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Study of the strength of a removable module with a container when loading it into an open wagon

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Abstract

The main goal of this article is to present the design of a removable module that facilitates transportation of containers in open wagons. This module functions as an intermediary adapter between a wagon body and a container, and it ensures their reliable interaction. The loading of the removable module with the container into an open wagon is provided by suspended or other types of loading and unloading devices. Appropriate calculations were made to study the strength of the removable module during loading and unloading operations. The movement of the removable module using steel ropes and a spreader was considered. The calculation of the strength of the removable module was carried out in the SolidWorks Simulation software, which implements the finite element method. It was established that the strength of the removable module is ensured within the considered load schemes. The results of the conducted research will contribute to increasing the efficiency of container transportation by rail and to the development of a modular vehicle design.

Keywords

railway transport; design adaptation; removable module, structural load; container transportation

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1. Introduction

The increasing profitability of international transport led to the introduction of container transportation. The possibility of transporting containers by almost all types of vehicles ensures their mobility and widespread use in transport operations (Caban et al., 2021; Soloviova et al., 2020).

A significant share of container transportation is accounted for by rail transport: containers are carried on platform wagons (Haferkorn, 2022; Široky et al., 2024). The occasional lack of platform wagons in operation makes it necessary to use other types of wagons for container transportation, for example, open wagons. However, the use of open wagons for container transportation requires a reliable system of interaction, as open wagons are not designed for this purpose. The lack of compatibility might lead to damage not only of the container itself together with transported cargo, but also to the open wagon body (Medvediev et al., 2024; Milenković et al., 2023; Wang and Xie, 2024). This is also dangerous from an environmental point of view, because in the event of an accident, the release of cargo transported in unsecured containers into the environment might cause environmental hazards (Wickens et al., 2003; Norman, 2013; Graedel and Allenby, 2010; McDonough and Braungart, 2010). In this regard, the issues of situational adaptation of open wagon to transportation of containers are highly relevant and requires thorough research.

The purpose of the study presented here is to determine the load bearing structure of a removable module with a container when it is loading into an open wagon. To achieve this goal, the following tasks are defined:

- Determination of the strength of the removable module when it is lifted by steel ropes (the 1st load case)
- Determination of the strength of the removable module when it is lifted by a spreader (the 2nd load case)
- To conduct an experimental study of the strength of the hatch cover of an open wagon when loaded by the removable module.

2. Literature review

The issues of creation of railway vehicles for container transportation and their introduction into operation are quite urgent. For example, Lovska (2024) highlights the results of studies of the load concepts of the load-bearing structures of a platform wagon considering improvements to increase the efficiency of their operation in international transport. Measures are proposed to improve the load-bearing structures of platform wagons in order to extend their functions for transporting containers, timber or steel in rolls, wood chips or trailers; also to promote the use of platform wagons for military and strategic purposes. The author suggests the creation of articulated platform wagons based on existing structures. At the same time, solutions aimed at the adaptation of open wagons to the transportation of containers are not proposed in this work.

In order to increase the efficiency of container transportation by railway, Reidemeister et al. (2016) proposed to improve the supporting structure of a universal platform wagon by placing fitting stops on the longitudinal beams of the frame. The results of experimental studies of the strength of the wagon frame during shunting manoeuvres, considered the most unfavorable loading condition for the load-bearing structure of the wagon in operation, are presented. It was established that the proposed modernization is expedient. However, the authors did not investigate the feasibility of such modernization of open wagons for the purpose of transporting containers.

The work presented in Shaposhnyk et al. (2021) proposes the modernization of a universal platform wagon for enabling container transport . by applying a removable frame on a platform wagon. The results of the calculations proved the feasibility of using such a solution on platform wagons, but this study did not test open wagons for similar purposes either.

Some studies (Gerlici et al., 2023a; Lovska et al., 2024) have investigated the strength of a hatch cover of a universal open wagon when subjected to loading by a fitting stop. It was established that the transportation of containers in open wagons, whose floor is equipped with hatch covers, is not possible without additional modernization. However, the authors of this study did not propose an adaptation of an open wagon to the container transportation.

Measures for the safe transportation of containers in an RGS wagon type are proposed by Berescu et al. (2020). A special feature of the container fastening scheme on this wagon type is the use of special bolts. The authors made appropriate calculations and determined the optimal type of bolts for fixing containers. However, the authors did not examine the possibility of using such a fastening scheme for containers in open wagons.

