introduction of aluminum panels will improve the technical and economic indicators of wagons. However, this implementation will not increase the efficiency of using freight cars by reducing their empty mileage.

In [8], the results of justifying the improvement of technical and economic indicators of freight cars by the introduction of high-strength steels in their frames are presented. An experimental refinement of strength conditions of welded joints of cars made of high-strength materials was carried out. Methods for increasing the endurance of welded joints have been developed. However, the paper does not

present the results of implementing these measures on cars transporting goods that need protection from precipitation.

Analysis of loading of wagon frames under basic operating modes is carried out in [9]. The main indicators of the dynamics and strength of wagons are determined. Conditions for safe movement are defined. At the same time, no measures have been proposed to increase operation efficiency.

Measures to increase the efficiency of using wagons in international traffic were studied in [10, 11]. Structural improvements of wagon frames to reduce the maintenance and operation costs are proposed. Requirements for the design of modern wagons for international traffic are defined. However, the proposed solutions do not take into account the possibility of increasing the range of goods transported in the considered wagons to reduce their empty mileage.

The literature review suggests that it is advisable to conduct studies on improving the efficiency of using covered wagons in international traffic. The implementation of this task will help reduce the empty mileage, as well as increase the operation efficiency of covered wagons.

3. The aim and objectives of the study

The aim of the study is to identify loading features of the improved frame of East-West covered wagons by sectioning with a partition. To achieve the aim, the following objectives are defined:

- to propose measures to increase the efficiency of using covered wagons in international traffic;
- to determine the longitudinal loading of the covered wagon frame;
- to determine the main strength indicators of the covered wagon frame;
- to determine natural vibration frequencies of the covered wagon frame.

4. Research materials and methods

The object of the study is the process of loading the improved frame of the East-West covered wagon in basic operating modes.

The main hypothesis of the study is to increase the efficiency of using covered wagons in international traffic by sectioning their bodies with partitions. This will allow the transportation of various goods in one car and reduce the number of empty runs.

During the research, the following basic simplifications and assumptions were made:

- when constructing a spatial model of the covered wagon frame, elements that rigidly interact with each other were taken into account, i.e. mobile self-sealing doors were not taken into account;
- when creating a finite-element model of the covered wagon frame, welds were not taken into account;
- when calculating the strength of the covered wagon frame, it was taken into account that the sectional partition is loaded with pressure from bulk cargo;

– when determining the dynamic loading of the covered wagon frame, it was taken into account that the impact on the rear stops of the coupler is absolutely hard.

Rational parameters of the sectional partition were determined by conventional methods of material resistance, namely, plate design. Grain was chosen as bulk cargo, as it causes thrust pressure on the body structure.

In order to determine the dynamic loading of the covered wagon during shunting impact, a mathematical model developed by the Institute of Technical Mechanics (Dnipro, Ukraine) was used [12]. The model is designed to determine the acceleration of a tank container and a platform car under the action of the longitudinal force from a hammer car. Therefore, it has been revised in the study.

The solution of differential equations of dynamic loading of covered wagons was carried out in the MathCad software package (Boston, USA) [13–16]. Starting conditions are assumed to be zero [17–19]. It is taken into account that the wagon rests on trucks of model 18-100.

The strength and natural vibration frequencies of the covered wagon frame were studied by the finite element method [20–22]. It was implemented in the CosmosWorks software package (France).

The optimal number of grid elements was determined by the graphoanalytical method [23–26]. Ten-node isoparametric tetrahedra were used as finite elements [27–30]. The number of grid elements was 713,623, nodes – 252,850. The maximum size of the grid element is 100.0 mm, minimum – 20.0 mm, the maximum aspect ratio of the elements – 475.06, the percentage of elements with an aspect ratio of less than three – 8.66, more than ten – 46.9. The minimum number of elements in the circle is 22, the ratio of increase in element size is 1.8, the simplification factor of the model in the areas of rounds and holes is 0.4. The model was fixed by center plates and bearers of frame bolsters. The structural material is 09G2S steel.

