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ANALYSIS OF THE STRENGTH OF A HOPPER-TYPE CONTAINER WHEN TRANSPORTED BY A SEMI-TRAILER

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Abstract:
Ensuring sustainable and stable development of the state economy necessitates the introduction into operation of intermodal transport systems. One of the most promising and widespread among them is container transportation. In order to maintain the competitiveness of container transportation, it is important to put into operation modern designs of containers intended for the transportation of a wide range of goods. In this regard, within the framework of the article, the design of a hopper-type container is proposed, which allows to transport bulk materials, as well as cargoes that require protection from atmospheric effects with the possibility of further unloading by gravity under the influence of gravitational properties. The results of the calculation of the strength of the container when loaded on a semi-trailer, as well as during its transportation, are presented. It was established that with the considered load schemes, the strength of the container is ensured. The natural frequencies and shapes of the container's vibrations are determined. The results of the thermal analysis of its design are given. It was established that the strength of the supporting structure of the container is maintained at a temperature of the transported cargo of 96°C. The conducted research will contribute to the creation of multi-functional container designs and increase the efficiency of container transportation.

Key words:
transport transport mechanics, hopper-type container, load-bearing structure, strength, structural load, container transportation

1 INTRODUCTION

Prospects for the development of transport infrastructure dictate the need to create and put into operation solutions that will contribute to increasing the profitability of transportation. It is possible to achieve this by putting multimodal vehicles into operation (Anthony et al., 2021; Hilmola et al., 2021; Kilani et al., 2022).

A container is the most promising and widespread multimodal vehicle (Fig. 1).

Currently, their transportation is carried out by almost all types of transport, which is due to the mobility of the container. At the same time, maintaining the demand and competitiveness of container transportation necessitates the introduction into operation of modern container designs designed for the transportation of a wide range of goods, i.e. universal ones. Such containers should be able not only to transport and store goods, but also to carry out their self-unloading. This will contribute to the reduction of container maintenance time in the conditions of transport terminals, and accordingly, their circulation. Therefore, the issues of design and implementation of modern container designs are quite relevant and require research.

(a) (b)

Fig.1 *Universal containers: a) 20-foot; b) 40-foot*

Currently, there is a wide variety of design features and container processing technology. When designing and creating them, various calculation schemes are taken into account, which is due to the purpose of the containers, as well as their operating conditions. For example, the work (Ibramigov et al., 2015) highlights the features of creating a container for the transportation of fruit and vegetable products. The paper also states the requirements for the proposed supporting structure of the container. The results of the calculation of the strength of the container under the main operating loads are presented. However, at the same time, the authors did not take into account the loads that may act on the container during transportation by road.

Determination of inertial loads acting on the container during operational modes is carried out in the publication (Tierman et al., 2002). The calculated loads are taken into account when determining the main strength indicators of the container's supporting structure. It was established that with the considered load schemes, its strength is ensured.

Also, the peculiarities of determining the main indicators of the strength of the components of the supporting structure of the container are considered in the paper (Rzeczycki et al., 2016). The calculation was carried out in relation to a heavy-duty container of standard size 1AA. The conducted research made it possible to formulate recommendations for the safe operation of the container.

However, the strength calculations carried out in these works did not take into account the loads acting on the container during transportation by motor vehicles, which does not allow a comprehensive assessment of its operational strength.

The publication (Giriunas et al., 2012) provides an analysis and design features of load-bearing structures of ISO containers. Considered possible load schemes of their load-bearing structures in operation. The resistance of the structure to the action of external loads was evaluated. A solution is proposed regarding possible ways of improving containers. At the same time, the authors did not consider the issues of putting hopper-type container structures into operation.

Determination of longitudinal dynamic loads acting on a container placed on a platform car is carried out in work (Nikitchenko et al., 2016). A methodology is proposed that allows you to assess the impact of container movements on its dynamic load.

Also, the determination of the dynamic load of the container placed on the platform car is carried out in works (Fomin et al., 2021; Lovska et al., 2020). The shunting collision of a platform car loaded with 20-foot containers is taken into account. The authors proposed technical solutions to reduce the dynamic load of both containers and platform wagons by introducing flexible connections in their supporting structures. At the same time, the considered publications did not pay attention to the issue of loading containers during transportation by motor vehicles.