The research by Gerlici et al. (2023b) proposes a concept of a removable module for the situational adaptation of open wagons for container transportation. The design of the removable module is multifunctional, and it can be used for

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transporting other types of cargo if modernized. The study provides a justification of the use of such a module for fastening containers on open wagons. It also highlights the design features of the removable module using modern software tools. However, the strength of the load-bearing structure of an open wagon and the container considering the use of this module, was not examined in the study.

Determining the load of an open wagon when transporting containers is carried out by Gerlici et al. (2023c). A solution for improving the container fastening scheme in an open wagon is proposed. However, these solutions are proposed as concepts, and no examples of their implementation are provided.

The above analysis of the literature demonstrates that the issues of situational adaptation of wagons for container transportation are highly relevant. At the same time, the adaptation of the load-bearing structures of open wagons for container transportation has not been given appropriate attention. This makes it necessary to study this issue in more detail.

3. Analysis of the strength of the removable module

It is suggested to use a removable module for safe transportation of containers in an open wagon. This module works on a principle of an intermediate adapter between the container and the open wagon body (Fig. 1). The module consists of a frame, which is made up of lateral beams (1), end beams (2), longitudinal beams (3), end structures (4) and diagonal reinforcement beams (5). Further, it is equipped with corner fittings – lower (6) and upper (7) –, which allow the module to be fastened to an open wagon. These components are supplemented by additional fittings stops (8).

A detail of container fastening in the module by fitting stops is depicted in Fig. 2.

At the same time, the interaction of suspended devices with the removable module is assumed at its upper fittings. The results of evaluating the loading of the removable module during transportation in an open wagon – considering the most unfavourable loading conditions – showed that the strength of the module is ensured, and the proposed container fastening scheme is appropriate (Panchenko et al., 2024).

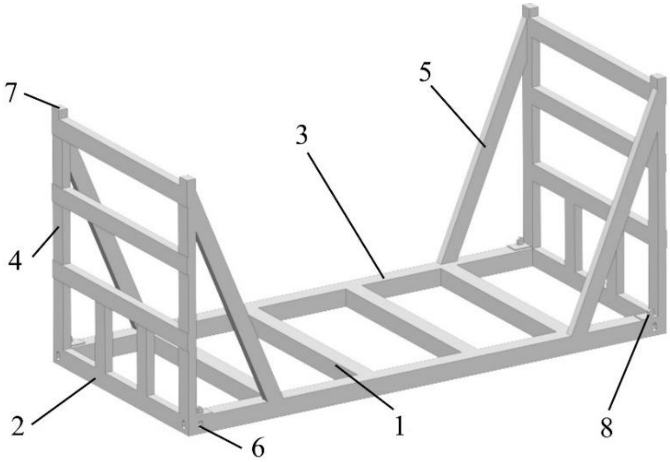

Figure 1. Removable module for container fastening in an open wagon

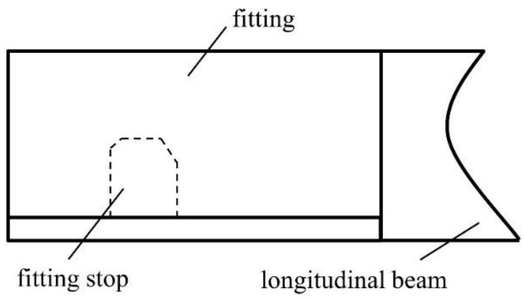

Figure 2. A scheme of interaction of the fitting stops with the fitting of the removable module

Loading of the removable module together with a container into an open wagon is achieved by suspended or other types of loading and unloading devices, as shown in Fig. 3.

