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REVEALING THE EFFECT OF STRUCTURAL COMPONENTS MADE OF SANDWICH PANELS ON LOADING THE CONTAINER TRANSPORTED BY RAILROAD

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The object of this study is the processes of emergence, perception, and redistribution of loads in the supporting structure of a 1CC size container with end walls made of sandwich panels.

To reduce the longitudinal load of the container under operational modes, the introduction of sandwich panels into its design is proposed. This solution is implemented on the example of its end walls as the most loaded component of the body in operation.

The thickness of the sandwich panel sheet was determined, provided that the strength in operation is ensured. Mathematical modeling of dynamic load of a container with end walls made of sandwich panels placed on a platform car during shunting co-impact was carried out. It was established that taking into account the proposed improvement makes it possible to reduce the dynamic loads that the container perceives by 10 % compared to the typical structure. The results were confirmed by computer simulation of the dynamic load of the container. The models formed within the framework of the study were verified according to the F-criterion.

The results of calculations for the strength of the container showed that the stresses in its structure are 15 % lower than those in the typical one.

A feature of the findings is that the proposed improvement of the container helps improve its strength in operation by reducing the loads acting on it.

The scope of practical use of the results is the engineering industry, namely, railroad transport. At the same time, the conditions for the practical application of the research results are the introduction of energy-absorbing material as a component of the sandwich panel.

This study will contribute to devising recommendations for designing modern structures of vehicles of a modular type and for improving the efficiency of the transport industry

Keywords: ISO container, sandwich panel, dynamic container load, container strength, container transportation

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1. Introduction

Ensuring the competitiveness of the railroad industry necessitates the commissioning of vehicles with improved technical [1, 2], operational [3, 4], and environmental characteristics [5, 6]. For a long time, one of the most priority components of the transport industry is container transportation.

Almost all types of cargo are transported in containers, which predetermines demand for them. At the same time, to ensure further efficiency of operation of container transportation, it is important to introduce new structural solutions in the design of containers. Such solutions should be aimed at improving their functionality, which will improve not only the efficiency of container transportation but also the transport industry as a whole.

The possibility of transporting containers by almost all types of transport determines their loading under different operating conditions. Analysis of these regimes led to the conclusion that the most unfavorable are the loads that are inherent in rail transportation. We are talking about the shunting co-impact of the platform car with the containers placed on it. Due to the significant magnitude of the longitudinal force acting on the rear stop of the automatic coupling during the shunting co-impact of the platform car, containers are damaged. These damages can be caused both by the movement of goods inside the containers and by the natural movements of containers to the size of the technological gaps between the fittings and the fitting stops. This circumstance necessitates the implementation of additional costs for keeping containers in operation. In addition, it can also affect the safety of rail transportation once internal defects appear in containers that, under the influence of operational loads, can develop on the route.

In this regard, to improve the efficiency of operation of the railroad industry, it is important to conduct research on the improvement of container structures in order to reduce their dynamic loading during transportation.

2. Literature review and problem statement

Issues of improvements in the supporting structures of containers to improve the efficiency of their operation are covered in a considerable number of papers. Thus, study [7] reports the analysis and design features of the supporting structures of ISO containers. Possible schemes of loads of their supporting structures in operation are considered. The resistance of the structure to the action of external loads is evaluated. At the same time, the authors did not propose solutions aimed at improving the strength of containers in operation.

Features of determining the main indicators of strength of the components of the supporting structure of the container are considered in [8]. The calculation was performed in relation to a heavy-duty container of size 1AA. Studies have made it possible to formulate recommendations for the safe operation of the container. However, at the same time, the authors did not study the load of the container during transportation by rail although, in this case, its structure perceives greater loads.

Work [9] highlights the features of building an improved container for the transportation of fruit and vegetable products. The basic requirements for the proposed supporting structure of the container are indicated. The paper also reports the results of calculating the strength of the container under the main operational loads. It should be noted that when designing this container structure, the authors did not propose solutions to improve its strength under operating modes, in particular during transportation by rail.