In the article (Chuan-Jin et al., 2020), the prospects for the use of removable bodies, which function according to the principle of containers, are indicated. The research was conducted in relation to the Chinese transport infrastructure. The requirements that removable bodies must meet to increase the efficiency of the use of the transport system are given. However, the authors did not investigate the issues and prospects of creating hopper-type containers, which also ensure the profitability of transportation.

The study of the strength of the bearing structure of the container with components made of composite material is carried out in (Panchenko et al., 2023). Determination of dynamic loads that act on the container in operation is carried out by mathematical modeling. The obtained results were used in the calculation of the main indicators of the strength of the container. The expediency of the design solutions adopted during the creation of the container concept is substantiated. At the same time, the proposed design of the container does not provide the possibility of transportation of bulk and bulk cargo, which narrows its demand in operation.

The analysis of publications (Ibragimov et al., 2015; Tiernan et al., 2002; Rzeczycki et al., 2016; Giriunas et al., 2012; Nikitchenko et al., 2016; Fomin et al., 2021; Lovska et al., 2020; Chuan-Jin, 2020; Panchenko et al., 2023) allows to conclude that the issues of determining the load capacity of containers and their design are quite relevant. However, they need further development in order to increase the efficiency of operation of the transport industry.

The purpose of the study is to determine the main strength indicators of the load-bearing structure of a hopper-type container when transported by motor vehicle. To achieve this goal, the following tasks are set:

- calculate the strength of a hopper-type container when loaded onto a semi-trailer;
- calculate the strength of the hopper type container when transported by a semi-trailer;
- conduct a modal analysis and determine the temperature load of a hopper-type container.

2 METHODS AND METHODOLOGY

To increase the efficiency of container transportation operation, the concept of the design of a hopper-type container is proposed (Fig. 2). A dry cargo container of standard size 1SS was chosen as the prototype. The proposed design of the container allows the transportation of bulk and bulk cargo with the possibility of further unloading by gravity under the influence of the gravitational properties of the cargo. The container is unloaded through the unloading hatches (4 pieces), which form the floor of the container. At the same time, the end walls of the container are placed at an angle of 30° in relation to the vertical axis. It is also possible to transport cargo in a container that needs protection from atmospheric precipitation. At the same time, the container can be equipped with a removable roof.

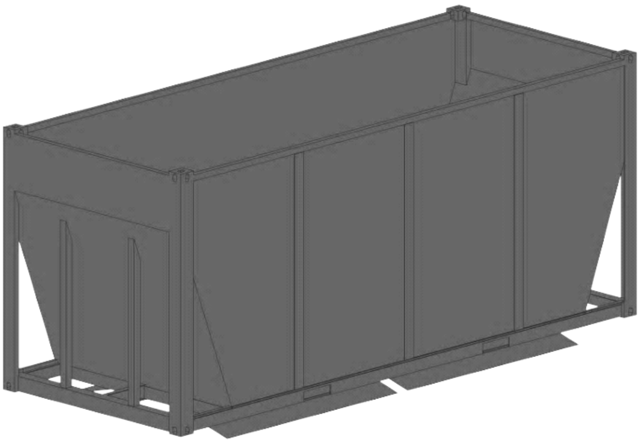


Fig.2 *A hopper type container*
Source: (authors)

The supporting structure of the container is formed by the frame (Fig. 3), which consists of upper and lower binding, corner and intermediate supports, slope supports, the main longitudinal beam and intermediate beams. Fastening of the container skin to the frame is carried out by welding. For fixing the container on the vehicle, as well as carrying out loading and unloading operations, it is equipped with corner fittings of a standard configuration.

The container's tare is 3.8 t, and the carrying capacity is 25.5 t. The useful volume of the container's body is 62.25 m^3.

For the possibility of transporting the container by motor vehicle, its strength was calculated using the finite element method in the SolidWorks Simulation software complex (Alyamovsky 2010; Alyamovsky 2007). When carrying out calculations, structural elements that rigidly interact with each other by welding are taken into account. That is, in the calculation model, the covers of the unloading hatches are not taken into account, since they have a hinged interaction with the supporting structure.