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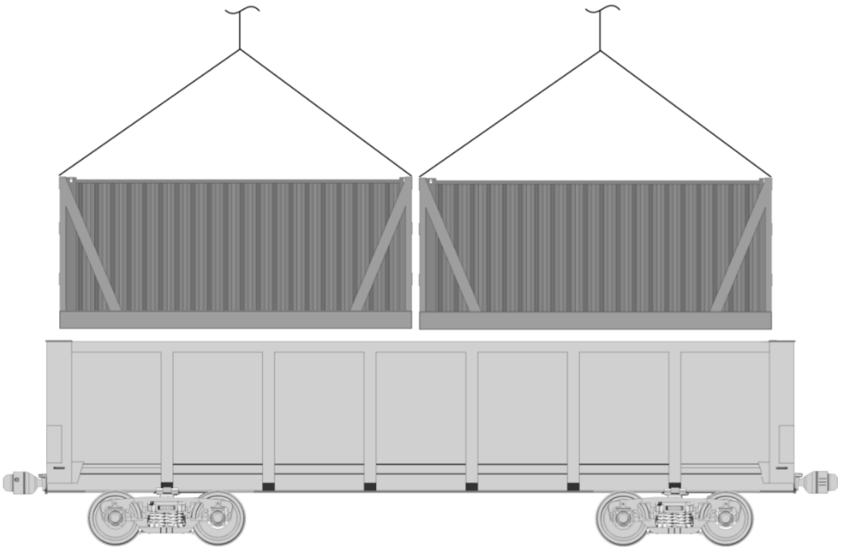

Figure 3. Loading of removable modules with containers in an open wagon

To study the strength of the removable module during loading and unloading operations, appropriate calculations were carried out. Two loading scenarios are considered:

- by means of steel ropes – the 1st loading case (Fig. 4a)
- by means of a spreader – the 2nd loading case (Fig. 4b)

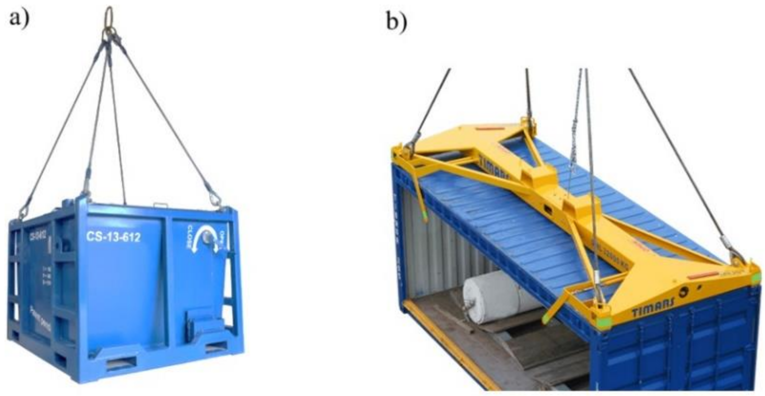

Figure 4. Suspended means of transport when interacting with containers:
a) steel ropes; b) a spreader

At the initial stage of research, the strength of the removable module was determined when it was lifted using steel ropes, i.e. for the 1st loading case. The strength calculation was carried out in the SolidWorks Simulation software using the finite element method (Kozyar et al., 2018; Pustylga et al., 2018).

A calculation scheme of the removable module for the 1st loading case is shown in Fig. 5.

It is considered that the removable module is loaded by the force P_v (the load of the own mass) as well as the gross weight of the container P_k. In the areas of interaction of the removable module with the steel ropes (upper corner fittings), the load P_s was applied. This load is divided into two components (vertical and horizontal), taking into account of the angle of inclination of steel ropes, which is assumed to be 45°.

The finite-element (FE) model of the removable module is constructed using tetrahedrons. Their optimal number was determined by a graphical-analytical method. Considering the calculations, the number of elements of the finite element mash was of 95,235 with a maximum size of 100 mm and a minimum of 20 mm. The number of nodes of the FE mesh was 33,147.

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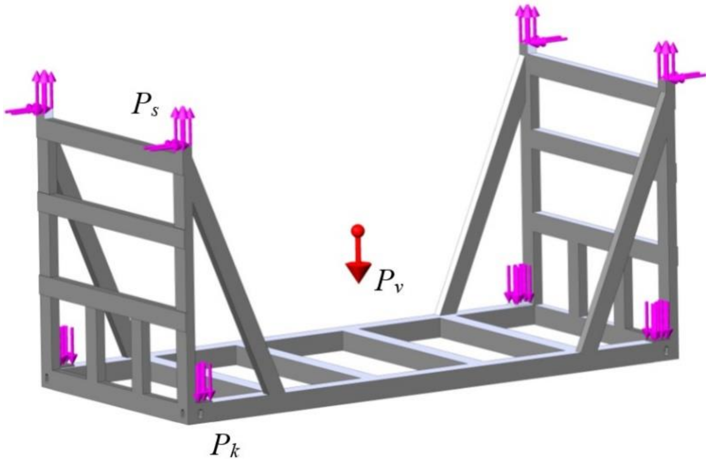

Figure 5 A calculation scheme of the removable module during its lifting by steel ropes

Steel 09G2S was selected as a construction material for the designed removable module. This steel type was chosen because it is the most common steel used for manufacturing wagon structures, and it is used not only for the load-bearing structures of wagons, but also for modular transport units. The results of strength calculations for the removable module for the 1st loading case are shown in Fig. 6 and Fig. 7.