Determination of the dynamic load of the container placed on the platform car is carried out in [10]. The shunting co-impact of the platform car loaded with 20-foot containers was taken into account. The authors proposed technical solutions to reduce the dynamic load of both containers and platform cars by introducing pliable bonds into their supporting structures. At the same time, the authors did not consider the impact of the proposed solutions on the strength of the walls of the container.

Work [11] is of scientific interest; it highlights the prospects for the use of removable bodies that operate on the principle of containers. The paper gives the requirements that modern removable body designs must meet. However, the authors did not disclose questions about increasing their operation by reducing maintenance costs, in particular repairs.

To reduce the load of the bodies of railroad vehicles, it is possible to use sandwich panels in their components. So, for example, in [12], the use of such panels on a freight car is justified. The authors noted that such an improvement can be carried out not only in the manufacture of vehicles but also in their modernization. A similar solution is proposed in [13]. At the same time, the author's team focused on improving the reliability indicators of load-bearing structures of vehicles by introducing composite panels. It was proven that the use of such panels helps to improve the endurance of vehicle bodies. It must be said that in works [12, 13] the dynamic load of cars with walls made of sandwich panels under operating modes was not investigated. Also, the expediency of introducing sandwich panels on modular vehicles, in particular containers, was not considered.

Non-trivial solutions to reduce the load of railroad vehicles are proposed in [14]. In this case, the authors considered the feasibility of manufacturing the components of the supporting structure of the vehicle from round pipes filled with foam aluminum. Studies were conducted on the example of a gondola car. It was found that when taking into account the use of polyurethane foam as a filler of the girder beam, the maximum equivalent stresses in the supporting structure of the gondola are reduced by almost 8 % compared to the supporting structure without filler. It must be said that such implementation is quite difficult in practice. In addition, the authors limited themselves to implementing the proposed solution on only one type of car. Given the accelerated growth rate of container transportation, it becomes expedient to consider issues related to the improvement of container designs.

Features of optimization of rail vehicle by using functionally graduated flow panels in its design are described in [15]. The study was conducted in relation to the supporting structure of the hopper car. A methodology for optimizing the body of a hopper car is proposed. It was found that the mass of the optimized body structure of the hopper car is 16.36 % lower than that of the prototype. However, the justification for the use of honeycomb panels in the design of the container for reducing its load in operation was not paid attention to.

Our review of literary sources [7–15] reveals that the issues of improving containers to increase the efficiency of their operation are quite relevant. At the same time, the improvement of their strength by introducing sandwich panels into supporting structures has not yet been given due attention. This circumstance necessitates research in this area.

3. The aim and objectives of the study

The aim of our study is to identify the possibilities of using sandwich panels in the design of the container during transportation by rail. This will help reduce its loading under operating conditions, and, accordingly, damage and maintenance costs.

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

– to substantiate the structural features of the sandwich panel;

– to simulate the longitudinal dynamic load of a 1CC size container with end walls made of sandwich panels;

– to determine the strength of a container of 1CC size with end walls made of sandwich panels.

4. The study materials and methods

The object of this study is the processes of emergence, perception, and redistribution of loads in the supporting structure of a container of size 1CC according to ISO with end walls made of sandwich panels.

The main hypothesis of the study assumes that a decrease in the longitudinal load of the supporting structure of the container during rail transportation is possible due to the use of end walls made of sandwich panels (Fig. 1).

To determine the thickness of the container cladding, appropriate calculations were performed using the Bubnov-Galerkin method. In this case, sheets of cladding were considered as thin-walled slabs having a width of a=2,438 m and a height of b=2,591 m (Fig. 2). The area of the plate is exposed to a uniformly distributed load P [16]. Fixing the plate is carried out along its perimeter, which corresponds to the scheme of fixing the sheet of sheathing of the container.