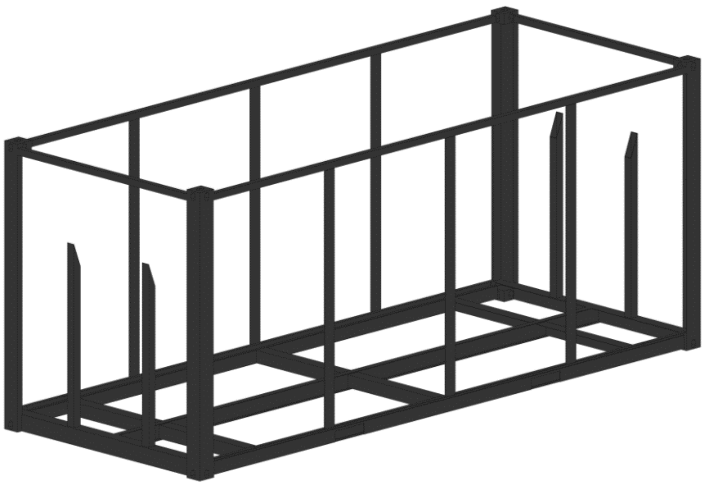


Fig.3 *A container frame*
Source: (authors)

3 RESULTS

The loading of the container on the motor vehicle is carried out with the help of lifting and transport equipment. At the same time, the slings are attached to the upper corner fittings. When calculating the strength of the container, taking into account the load of its structure through the upper corner fittings, it is taken into account that the slings are placed at an angle α = 45° to the horizontal axis of symmetry of the fitting (Containers for transportation, 2005). In this regard, the R_f load, which is transmitted to the upper corner fittings, is divided into two components - horizontal R_{fg} and vertical R_{fv} (Fig. 4).

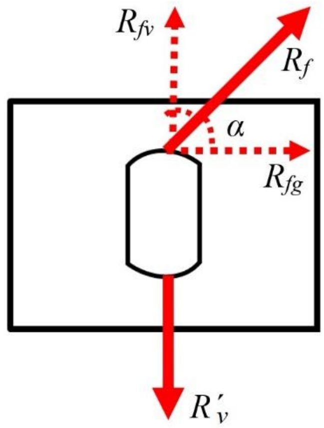


Fig.4 *A scheme of force action on the upper fitting of the container*
Source: (authors)

The vertical load caused by the gross weight of the container, which acts on the upper fittings when it is lifted, in Fig. 4 is marked as R'_v.

When drawing up the calculation scheme it is taken into account that the container is also subjected to a vertical load R_v (Fig. 5), due to the weight of the cargo placed in the container. To the side and end walls, the pressure of the spacer of the bulk cargo was applied R_R. The calculation was carried out taking into account the placement of hard coal in the container.

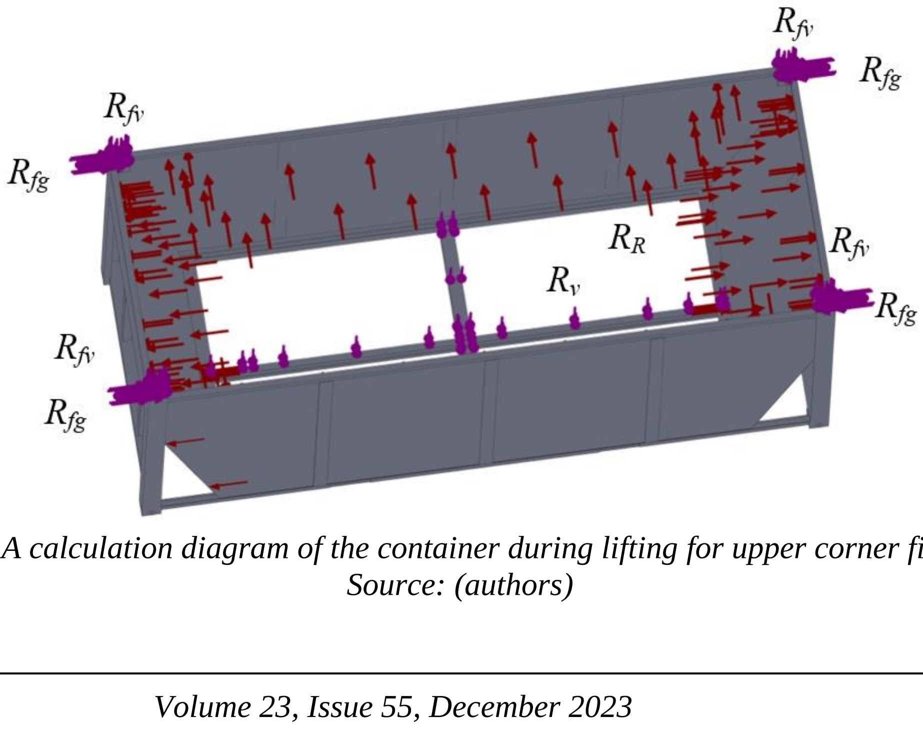


Fig.5 *A calculation diagram of the container during lifting for upper corner fittings*
Source: (authors)