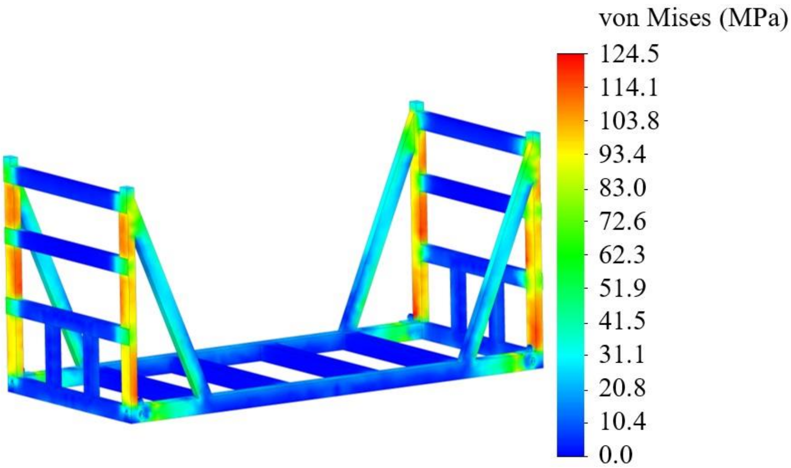

Figure 6. Stress distribution in the removable module structure in the 1st load case

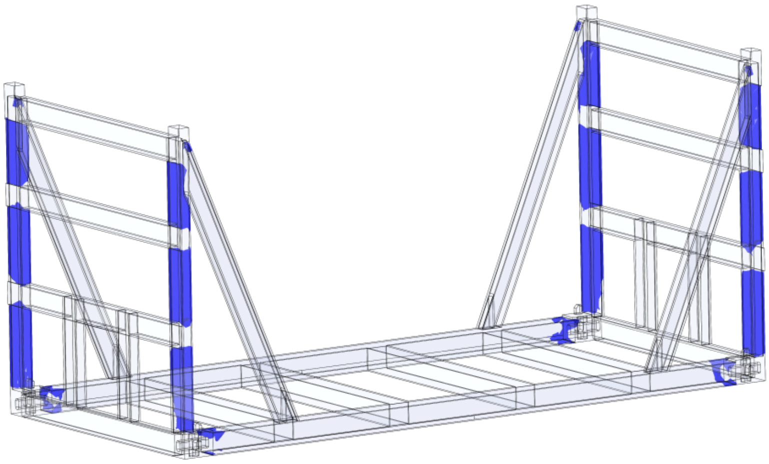

Figure 7. The most loaded areas of the removable module are the end structures in the 1st load case

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Maximum stresses occur in the zones of interaction of end beams with longitudinal beams. These stresses amounted to 124.5 MPa (Fig. 6). These values do not exceed the permissible values given in the standard (DSTU, 2014). Therefore, the strength of the removable module design within the applied load scheme (the 1st load case) is ensured.

The stress distribution along the height of the end beams is shown in Fig. 8.

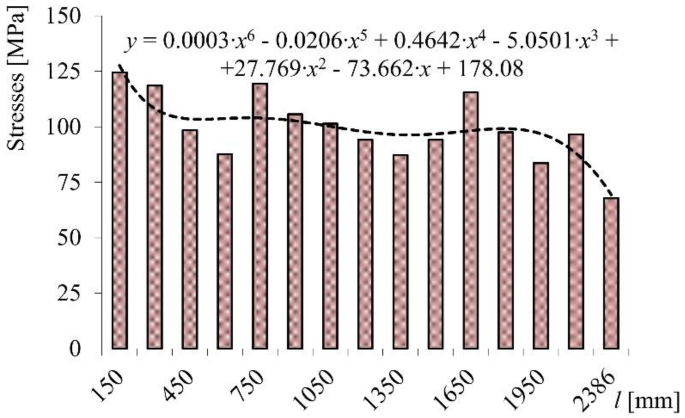

Figure 8. A distribution of stresses along the height of the removable module end structures for the 1st load case

As it can be seen in Fig. 8., the stresses distributed in the removable structure have a variable character. This phenomenon can be explained by the presence of diagonal reinforcement beams in the end superstructures, and accordingly, by the variable stiffness of end structures in height.