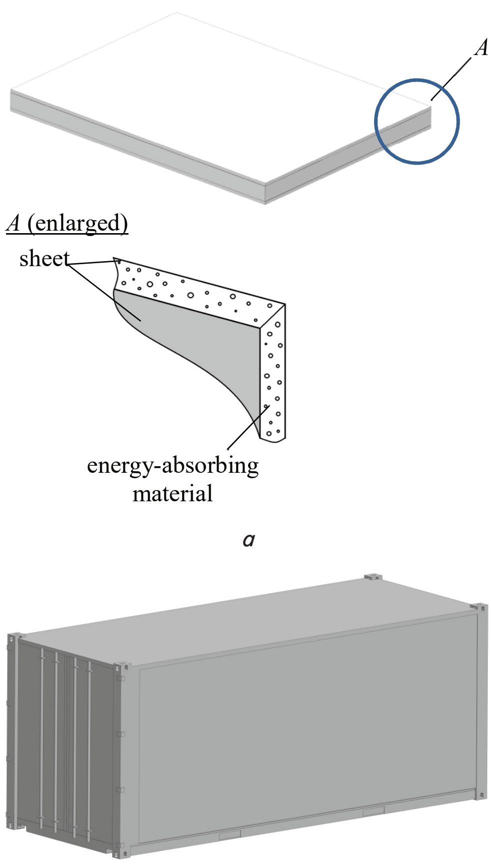

Fig. 1. 1CC size container with sandwich panel walls: *a* – sandwich panel; *b* – general view of the container

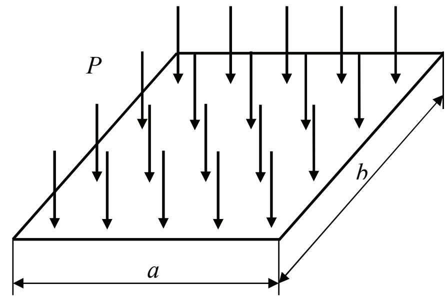

Fig. 2. Estimation scheme of the plate

In this case, the following formula is used to determine the maximum stresses [16]:

$$\sigma = P\cdot\frac{96}{\pi^4}\cdot\frac{\left(b^2+\mu\cdot a^2\right)\cdot a^2\cdot b^2}{\left(a^2+b^2\right)^2\cdot\delta^2}, \tag{1}$$

where μ is the Poisson coefficient;

δ – plate thickness.

Then:

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

At the next stage of the study, mathematical modeling of the longitudinal dynamic load of a 1CC size container with end walls made of sandwich panels was carried out. For this purpose, a mathematical model has been built that describes the shunting co-impact of the platform car with the containers placed on it.

It is taken into account that the dynamic system consists of three bodies: a platform car, a container, and a cargo placed in a container. The interaction of the platform car with the container was described via the friction forces that arise between the fittings and the fitting stops [17]. The limitation of the model is that it does not take into account the shock loads that occur between the container fittings and the fitting stops of the platform car, as well as the friction forces between the load and the inner surface of the container. This limitation is explained by the fact that the simulation considered conditional cargo using the full carrying capacity of the container.

The solution to the mathematical model was derived in the software package Mathcad (USA) under initial conditions equal to zero [18–20]. In this case, the model was reduced to the normal form of Cauchy [21–25].

To verify the formed mathematical model, computer simulation of the dynamic load of the container was also carried out. The study was carried out on condition of placing the container on the platform car of the model 13-401, which is modernized for the transportation of containers by setting fitting stops.

The spatial model of the supporting structure of the platform car and container was built in the SolidWorks software package (France); the calculation was carried out in SolidWorks Simulation using the finite element method [26–28].

Friction forces between fittings and fitting stops were not taken into account. The material of the supporting structure of the platform car and containers is the steel of grade 09G2 [29]. The model was fixed in the zones of support of the supporting structure of the platform car on bogies [30, 31].

In drawing up the finite-element model, spatial tetrahedra were used. The number of nodes of the finite-element model is 373575, elements – 1119509. The maximum size of the element is 80 mm, the minimum is 16 mm.

Verification of the model was carried out according to the F-criterion [32, 33]. The optimal number of measurements is determined by the Student's criterion [34–36].