At the same time, the pressure of the spacer of the bulk cargo is determined by the formula (DSTU 7598:2014; EN 12663-2, 2010):

$$R_R = \gamma \cdot g \cdot H \cdot \tan^2\left(\frac{\pi}{4} - \frac{\varphi}{2}\right), \tag{1}$$

where: γ *- the density of the bulk cargo, t/m*^{3}*,*
H *- height of the side wall, m,*
φ *- the angle of the natural slope of the cargo, rad,*
g *- acceleration of free fall, m/s*^{2}*.*

When creating a continuous model of the container, tetrahedra were used. Their optimal number is determined by the graphoanalytic method (Vatulia et al., 2017a; Vatulia et al., 2017b). The model has 37163 nodes and 113342 elements. At the same time, the maximum size of the element is 120 mm, the minimum is 24 mm. The construction material of the container is 09G2S steel, which has elastic isotropic properties. The main physical and mechanical properties of this steel are given in Tab. 1.

Tab. 1 *The physical and mechanical properties of the used steel*

Parameter	Value	Unit
Young's modulus	2.1·105	MPa
Poisson's ratio	0.28	-
Density	7800	kg/m^3
Ultimate strength	490	MPa
Yield strength	345	MPa
Coefficient of thermal expansion	$1.5 \cdot 10^{-5}$	1/K

Source: (authors)

Based on the calculations, it was established that the maximum equivalent stresses in the container occur in the zones of interaction of the main longitudinal and intermediate beams and amount to 142.6 MPa (Fig. 6). The resulting stresses are 58.7% lower than the yield stress of the construction material, which is equal to 345 MPa (DSTU 7598:2014; EN 12663-2, 2010).

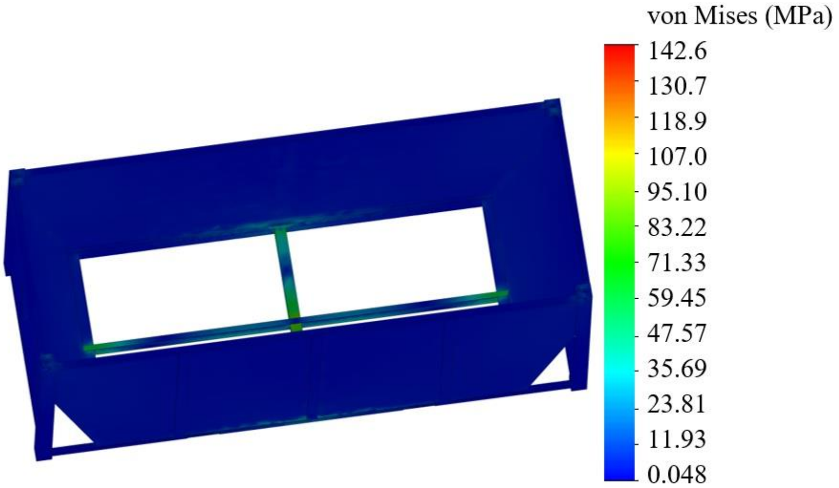


Fig.6 *The stresses distribution in the container structure during lifting*
Source: (authors)

To determine the strength of the container during transportation by motor vehicle, its loading with inertial forces of 1.2g is taken into account - in the longitudinal direction following the movement of the motor vehicle; 0.8g – in the longitudinal direction against the direction of movement; 0.5g – in the transverse direction.

Fig. 7 shows the calculation diagram of the container when it is loaded with an inertial force of 1.2g in the longitudinal direction following the movement of the motor vehicle. When drawing up the scheme, it is taken into account that the vertical load R_v acts on the container, caused by the weight of the transported cargo; the pressure of the spacer of the bulk cargo R_R, as well as the inertial forces R_f, which are applied to the lower corner fittings.