5. Results of research on improving East-West covered wagons by sectioning with partitions

5.1. Measures to increase the efficiency of using covered wagons in international traffic

In order to expand the range of goods transported in covered wagons through international transport corridors, it is proposed to improve their frames by dividing the internal volume into separate sections. To carry out loading and unloading operations, it is proposed to install two self-sealing doors on each side of the body (Fig. 2). The body is divided into two sections by a sectional partition. The 11-217 covered wagon was chosen as a base model.

The diagram of distribution of bulk cargo pressure on the sectional partition of the body by height is given in Fig. 3. It is considered that the plate is loaded by the thrust force.

The bulk cargo pressure is calculated by the formula [26]

$$p = \gamma \cdot y \cdot \text{tg}^2(45^\circ - 0.5\alpha), \tag{1}$$

where γ and α are, respectively, the specific weight and the natural slope angle of cargo, the values of which in the design mode I are taken in accordance with regulations [31–34].

In the design mode III, $\alpha=0$ and the value of γ is multiplied by $(1+k_d)$, where k_d is the factor of vertical dynamics.

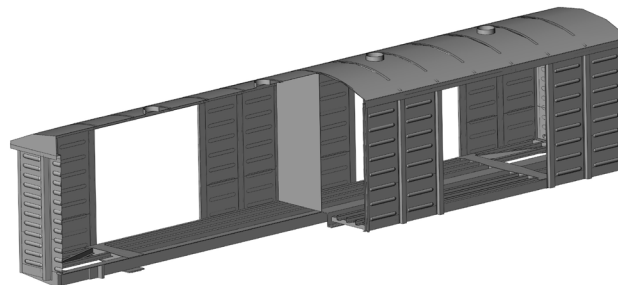


Fig. 2. Section of the covered wagon frame

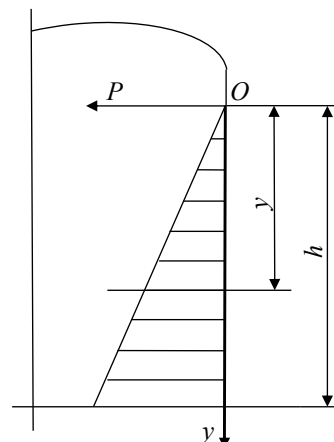


Fig. 3. Diagram of distribution of bulk cargo pressure on the sectional partition of the body by height

Based on the calculations, $P_I=8.7$ kPa, $P_{II}=28.7$ kPa.

We consider the case of loading the plate with a pressure distributed in the form of a triangular prism, the basis of which is an isosceles triangle perpendicular to the two edges of the plate (Fig. 3).

It is found that taking into account the design features of the wagon body, its width a is greater than height b , so the calculation was performed for the case when $a>b$ (Fig. 4).

The polar moment of inertia about the x and y -axes, respectively, is calculated by the formulas