At the next stage of the study, the strength of a 1CC size container with end walls made of sandwich panels was determined using the method of finite elements. When building a finite-element model, tetrahedra were used. The number of mesh elements was 234286, nodes – 75417. The maximum size of the element is 75 mm, the minimum is 15 mm.

5. Results of detection of the influence of sandwich panels on the load of a container of size 1CC

5. 1. Justification of the structural features of the sandwich panel

It was believed that the sheet that forms the sandwich panel is made of 09G2C steel, which is typical of metal structures of containers. The main technical characteristics of this steel are given in Table 1.

When performing calculations, it is taken into account that the permissible stresses are 310.5 MPa [37]. Foreign analog of this standard is [38].

Taking into account our calculations, it was established that the thickness of the sandwich panel sheets is about 3 mm. In this regard, the thickness of the filler, which is located between the sheets, is taken to be equal to 33 mm, provided that the dimensions of the wall are observed within what is typical (Fig. 3 [39]).

It must be said that this calculation was carried out for the case of action on the end wall of a force of $0.4{\cdot}P{\cdot}g$, where P is the carrying capacity of the container (P=21.25 tons).

Table 1

The main technical characteristics of grade 09G2S steel

Parameter name	Value
Modulus of elasticity, MPa	$2.1 \cdot 10^5$
Poisson's ratio	0.28
Density, t/m^3	7.8
Shear modulus, MPa	$7.9 \cdot 10^4$
Strength limit, MPa	490
Yield strength, MPa	345

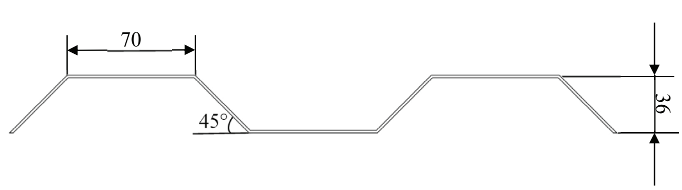

Fig. 3. Cross-section of a typical container cladding

5. 2. Mathematical modeling of longitudinal dynamic load of a 1CC size container with end walls made of sandwich panels

To determine the elastic-viscous characteristics of the sandwich panel filler, mathematical modeling of the dynamic load of the container placed on the platform car during shunting co-impact was carried out (Fig. 4).

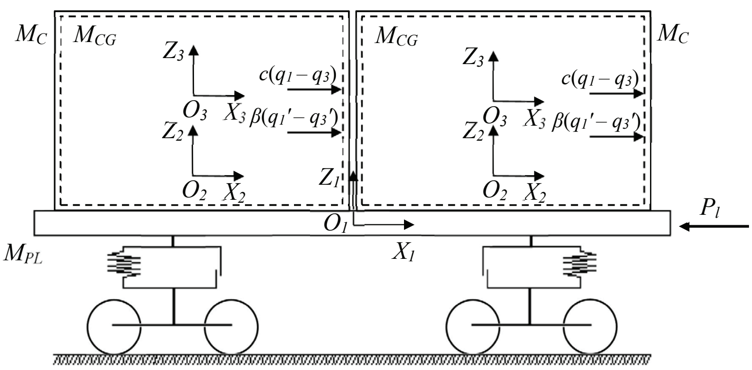

Fig. 4. Estimation scheme of the platform car loaded with containers

For this, a mathematical model has been built (3):

$$\begin{cases} M_{PL}\cdot\ddot{q}_1 = P_l - \sum_{i=1}^{n} F_{FR}\cdot\operatorname{sign}(\dot{q}_1-\dot{q}_2), \\ M_C\cdot\ddot{q}_2 = F_{FR}\cdot\operatorname{sign}(\dot{q}_1-\dot{q}_2)+ \\ +C\cdot(q_2-q_3)+\beta\cdot(\dot{q}_2-\dot{q}_3), \\ M_{CG}\cdot\ddot{q}_3 = C\cdot(q_2-q_3)+\beta\cdot(\dot{q}_2-\dot{q}_3), \end{cases} \quad (3)$$

where M_{PL} – mass-gross platform car; P_l – the value of the longitudinal force acting on the autocoupling (3.5 MN); n – the number of containers placed on the platform car; F_{FR} – friction force between fitting stops and fittings; M_C – container weight; C – filler rigidity; β – coefficient of viscous resistance of the filler; M_{CG} – cargo weight; q_1, q_2, q_3 – coordinates that determine the movement, respectively, of the container platform car and cargo relative to the longitudinal axis.

