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Study of loading of a universal container during sea transport

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Abstract

Intermodal and combined container transportation is an inseparable part of a sustainable transportation system. Railway transport, in combination with railway ferry services, plays a crucial role within this system. The research presented in this contribution highlights the features of studies on the loading of a universal container when transported by a railway ferry. This research consisted of two stages: a study of the strength of a universal container when transported by a railway ferry, and a study of the container's stability relative to the frame of a flat wagon. The calculation of the container's strength was carried out using the finite element method, which is implemented in SolidWorks Simulation. It was established that the stresses in the container structure in the case of its placement on the track farthest from the bulwark exceed the permissible ones by 23%. When the container is placed on the track second from the bulwark, as well as on the middle track, the stresses are within the permissible limits. Studies of the stability against overturning of the container relative to the flat wagon frame showed that in the case of its placement on the track farthest from the bulwark, the container does not maintain equilibrium stability. Therefore, it is recommended to place flat wagons with containers on the track second from the bulwark or the middle tracks. The results of the research will contribute to the creation of recommendations for the safe transportation of containers in combined transport trains by sea, as well as the sustainable development of international freight transportation.

Keywords

container, container strength, container equilibrium stability, rail-ferry transportation, combined transportation

1. Introduction

The development of a competitive environment in the railway services market, increasing the efficiency of railway transport together with demands on sustainable transport solutions, as well as meeting the needs of the national economy and the population in transportation, leads to the development of combined transport systems (Russo et al., 2024; Čižiūnienė et al., 2024; Soloviova et al., 2020; Berki and Bede, 2025; Jóvér et al., 2025; Zalacko et al., 2020). Positive experience with operating such systems is evident from the example of rail–ferry transportation.

The increase in the efficiency of container operations along international transport corridors predicts the transportation of containers by flat wagons through the railway ferry routes of Ukraine to Georgia and Turkey (Figure 1).

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(a) (b)

Figure 1. Transportation of flat wagons loaded with containers on railway ferries: (a) rolling of flat wagons onto the railway ferry (Makeev, 2025); (b) placing of flat wagons on the railway ferry (European Pravda, 2025).

However, there are currently few developments in ensuring the technical adaptation of flat wagons for the transportation of containers by railway ferries at sea, as well as the strength of the supporting structures of containers when they are fixed to flat wagons. These objective of this research is to address these necessities.

2. Literature review

Generally, containers and flat wagons are exposed to forces due to both static loads and dynamic loads. The static load is caused by the wagon's own weight and the payload. The dynamic loads arise during wagon movement on a railway track. Excitation of a wagon together with a transported container leads to cumulation of dynamic forces, which are the result of track irregularities, such as rail joints, weld imperfections, changes of geometrical parameters and others (Fischer, 2025; Fischer et al., 2024; Jóvér et al., 2022; Ézsiás et al., 2024a; 2024b). To identify the state of the issue of studying the loading of a universal container during railway ferry transportation, an analysis of existing publications in this area was conducted. Thus, in works (Miamlyn et al., 2012; Lisowski and Czyżycki, 2011), the results of optimizing container structures are presented. The feasibility of designing and implementing containers as vehicles is substantiated. Improved container structures are developed. However, the authors did not conduct a study of the loading of containers during transportation by rail ferries.

A study of dynamic loads acting on a container during rail transportation is presented in work by Fomin (2019). The authors formed a mathematical model that describes the dynamic loading of a container placed on a platform wagon during a shunting collision. However, the authors limited themselves only to this mode of loading the container and did not study its loading during transportation by rail ferry.

A study on the dynamics of the wagon body during cargo transportation is presented in the research by Lovska et al. (2024). To determine the accelerations acting on the wagon bodies during their transportation by sea, a mathematical model of the wagon bodies' movements was developed.

The assessment of external forces acting on the wagons during transportation by rail ferry is given in Shan (2026). At the same time, the accelerations acting on the wagon bodies in conditions of sea turbulence are determined based on the calculation of the swaying of the railway ferry, which occurs with six degrees of freedom in conditions of irregular three-dimensional turbulence when moving at a speed of 6.5 knots. However, the authors Lovska et al. (2020) of the work did not study the dynamic loading of containers during sea transportation.

The analysis of publications reveals that the research on the loading of containers during railway ferry transportation requires further investigation. Therefore, the purpose of the article is to highlight the results of research conducted by the authors on the loading of containers during railway ferry transportation.

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The aim of the research is to determine the loading of a universal container during transportation by a railway ferry. This aim was achieved by solving the following tasks:

- To determine the strength of a container placed on a flat wagon during transportation by rail ferry by sea;
- To investigate the stability of the equilibrium of a container placed on a flat wagon.