At the next stage, the strength of the removable module when it is lifted by a spreader, i.e. for the 2nd load case, was investigated. A calculation scheme of the removable module for the 2nd load case is shown in Fig. 9.

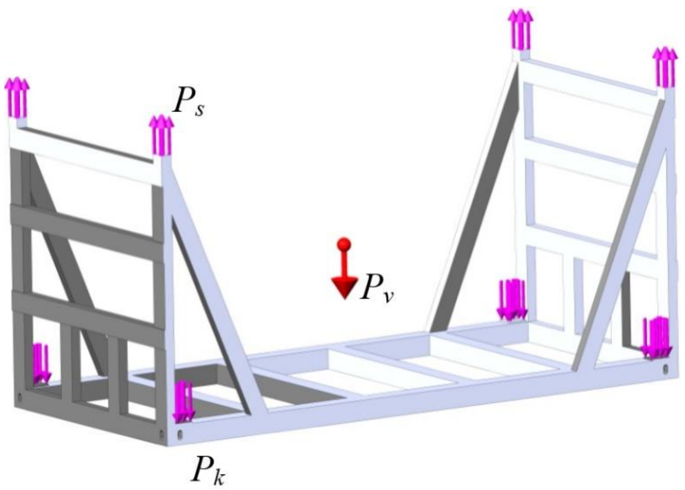

Figure 9. A calculation scheme of the removable module for the 2nd load case

The force P_v (the load of the own mass) as well as the gross weight of the container P_k are taken into account as the load of the removable module for the 2nd load case. The load of P_s is applied in the areas of interaction of the removable module with the spreader (upper corner fittings).

The results of the strength analysis of the removable module are shown in Fig. 10 and Fig. 11. The maximum stresses were identified in the zones of interaction of end structures with the longitudinal beams. These stresses amounted to the value of 135.7 MPa (Fig. 10). However, the permissible values of the strength of the used material are not exceeded (DSTU, 2014) in this case either.

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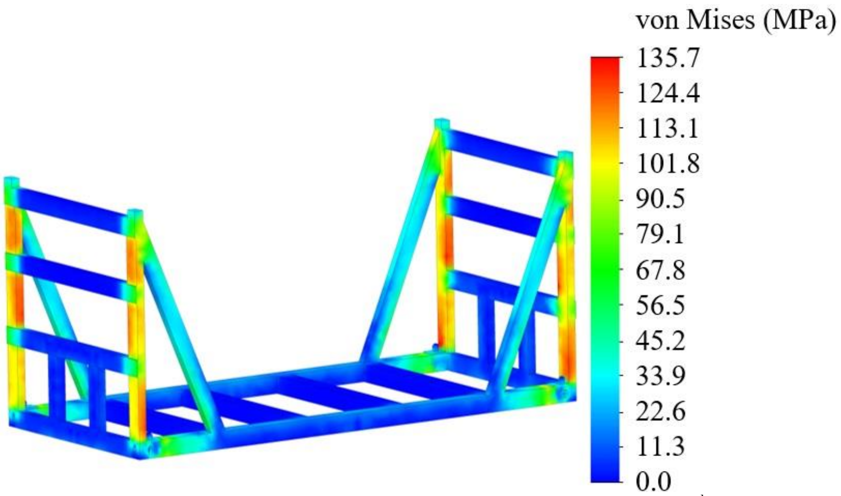

Figure 10. A stress distribution in the removable module structure for the 2nd load case

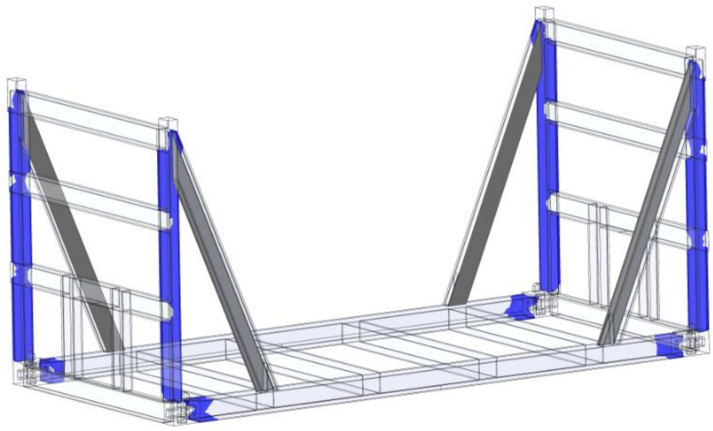
Figure 11. The most loaded areas of the removable module for the 2nd load case