Taking into account the fact that $q_1=y_1$, $q_2=y_2$, $q_3=y_3$, we have:

$$\frac{d}{dt}y_1 = y_4, \quad (4)$$

$$\frac{d}{dt}y_2 = y_5, \quad (5)$$

$$\frac{d}{dt}y_3 = y_6, \quad (6)$$

$$\frac{d}{dt}y_4 = \frac{P_l - \sum_{i=1}^{n} F_{FR}\cdot\operatorname{sign}(y_4-y_5)}{M_{PL}}, \quad (7)$$

$$\frac{d}{dt}y_5 = \\ = \frac{F_{FR}\cdot\operatorname{sign}(y_4-y_5)+C\cdot(y_2-y_3)+\beta\cdot(y_5-y_6)}{M_C}, \quad (8)$$

$$\frac{d}{dt}y_6 = \frac{C\cdot(y_2-y_3)+\beta\cdot(y_5-y_6)}{M_{CG}}. \quad (9)$$

The next step in solving the mathematical model was the integration of equations (9) to (14) using the Runge-Kutta method [40, 41]:

$$K(t,y)= \begin{bmatrix} y_4 \\ y_5 \\ y_6 \\ \dfrac{P_l - \sum_{i=1}^{n} F_{FR}\cdot \operatorname{sign}(y_4-y_5)}{M_{PL}} \\ \dfrac{F_{FR}\cdot \operatorname{sign}(y_4-y_5)+C\cdot(y_2-y_3)+\beta\cdot(y_5-y_6)}{M_C} \\ \dfrac{C\cdot(y_2-y_3)+\beta\cdot(y_5-y_6)}{M_{CG}} \end{bmatrix}, \qquad (10)$$

T=*rkfixed* (*Y*0, *tn*, *tk*, *n*, *K*),

where *Y*0 is the vector that includes the initial conditions, *tn*, *tk* are the values that determine the initial and final integration variable, *n'* is the number of fixed steps, *K* is the symbolic vector.

Generalized accelerations were calculated in the corresponding $ddq_{j,i}$ arrays. Based on our calculations, it was established that the maximum accelerations occur at the initial moment of the dynamic process and are about 18 m/s^2 (Fig. 5), not exceeding the permissible ones. In this case, the value of the filler stiffness coefficient is taken to be 27 kN/m, and the coefficient of viscous resistance is 35 kN·s/m. These parameters are determined by sequential selection, subject to compliance with accelerations within the permissible values.

To verify the formed mathematical model (3), computer simulation of the dynamic load of the container placed on the platform car during shunting co-impact was carried out.

When drawing up the estimation scheme, it is taken into account that the containers are subject to a vertical load P_{vl}, taking into account the use of its full carrying capacity (Fig. 6). A longitudinal load P_l of 3.5 MN was applied to the rear stop of the platform car.

To take into account the elastic-viscous link in sandwich panels, which form end walls, the options of the software package were used to establish the spring-damper connection (Fig. 7).

The results of the calculations are shown in Fig. 8. The maximum accelerations were registered in the cantilever parts of the platform car, which amounted to 33.5 m/s^2. As for containers, the maximum acceleration is registered in the end walls from the side of the cantilever parts of the platform car and is equal to 19.3 m/s^2. According to the estimation scheme shown in Fig. 6 and the mathematical model (3), variational calculations were carried out. As a variational value, the impact force of the platform car is taken. The results of the calculations are given in Table 2. The accelerations acting on the container are used to verify the formed models of its dynamic load.