$$W_x = \frac{i_x}{(a/2)}, \tag{2}$$

$$W_y = \frac{i_y}{(b/2)}. \tag{3}$$

Stresses relative to the longitudinal x -axis are calculated as follows

$$\sigma_x^I = \frac{M_x^I}{W_x}, \tag{4}$$

$$\sigma_x^{III} = \frac{M_x^{III}}{W_x}. \tag{5}$$

Stresses relative to the transverse y -axis are calculated by the formulas

$$\sigma_y^I = \frac{M_y^I}{W_y}, \tag{6}$$

$$\sigma_y^{III} = \frac{M_y^{III}}{W_y}. \tag{7}$$

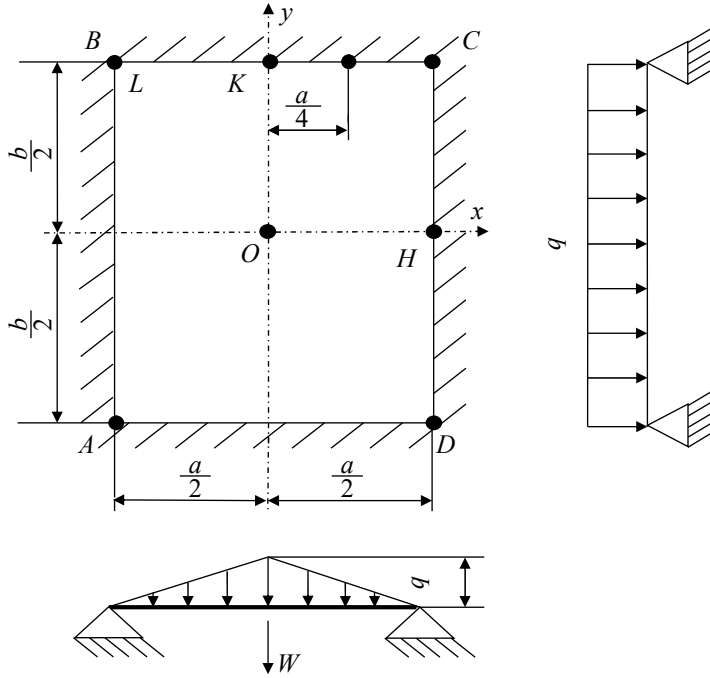


Fig. 4. Magnitudes of deflections and forces at the plate points

Main stresses relative to the longitudinal axis in the design mode I are calculated

$$\sigma_I = \frac{Q_x^I}{a} \tag{8}$$

Main stresses relative to the longitudinal axis in the design mode III are determined

$$\sigma_{III} = \frac{Q_x^{III}}{a} \tag{9}$$

After determining the stress values, the safety margin of the plate of arbitrary thickness (initially assumed to be 15 mm) and the allowable moments of resistance of the plate are calculated

$$[W] = \frac{M}{\sigma_i} \tag{10}$$

Taking into account the calculations, it was found that the optimal thickness of the sectional partition is 14.3 mm.

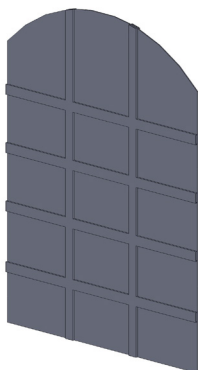


Fig. 5. Design features of the partition

In order to increase the rigidity of the plate (partition), and accordingly to ensure strength, it is proposed to strengthen it with stiffeners (Fig. 5).

The geometric parameters of stiffeners are taken similar to those used on the prototype wagon.

5. 2. Determination of the longitudinal loading of the covered wagon frame

To determine the longitudinal loading of the covered wagon frame, mathematical modeling was performed.

The dynamic loading of the covered wagon frame was calculated using the flat design scheme shown in Fig. 6. The design scheme allows considering vibrations of the covered wagon in the longitudinal-vertical plane.

The motion of the experimental system is described by the differential equations

$$\left(M_c + 2 \cdot m_T + \frac{n \cdot I_{ws}}{r^2} \right) \ddot{x}_c + M_c h \ddot{\phi}_c = S_c, \tag{11}$$

$$I_c \ddot{\phi}_c + M_c h \phi_c - q \phi_c M_c h = l F_{FR} (\text{sign} \dot{\Delta}_1 - \text{sign} \dot{\Delta}_2) + l (k_1 \Delta_1 + k_2 \Delta_2), \tag{12}$$

$$M_c \ddot{z}_c = k_1 \Delta_1 + k_2 \Delta_2 - F_{FR} (\text{sign} \dot{\Delta}_1 - \text{sign} \dot{\Delta}_2), \tag{13}$$

$$\Delta_1 = z_T - l \cdot \phi_T, \quad \Delta_2 = z_T + l \cdot \phi_T,$$

where x_c, z_c, ϕ_c – longitudinal, vertical and angular motion of the covered wagon, m_T – truck mass; I_{ws} – moment of inertia of the wheelset, r – radius of the medium-worn wheel; n – number of truck axles; S_c – value of the longitudinal force of impact on the coupler, M_c – sprung mass of the wagon, F_{FR} – absolute value of the dry friction force in the spring set, k_1, k_2 – stiffness of the spring sets of wagon trucks; l – half-wheelbase; h – height of the center of mass of the covered wagon frame.