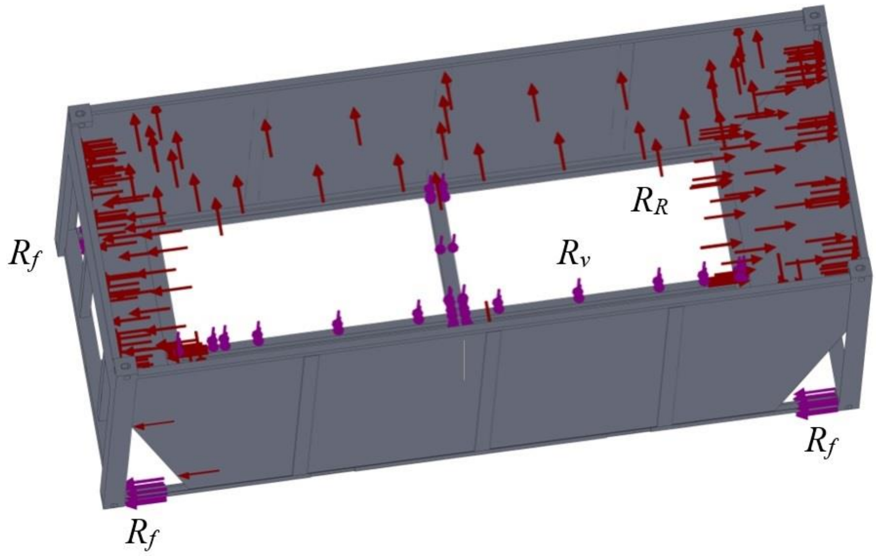


Fig.7 *A calculation diagram of the container when it is loaded with inertial forces in the longitudinal direction following the movement of a semi-trailer*
Source: (authors)

It was established that the maximum equivalent stresses occur in the zones of interaction of the lower binding with the lower corner fittings and amount to 225.6 MPa (Fig. 8). The resulting stresses do not exceed the yield stress of the material of the container structure and are lower than them by 34.6% (DSTU 7598:2014; EN 12663-2, 2010).

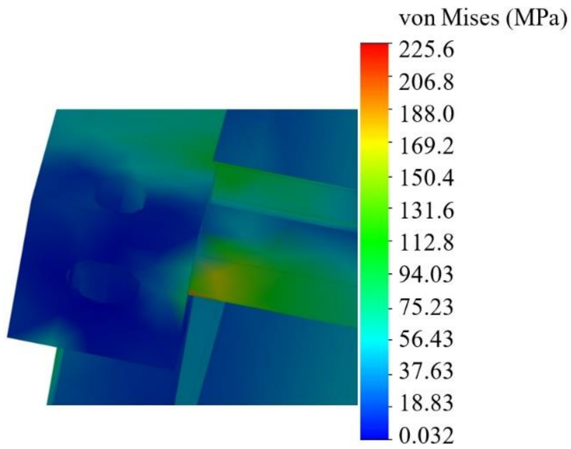


Fig.8 *The stresses distribution in the container structure when it is loaded with inertial forces in the longitudinal direction following the movement of a semi-trailer*
Source: (authors)

The maximum equivalent stresses in the structure of the container when it was loaded with inertial forces in the longitudinal direction against the direction of the vehicle were 204.5 MPa, and in the transverse direction - 203.6 MPa. That is, with the considered calculation schemes, the resulting stresses do not exceed the permissible values.

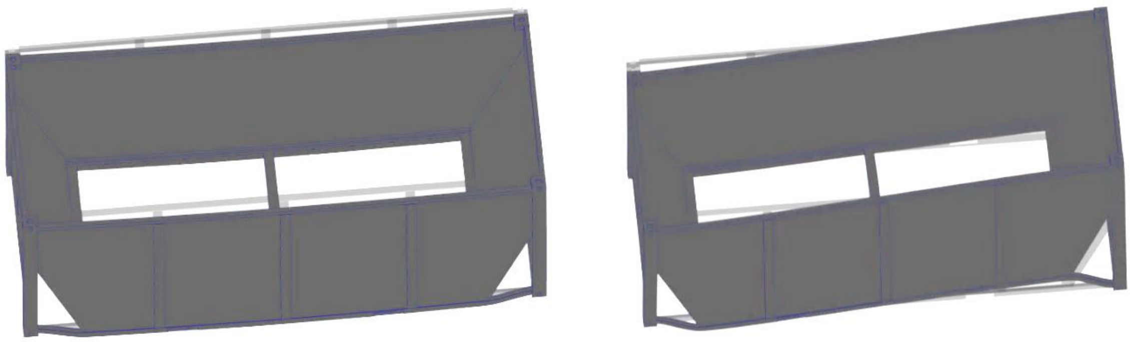
To ensure the safety of container transportation, a modal analysis of its supporting structure was also conducted. The main purpose of the performed modal analysis is to ensure, that the designed container hopper-type wagon will be used for a long time within a safe limit. As the container is exposed to the dynamical loads due to the road and rail irregularities, the improper modal properties of the container could lead to the excitation of resonance of its structure. Transportation safety was assessed based on the first natural frequency of oscillations, the numerical value of which should be at least 8 Hz (DSTU 7598:2014; EN 12663-2, 2010). It means, that eigenfrequencies of the container must be higher than 8 Hz. The calculation was carried out according to the scheme shown in Fig. 7. However, the longitudinal inertial load was not taken into account. The obtained results established that the first natural frequency of oscillation of the container has a value of 56.4 Hz, that is, it is not higher than the permissible value (Tab. 2). The reached results (eigenfrequencies) of the modal analysis show, that the operation of the container is safe, as all values are much higher than the permissible value of 8 Hz.