The results of our calculations showed that with the variance of reproducibility $S_r^2=3.92$ and the variance of adequacy $S_{ad}^2=4.66$, the actual value of the F-criterion is F_p=1.19, which is less than the tabular value (F_t=3.58). That is, the adequacy hypothesis is not rejected.

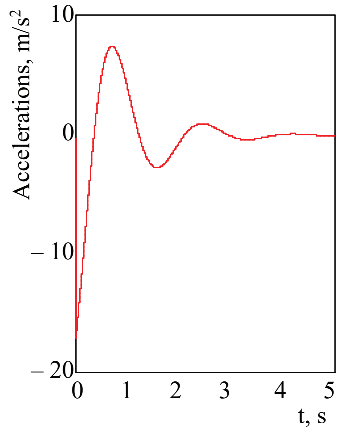

Fig. 5. Accelerations that act on the container during shunting co-impact

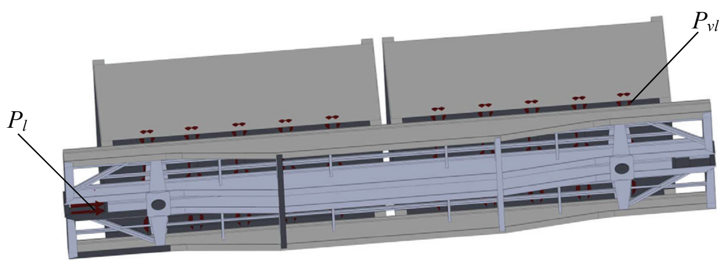

Fig. 6. Estimation scheme of the container placed on the platform car

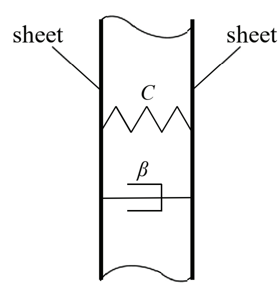

Fig. 7. Scheme of placement of elastic-viscous links in the walls of the container

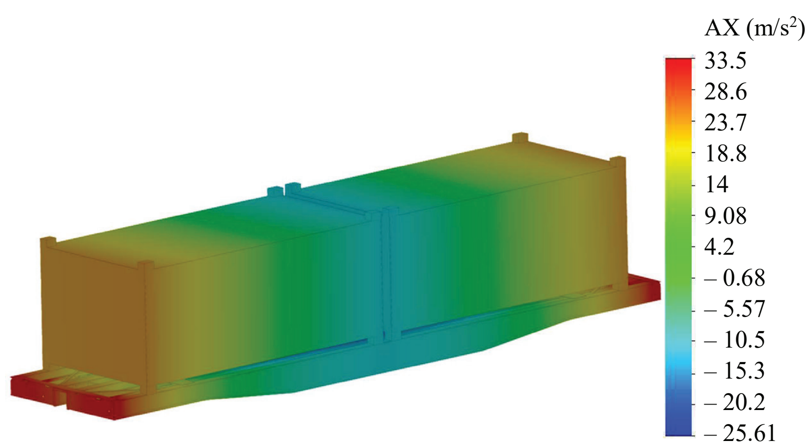

Fig. 8. Acceleration distribution fields relative to the supporting structure of the platform car and containers

Table 2

Dependence of the accelerations that act on the container placed on the platform car on the impact force in the automatic coupling

Model	Impact force in auto-coupling, MN							
	2.8	2.9	3.0	3.1	3.2	3.3	3.4	3.5
Mathematical	12.2	12.8	13.6	14.9	15.4	16.1	16.9	17.8
Computer	13.1	13.8	14.6	15.8	16.7	17.1	18.2	19.3

The discrepancy between the results of mathematical modeling and computer simulation of the dynamic load of the container is shown in Fig. 9.

The maximum percentage of discrepancy occurs with an impact force of 3 MN and 3.5 MN and is about 7.8 %.