The solution of the mathematical model in the MathCad software package was carried out as follows

$$F(t, y) = \begin{bmatrix} y_2 \\ y_4 \\ y_6 \\ \frac{S_c - M_c \cdot h \cdot \dot{y}_4}{M_c + 2 \cdot m_T + \frac{n \cdot I_{ws}}{r^2}} \\ \frac{l \cdot F_{FR} (\text{sign} \dot{\Delta}_1 - \text{sign} \dot{\Delta}_2) + l (k_1 \cdot \Delta_1 + k_2 \cdot \Delta_2) - M_c \cdot h \cdot y_3 + q \cdot y_3 \cdot M_c \cdot h}{I_c} \\ \frac{k_1 \cdot \Delta_1 + k_2 \cdot \Delta_2 - F_{FR} (\text{sign} \dot{\Delta}_1 - \text{sign} \dot{\Delta}_2)}{M_c} \end{bmatrix}, \tag{14}$$

$$Z = \text{rkfixed}(Y0, tn, tk, n, F).$$

In this case $y_1 = q_1, \dots, y_3 = q_3, \dots, y_5 = q_5, y_2 = \dot{y}_1, y_4 = \dot{y}_3, y_6 = \dot{y}_5$.

Acceleration of the covered wagon frame during impact in the loaded and empty states is shown in Fig. 7.

From the above dependencies, it can be concluded that the acceleration acting on the covered wagon frame in the loaded state is 0.37g, empty – 0.42g, which does not exceed the standard values [31–34]. The wagon motion is rated “excellent”.