The stress distribution along the removable module end structures is shown in Fig. 12. The nature of the stresses varying in height of the end structures of the removable module is explained in the same way as in the previous load case (i.e. the 1st load case).

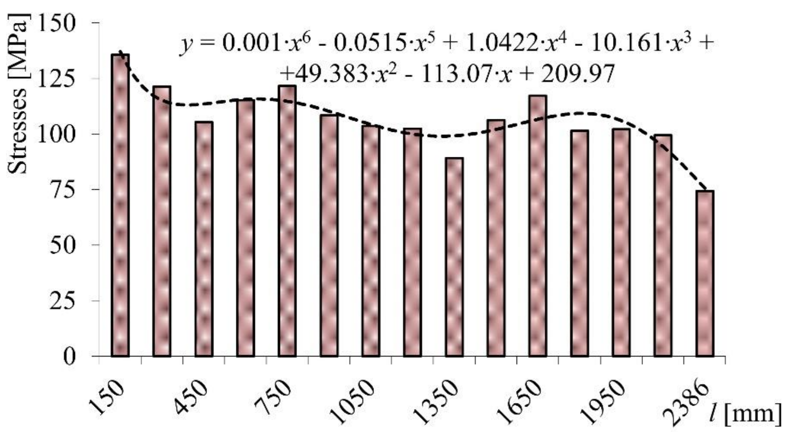

Figure 12. A distribution of stresses along the removable module end structures for the 2nd load case

The performed calculations prove that the strength of the removable module for container transport is ensured for its loading and unloading operations. The performed analyses revealed that the load of the removable module is slightly higher

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for the manipulation with a spreader in comparison with manipulation with steel ropes. This can be caused by the angle of inclination of steel ropes, which leads to dividing the load into two components and, accordingly, this causes a decrease of stresses in the design of the removable module.

To substantiate the use of a removable module for fastening containers in an open wagon, an experimental determination of stresses in the hatch cover of an open wagon was carried out. This structural unit of the wagon body forms its floor (Fig. 13). When the fitting stop is placed on the hatch cover, it is exposed to the load. Therefore, it is advisable to examine its strength. Bench tests were run in the research laboratory of the "Center for Diagnostics of Transport Structures" at the Ukrainian State University of Railway Transport. The determination of stresses in the hatch cover structure was carried out using the method of electrical strain gauge measurement. The strain gauges were calibrated before installing the strain gauge resistors. Strain gauge resistors with a base of 10 mm and a resistance of 100 Ohms were used in this case (Fig. 14).

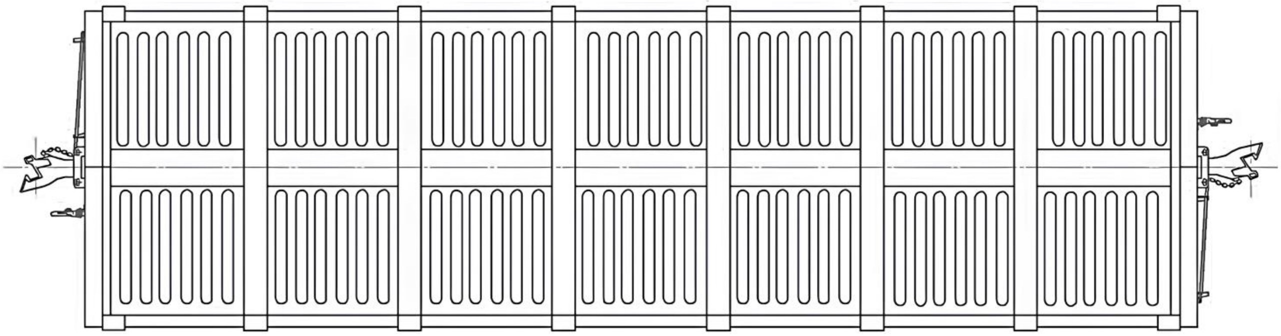

Fig. 13. A placement of hatch covers on the wagon body floor (a top view)

Figure 14. Placement of strain gauges on the hatch cover

The strain gauges were installed according to the bridge scheme. The locations of the strain gauges on the hatch cover were determined by the theoretically obtained stress fields. The scheme of the groups of strain gauges on the hatch cover is shown in Fig. 15. Strain gauges were also placed at the bottom of the hatch cover in the same areas as at the top.