3. Materials and methods of research

To ensure the safety of moving flat wagons loaded with containers by sea, the supporting structure of the universal flat wagon has been improved to be reliably transported by the railway ferry, as described by Lovska et al. (2024). Since, in this case, the container is a component of the combined system "railway ferry – flat wagon – container", it is necessary to assess its strength and stability of equilibrium under the condition of placement on the flat wagon and transportation on the railway ferry.

To study the strength of the container, as a removable body unit, when placing it on the flat wagon modernization project (Lovska, 2013; NVC Wagons, 2025), which is located on the upper deck of the railway ferry, where maximum inertial loads occur under sea wave conditions of, a spatial model was developed. In general, the structural frame of the container, for example, size 1CC (Fig. 2), consists of upper and lower frames and racks. On the outside, the frame is sheathed with 1.5 mm thick corrugated steel, featuring a 150 mm corrugation pitch and a height of 12 mm. The lower frame of the container has a welded structure, assembled from two longitudinal and transverse beams made of channel No. 6.5. The upper frame is also welded and consists of two longitudinal and transverse beams, which are made of a 50×50×5 mm angle. The joints of the longitudinal and transverse beams are technologically reinforced with gusset plates. On the top, this frame is covered with a 1.5 mm thick sheet of steel. The metal sheet that forms the roof of the container is welded to the longitudinal and transverse members of the upper frame. The floor of the container is made of 25 to 27 mm thick boards (Conatainex, 2013).

When building a spatial model (3D), the main attention was paid to the elements of the real container structure, which rigidly interact with each other. The end door was replaced by a wall of equivalent rigidity, since it does not have a significant impact on the strength in conditions of angular displacements of the container around the longitudinal axis (Figure 3). Additionally, when building the model, the wooden floor was not taken into consideration.

Figure 2. An illustration of a container, size 1CC.

When drawing up the calculation scheme of the container under these conditions, the case of angular displacements of the railway ferry around the longitudinal axis (roll) was considered. This displacement has the greatest impact on the stress state and stability of the flat wagon with containers placed on it. In this case, the following loads will act on the container:

1) Vertical-static load, which is due to the mass of the container's tare and its carrying capacity;
2) Inertial load, which arises as a result of angular displacements of the flat wagon relative to the initial position;
3) Wind load.

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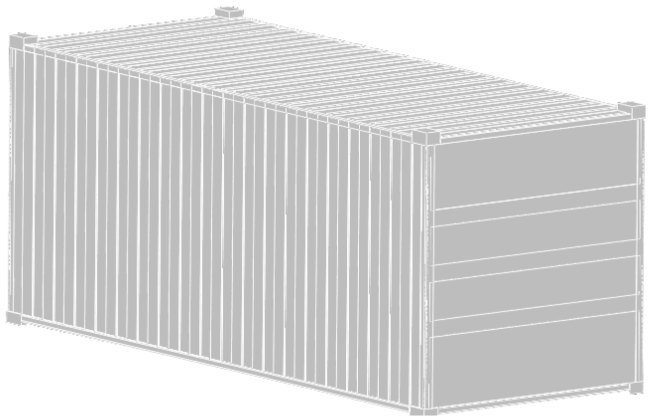

Figure 3. A spatial model of the container, size 1CC.

The limitations of this strength model are the absence of container movements relative to the supporting structure of the flat wagon, as well as longitudinal forces from the auto-coupling device.

The design function of the model is to obtain container strength indicators when placing it on the flat wagon, which is located on the upper deck of the railway ferry in rough sea conditions.

The design diagram of the container is shown in Figure 4.

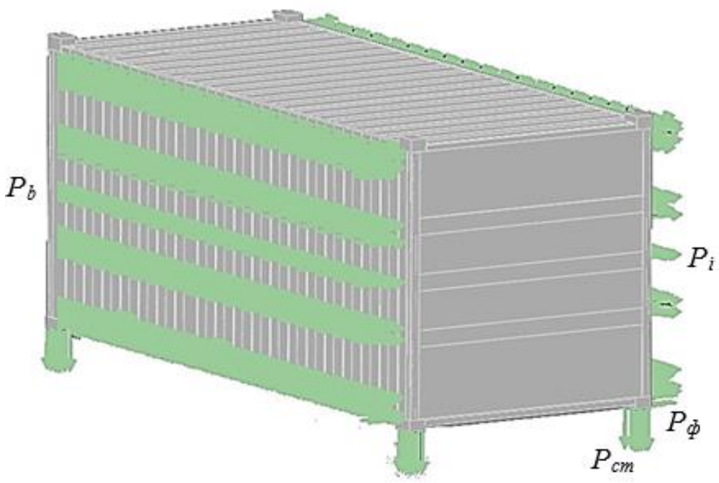

Figure 4. A calculation scheme of the container.