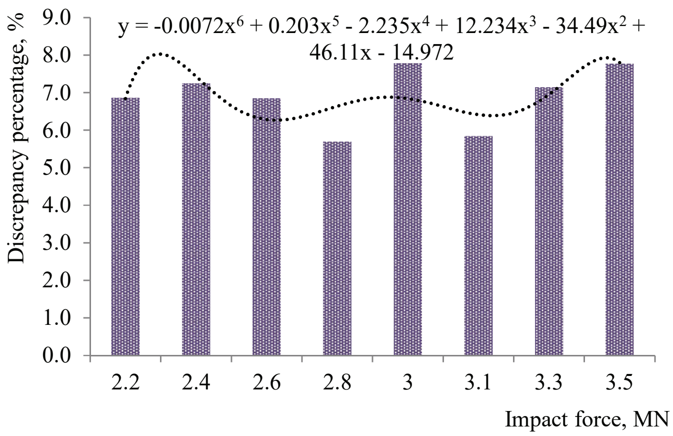

Fig. 9. Discrepancy between the results of mathematical modeling and computer simulation

5. 3. Determining the strength of a 1CC size container with end walls made of sandwich panels

To determine the strength of a 1CC size container with end walls made of sandwich panels, the calculation was carried out using the method of finite elements. The estimation scheme of the container takes into account the following loads (Fig. 10): vertical static P_v, as well as longitudinal P_l, which was applied to the end wall.

Fixing the model was carried out using fittings. Steel 09G2S was used as a construction material. The results of the calculation are shown in Fig. 11.

The maximum stresses were recorded in the zone of interaction of the side wall with the corner stand and amounted to 265.2 MPa, which is lower than the permissible one. It is important to say that the resulting stress value is 15 % lower than that which occurs in a typical container structure.

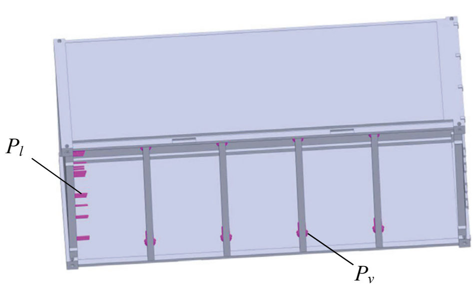

Fig. 10. Container estimation scheme

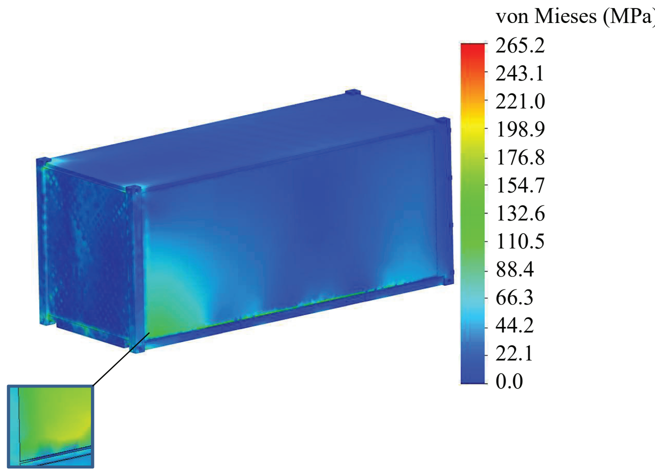

Fig. 11. Container stressed state

The distribution of stresses behind the side beam of the container frame is shown in Fig. 12.

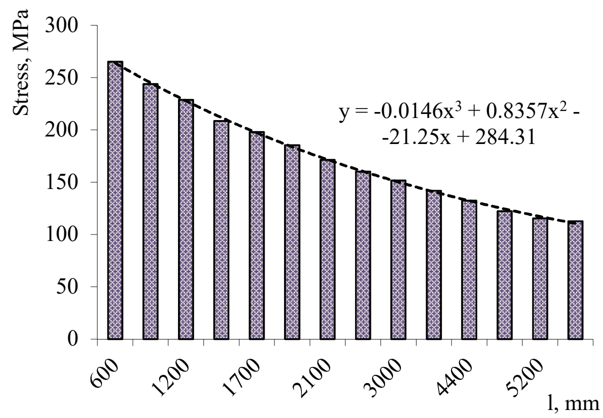

Fig. 12. Distribution of stresses behind the side beam of the container frame

Analyzing the data shown in Fig. 12, we can conclude that the maximum stresses occur in the cantilever part of the side beam of the container frame and are about 260 MPa. Due to the absorption of the kinetic energy of the impact by the sandwich panel, the magnitude of the stresses along the length of the side beam decreases.