Tab. 2 *Eigenfrequencies of the eigenmodes of the container*

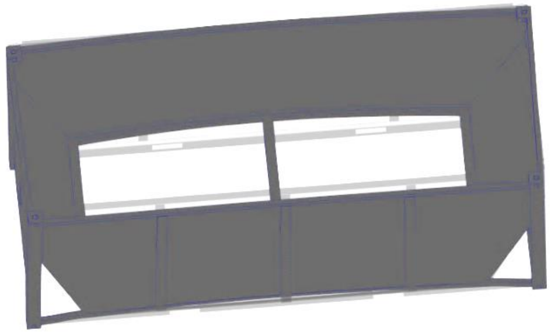
Eigenmode	Eigenfrequency [Hz]	Eigenmode	Eigenfrequency [Hz]
1	56.4	6	128.1
2	63.7	7	137.9
3	67.2	8	141.2
4	84.3	9	151.2
5	91.0	10	161.5

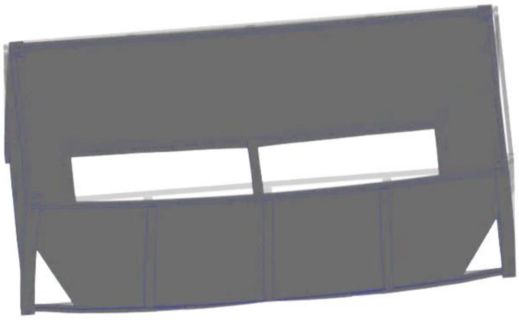
Source: (authors)

The performed calculation also made it possible to determine the forms of oscillations of the supporting structure of the container. Some of them are shown in Fig. 9 as an example.



(a) (b)





(c) (d)

Fig.9 *Forms of oscillations of the supporting structure of the container (scale of 5:1): (a) the 1st mode, (b) the 5th mode, (c) the 6th mode, (d) the 8th mode*
Source: (authors)

Alternatively, the designed hopper-type of the container can be used for transportation of high-temperature cargo. Therefore, the possibility of transporting high-temperature cargo in a container was investigated. In order to identify the maximal accepted temperature of the transported cargo, a thermal calculation was performed. At the same time, the calculation model of the container takes into account the pressure of the spacer of the bulk cargo, as well as the temperature load R_T, which was applied to the inner surfaces of the container (Fig. 10).

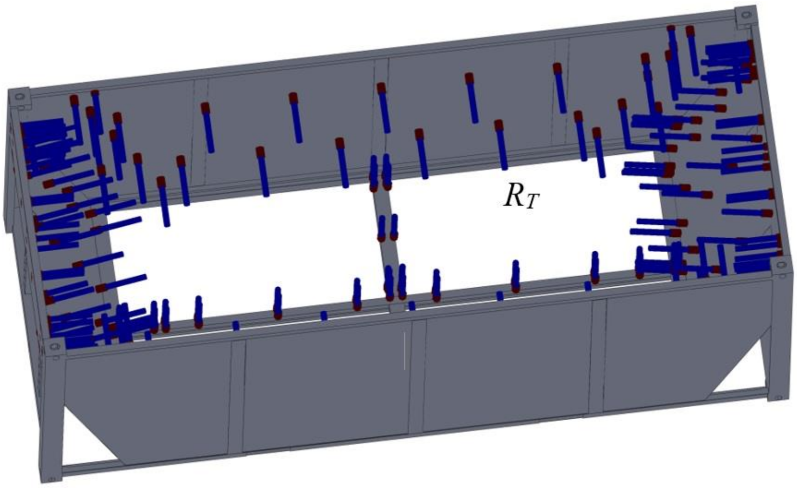


Fig.10 *A scheme of application of the temperature load to the inner surfaces of the container*
Source: (authors)

Figure 10 shows the boundary conditions of the thermal analysis of the designed hopper-type container. An application of heat was defined from inside the container. It is marked by blue indicators (R_T) in Fig. 10.