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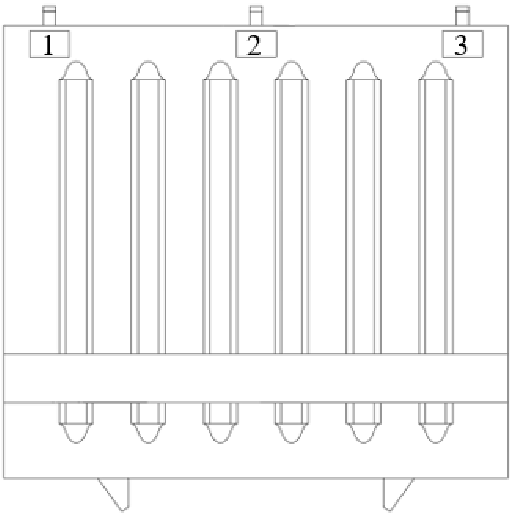

Figure 15. An arrangement of groups of strain gauges on the hatch cover: 1 – the first group; 2 – the second group; 3 – the third group

A special stand was created to test the hatch cover, which was secured by hinges using metal pins (Fig. 16).

The load was transferred to the hatch cover through a metal plate (Fig. 15, 16), whose width was equal to the width of the longitudinal beam of the removable module.

The load on the plate was transferred through an I-beam, which, in turn, perceived the load from a jack. The load value was controlled by a dynamometer. In this case, the maximum load value was 6 t (60 kN), which corresponds to the maximum loaded state of a 1CC size container.

The largest deformation readings during the tests were recorded by the strain gauges in Group 3 (Fig. 17). It can be seen in Fig. 17 that the dependence of relative deformations on the load is linear. The stresses arising in the hatch cover are shown in Fig. 18.

Figure 16. The placement of the hatch cover on the test stand

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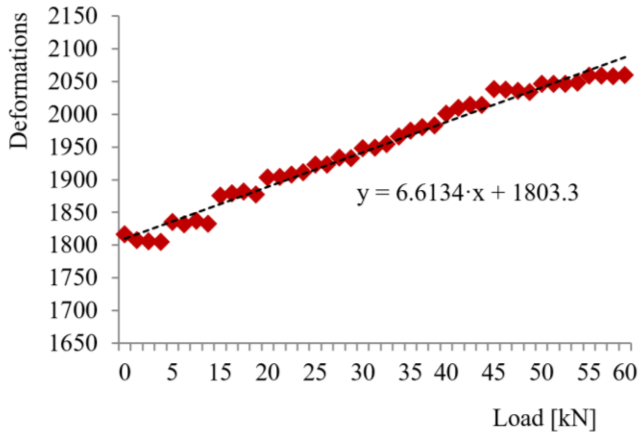

Figure 17. Dependence of relative deformations in the hatch cover on vertical load (strain gauge Group 3)