6. Discussion of results of identifying the influence of structural components from sandwich panels in a container on its load

To reduce the dynamic load of the container during railroad transportation, the manufacture of its walls from sandwich panels is proposed. The study was conducted on the example of the end wall as the most loaded component of the body in operation.

To determine the thickness of the sandwich panel sheet, an analytical equation (2) is derived. It has been established that in order to ensure strength, the sheet thickness should be 3 mm.

To determine the dynamic load of the container of the improved design, mathematical modeling was carried out. For this, a mathematical model has been built (3). The limitation of this model is that it does not take into account the shock loads that may occur between the container fittings and the fitting stops of the platform car. Also, the model does not take into account the friction forces between the load and the inner surface of the container since the cargo is considered as conditional using the full carrying capacity of the container.

It was established that taking into account the proposed solutions makes it possible to reduce the dynamic loads acting on the container by 10 % compared to the typical design. The accelerations determined by mathematical modeling are confirmed by computer simulation. The models formed within the framework of the study are verified according to the F-criterion.

The results of calculations for the strength of the container established that the improvement of its structure helps reduce stresses in it by 15 % compared to the typical one.

The advantage of this study in comparison with those reported in [7–11] is that the proposed improvement of the container contributes to an increase in the efficiency of its operation by reducing maintenance costs. This is achieved through the use of sandwich panels in its design, which reduce its load and, accordingly, damage in operation. In contrast to works [12–15], the introduction of sandwich panels is carried out not on non-traction vehicles but on modular ones, which are currently becoming widespread, including international traffic.

As a disadvantage of this study, it can be noted that the constructed mathematical model does not take into account the angular movements of the platform car with containers upon impact. That is, we considered the case of an absolutely hard blow, which falls behind the axis of symmetry of the supporting structure of the platform car.

As a further development of this study, it is necessary to note the need for a physical experiment, which is planned to be carried out by the method of likeness. It is also advisable to consider the feasibility of using corrugated sheets that form a sandwich panel. These issues will be given attention in our further studies.

7. Conclusions

1. We have substantiated the structural features of the sandwich panel for the manufacture of the end wall of the container. A feature of the sandwich panel is that it is formed by two metal sheets, between which there is a filler in the form of an energy-absorbing material. The dependence is determined, which allows one to calculate the thickness of the sheet of the sandwich panel of the container, provided that its strength is ensured. The thickness of the sheet was 3 mm.

The thickness of the filler, which is located between the sheets, is taken to be equal to 33.0 mm, provided that the dimensions of the end wall are observed within what is inherent in the typical structure.

2. Simulation of longitudinal dynamic load of a 1CC size container with end walls made of sandwich panels was carried out. The results of mathematical modeling found that the maximum accelerations of the container placed on the platform car during shunting co-impact are about 18 m/s^2. The resulting acceleration value is 10 % lower than that in a typical container design.

The results of computer simulation of the dynamic load of the container established that the maximum acceleration occurs in its end walls from the side of the cantilever parts of the platform car and is equal to 19.3 m/s^2. Thus, the discrepancy between the results of mathematical modeling of the dynamic load of the container and computer simulation was 7.8 %.

Verification of the formed models of dynamic load of the container was carried out. It has been established that the hypothesis of adequacy is not rejected.

3. The strength of the 1CC size container with end walls made of sandwich panels was determined. In this case, the maximum stresses were registered in the zone of interaction of the side wall with the corner stand and amounted to 265.2 MPa, which is lower than the permissible ones. It is important to say that the resulting stress value is 15 % lower than that which occurs in a typical container structure.

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.

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Data availability

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

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