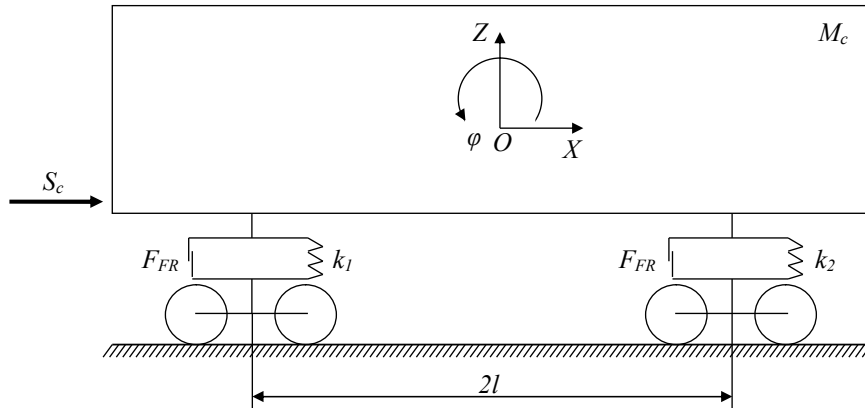


Fig. 6. Design scheme of the covered wagon

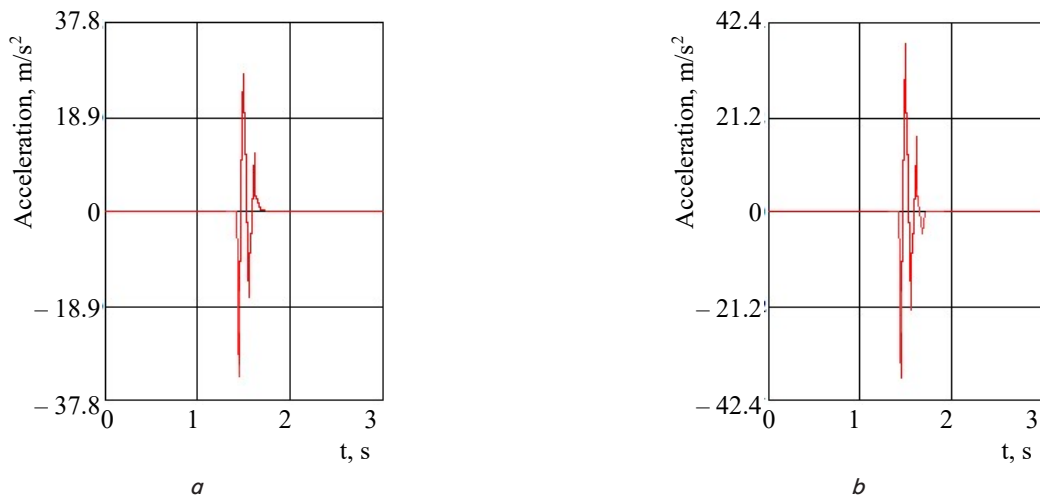


Fig. 7. Acceleration of the body of the covered wagon during shunting impact: *a* – in the loaded state; *b* – in the empty state

5. 3. Determination of the main strength indicators of the covered wagon frame

The acceleration values of the covered wagon frame determined by mathematical modeling are taken into account in the strength calculations.

The design scheme of the covered wagon frame in the design mode I (impact), as the case of the greatest loading of the frame in operation, is shown in Fig. 8.

The results of calculating the strength of the covered wagon frame in the design mode I (impact) are shown in Fig. 9, 10.

The studies showed that in the design mode I (impact), the value of maximum equivalent stresses is concentrated in the area of interaction of the center sill with the bolster beam and equals 340 MPa. The obtained stress value is lower than the yield stress of the material of the body metal structure. Maximum displacements occur in the middle of the frame beams and are about 12 mm.

The calculation was performed for the main design modes. The calculation results are given in Table 1.

According to Table 1, it can be concluded that the strength of the covered wagon frame in the main operating modes is provided.

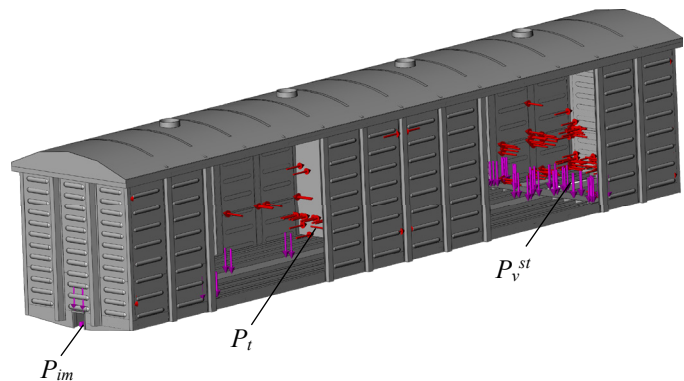


Fig. 8. Design scheme of the covered wagon frame: P_v^{st} – vertical static load; P_{im} – impact load; P_t – thrust pressure of bulk cargo

Table 1

Main strength indicators of the covered wagon frame

Strength indicator	Loading mode				
	mode I			mode III	
	impact	compression	snatch-stretching	impact-compression	snatch-stretching
Stress, MPa	340.9	326.6	315.4	296.8	269.5
Nodal displacement, mm	12.3	12.1	11.8	11.7	11.6