The heat calculation was performed for several temperatures, as Fig. 11 shows. It can be seen from this graph, that the permissible value of the strength of the container is ensured for the temperature of 96°C (Fig. 11).

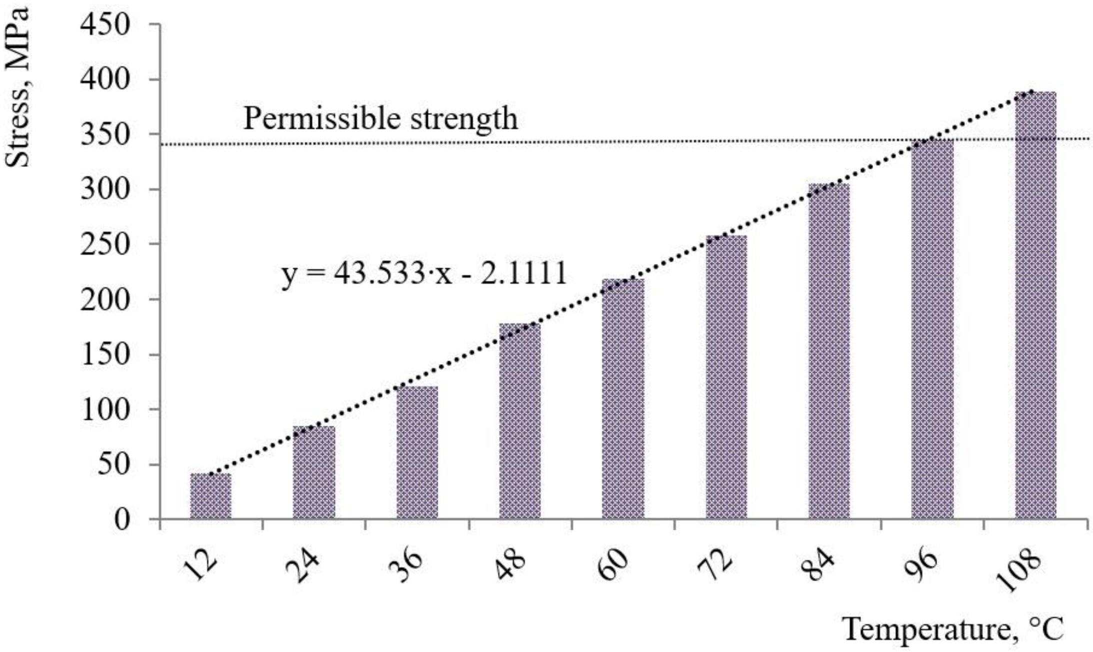


Fig.11 *Dependence of the maximum equivalent stresses in the container from the temperature of the cargo transported in it*
Source: (authors)

In the vertical racks, the maximum stress was about 320 MPa. In the main longitudinal beam, the maximum stresses are equal to 298 MPa, and in the intermediate beams - 286 MPa.

The conducted research will contribute to the creation of multi-functional container designs and increase the efficiency of container transportation.

4 CONCLUSIONS

1. The calculation of the strength of the hopper-type container when loaded on a motor vehicle was carried out. The maximum equivalent stresses in the container occur in the interaction zones of the main longitudinal and intermediate beams and amount to 142.6 MPa. The resulting stresses are 58.7% lower than the yield stress of the construction material, which is equal to 345 MPa.

2. The calculation of the strength of the hopper-type container during transportation by motor vehicle was carried out. The maximum equivalent stresses when the container is loaded with inertial forces in the longitudinal direction along the course of the vehicle are 225.6 MPa. The obtained stresses do not exceed the yield stress of the material of the container structure and are lower than them by 34.6%.

3. The maximum equivalent stresses in the structure of the container when it was loaded with inertial forces in the longitudinal direction against the direction of the vehicle were 204.5 MPa, and in the transverse direction - 203.6 MPa. That is, with the considered calculation schemes, the resulting stresses do not exceed the permissible values.

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