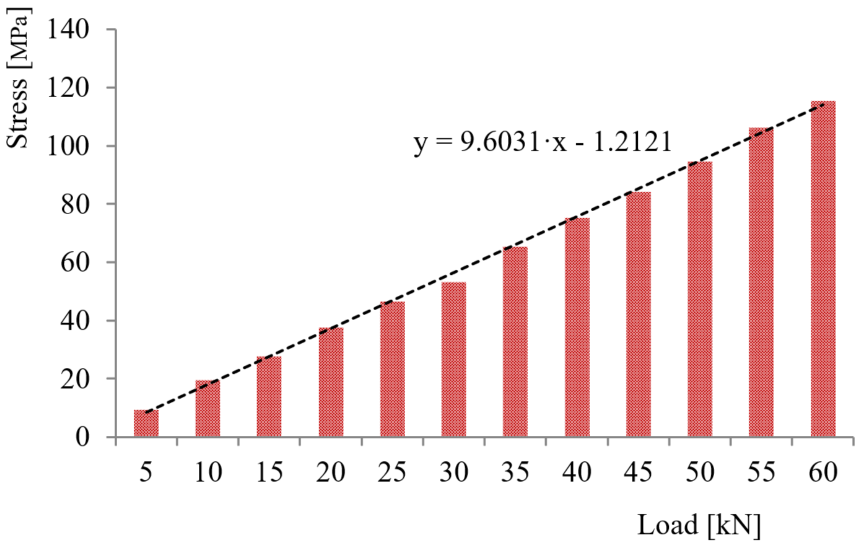

Figure 18. A dependence of stresses in the hatch cover on its load

The maximum stresses identified in the hatch cover were 103.5 MPa. These stresses are lower than the permissible ones introduced in (DSTU 7598:2014).

For a comparative analysis of the results of experimental studies with theoretical ones, the authors performed variational calculations of the strength of the hatch cover using the finite element method.

The discrepancy between the results of computer modelling of the strength of the hatch cover and experimental studies is shown in Fig. 19.

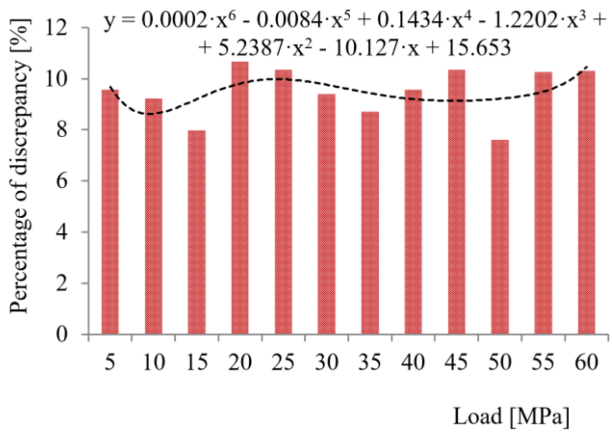

Figure 19. A discrepancy between the results of a computer simulation of the strength of the hatch cover and experimental studies

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It can be concluded from Fig. 17 that the largest percentage of a discrepancy is of 10.4%, and it is recorded when the load on the hatch cover is 20 kN.

Thus, the proposed scheme of fastening containers in an open wagon allows to reduce the stress in the hatch cover by three-times compared to the typical scheme of interaction of fittings with fitting stops (Rukavishnykov, 2025).

The presented study is a part of more expensive research, which includes also economic assessment of the proposed technical solution. The economic indicators are explained and calculated in details in the research work by Rukavishnykov (Rukavishnykov, 2025). Evaluation was performed on freight wagons with the number over 100,000. According to preliminary calculations, the economic effect of using the proposed technology of container transportation for the calculation period (10 years) is of 88.028 million UAH (1CC size containers) or 49.376 million UAH (1AA size containers). In this case, the economic effect is determined by the annual savings of the dependent part of operating costs compared to the basic option of using open wagons and one-time costs for their structural re-equipment for container transportation in the empty direction (Rukavishnykov, 2025).

4. Conclusion

(1) Determination of the strength of the removable module when lifting it with steel ropes was carried out (the 1st load case). The maximum stresses were recorded in the zones of interaction of the end structures with longitudinal beams. These stresses amounted to 124.5 MPa. These values did not exceed the permissible values of the used material (steel 09G2S). This distribution of stress fields is determined by a scheme of fastening and loading of the removable module.

(2) Determination of the strength of the removable module when it is lifted by a spreader was also carried out. The maximum stresses were recorded also in the zones of interaction of the end structures with longitudinal beams. These stresses amounted to 135.7 MPa, and they did not exceed the permissible values either.

(3) An experimental study of the strength of the hatch cover of an open wagon loaded by a removable module was conducted. The maximum stresses recorded in the hatch cover were of 103.5 MPa. The obtained stress value is lower than the permissible one. The largest percentage of discrepancy is of 10.4% and was recorded when the load on the hatch cover was 20 kN. The proposed scheme for fastening containers in an open wagon allows to reduce the stresses in the hatch cover by three-times compared to the typical scheme of interaction of fittings with fitting stops.

(4) The results of the conducted research will contribute to increasing the efficiency of container transportation by railway and to the development of modular rail vehicles. They will also help to improve the environmental friendliness of freight transportation by rail, that is, to the creation of sustainable transport.

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