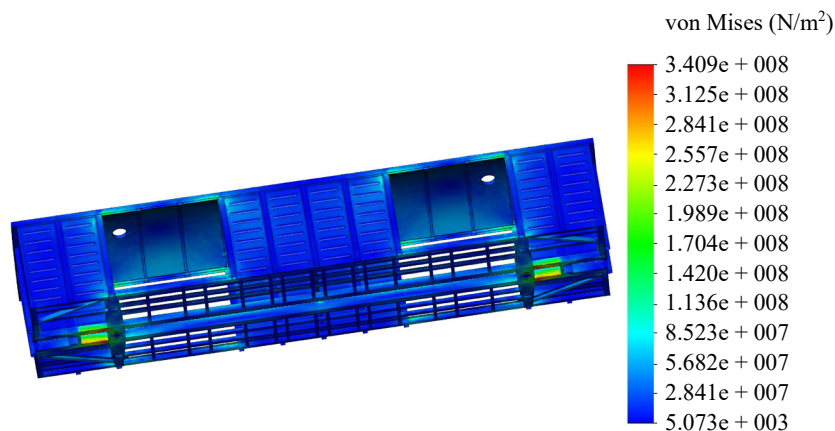


Fig. 9. Stress state of the covered wagon frame

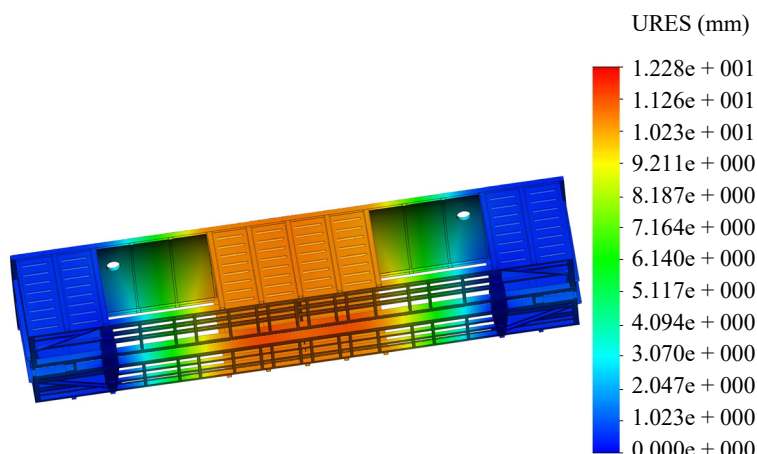


Fig. 10. Nodal displacements of the covered wagon frame

5. 4. Determination of natural vibration frequencies of the covered wagon frame

Natural vibration frequencies were calculated according to the compiled design scheme of the covered wagon frame (Fig. 10). To calculate them, a modal analysis was performed in the CosmosWorks software package.

The calculation results allowed determining the modes and numerical values of natural frequencies of vibration of the covered wagon frame. The first few vibration modes of the covered wagon frame are shown in Fig. 11. The numerical values of natural vibration frequencies are summarized in Table 2.

Table 2

Natural vibration frequencies of the covered wagon frame

Vibration mode	Frequency, Hz	Vibration mode	Frequency, Hz
1	9.4	6	47.7
2	19.1	7	53.0
3	24.3	8	57.3
4	26.1	9	65.4
5	30.8	10	71.3

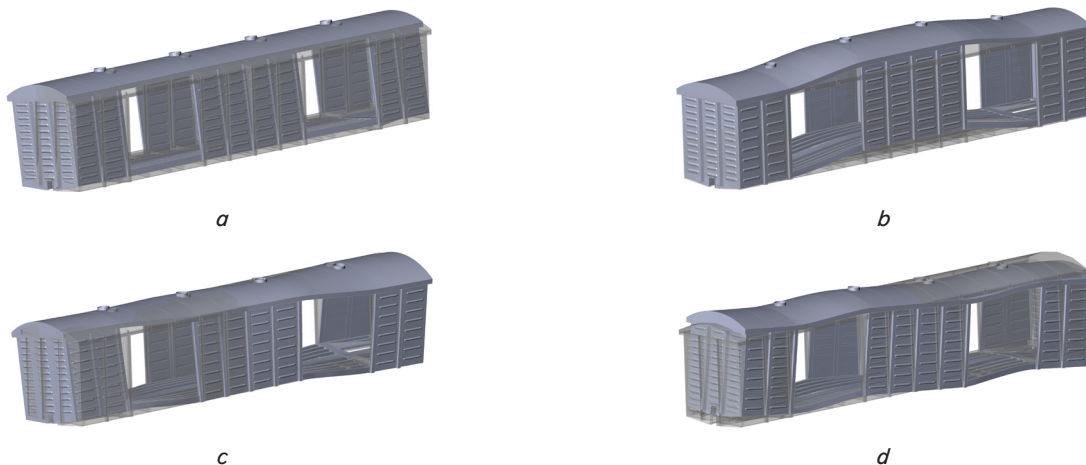


Fig. 11. Vibration modes of the covered wagon frame (deformation scale 30: 1): *a* – first mode; *b* – second mode; *c* – third mode; *d* – fourth mode

It is known that to ensure wagon safety, the first natural frequency of bending vibrations of the frame in the vertical plane must be at least 8 Hz [31, 32, 34]. The calculation results revealed that the values of natural vibration frequencies are within acceptable limits.

6. Discussion of the results of substantiating ways to increase the efficiency of using East-West covered wagons

To increase the efficiency of using covered wagons in international traffic, it is proposed to improve their designs. This improvement consists in using a sectional partition. This helps to divide the body into two separate sections, which allows the transportation of different goods in one car. For carrying out loading and unloading operations, it is proposed to install two self-sealing doors on each side of the body (Fig. 2).

Rational parameters of the sectional partition are determined. In this case, it was considered as a plate. The calculation results showed that its optimal thickness should be 14.7 mm, provided that strength is ensured. The calculation is made taking into account the loading of the partition by the thrust pressure of bulk cargo (Fig. 3). Grain is accepted as such cargo.

To determine the dynamic loading of the covered wagon, mathematical modeling was performed. Shunting impact was considered. The research was conducted in a flat coordinate system. It was found that the acceleration acting on the covered wagon frame in the loaded state is 0.37g, empty – 0.42g, which does not exceed the standard values (Fig. 9). The limitation of the model is that the impact is considered absolutely hard.

The main strength indicators of the covered wagon frame are determined. The calculation is made by the finite element method. The results showed that the maximum equivalent stresses of the covered wagon frame are within acceptable limits (Fig. 9). The modal analysis of the covered wagon frame is carried out. The natural vibration frequencies are within acceptable limits (Table 2).

The limitation of this study is that frame welds are not taken into account in the calculations. It is also important to note that when calculating the strength, the components of the covered wagon frame that rigidly interact with each

other are taken into account. That is, the design model does not take into account self-sealing doors (Fig. 8).

The next step in the direction of this study is to determine the vertical loading and fatigue strength of the covered wagon frame. It is also important to conduct an experimental determination of the loading of the covered wagon frame.

The research will help to increase the efficiency of using covered wagons in international traffic by reducing empty mileage.

7. Conclusions

1. Measures to increase the efficiency of using covered wagons in international traffic are proposed. The internal volume of the body is suggested to divide into separate sections for transporting different goods in one car. To carry out loading and unloading operations, the wagon is equipped with two self-sealing doors on each side of the body. Rational parameters of the sectional partition are determined. The calculation results showed that its optimal thickness should be 14.7 mm, provided that strength is ensured.

2. The longitudinal loading of the covered wagon frame is determined. The calculation is made using a flat design scheme. The results revealed that the acceleration acting on the covered wagon frame in the loaded state is 0.37g, empty – 0.42g, which does not exceed the standard values. The wagon motion is rated “excellent”.

3. The main strength indicators of the covered wagon frame are determined. The calculation was carried out during shunting impact, as the case of the greatest loading of the covered wagon frame in operation. The maximum equivalent stresses are concentrated in the area of interaction of the center sill with the bolster beam and amounted to 340 MPa, which is lower than the yield stress of the material. Maximum displacements occur in the middle of the frame beams and are about 12 mm.

4. Natural vibration frequencies of the covered wagon frame are determined. For this, a modal analysis was performed by the finite element method. It was found that the values of natural vibration frequencies are within acceptable limits. The value of the first natural frequency is 9.4 Hz.

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