The loads marked in Figure 4 are as follows: P_{cm} – vertical static load; P_b – wind force acting on the container; P_i – inertial force; P_Φ – force acting on the container through the fittings during angular movements of the flat wagon around the transverse axis.

The scheme for applying loads to the container through the fitting is shown in Figure 5. It is taken into account that the vertical static load will be transmitted to the flat wagon through four points of support of the container on the flat wagon (corner fittings of the container). During angular movements of the container relative to the longitudinal axis, an additional force will arise in the zones of its interaction with the fitting stops of the flat wagon, due to the resulting horizontal load (the inertial load and the wind load). Therefore, in Figure 5, the vertical static load on the fittings is designated as P_{cm} and is applied to their horizontal surfaces. The horizontal forces on the fittings are designated as P_f.

To determine the relationships in the zones of support of the container on the fitting stops of the flat wagon, it is necessary to study its possible movements in the horizontal plane.

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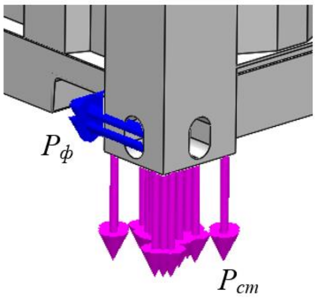

Figure 5. A diagram of the application of the loads acting on the container through the fitting (a detail).

The fixing of the container from horizontal (transverse) movements will be ensured if the following condition is met:

$$F_{mp} > P_z \quad (1)$$

where,

F_{mp} is the friction force that occurs between the horizontal plane of the container fitting [kN],

P_z is the resulting horizontal load, which includes the inertia force acting on the container in conditions of angular movements around the longitudinal axis and the wind load acting on the side wall of the container [kN].

The friction force will be determined as follows:

$$F_{mp} > P_{cm} \cdot \mu \quad (2)$$

where,

P_{cm} is the vertical-static load acting on the container [kN],

μ is the friction coefficient that occurs between the horizontal plane of the container fitting and the fitting stop plate (for the friction pair “steel - steel” $\mu = 0.03 \div 0.09$).

This load will be concentrated between the zones of support of the container on the flat wagon.

The resulting horizontal load will be:

$$P_z = P_i + P_b \quad (3)$$

where,

P_i is the inertia force acting on the container under conditions of angular displacements around the longitudinal axis [kN],

P_b is the wind load acting on the side wall of the container [kN].

This force will act on the container through the internal fittings on the slope side (Antala et al., 2021, Liguori et al, 2021). The numerical values obtained are listed in Table 1.

Table 1. Loads acting on the container in the areas of support on the flat wagon fitting stops.

The total friction force that occurs between the horizontal plane of the container fitting and the fitting stop plate placed on the flat wagon [kN]	Friction force that occurs between the horizontal plane of the container fitting and the fitting stop plate placed on the flat wagon [kN]	Total value of the resulting horizontal load acting on the container [kN]	The magnitude of the resulting horizontal load acting on the container through the fitting stop [kN]
13.7	3.4	82.1	41.0

That is, fixing the container from movements in the horizontal plane will not be ensured.

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Therefore, in the zones of support of the container on the flat wagon, additional connections were installed, which were simulated by rigid clamping, since the gross mass compared to the plane of support on the fittings has a much larger value. That is, the case was considered when the inner surface of the container fitting will interact with the vertical part of the flat wagon fitting stop. When compiling the container strength model, the assumption was made that it is loaded to the full load capacity with a conditional load. The calculated values of the forces acting on the container are given in Table. 2. The strength calculation was carried out using the finite element method (Wang et al., 2023; Yildiz, 2019). The number of nodal points in the grid was determined using the graph-analytical method. Ten-node isoparametric tetrahedra were used as grid elements (Oterkus, 2022).

Table 2. Forces acting on a container, size 1SS, gross weight 24 tons, when placed on a flat wagon located on the upper deck of the railway ferry in rough sea conditions.

Vertical static load through fitting [kN]	Inertia forces acting on the container [kN]	Wind load acting on the container [kN]	Force acting on the container through the fitting [kN]
57.3	50.2	22.8	36.4

4. Results of research

Based on the calculations, it was concluded that the stresses in the container structure exceed the permissible limits in the case of placing it on a flat wagon, located on the outermost track of the railway ferry from the bulwark, and amount to 403.2 MPa (Figure 6). The permissible stresses are taken to be 310.5 MPa (Lovska et al., 2024):.

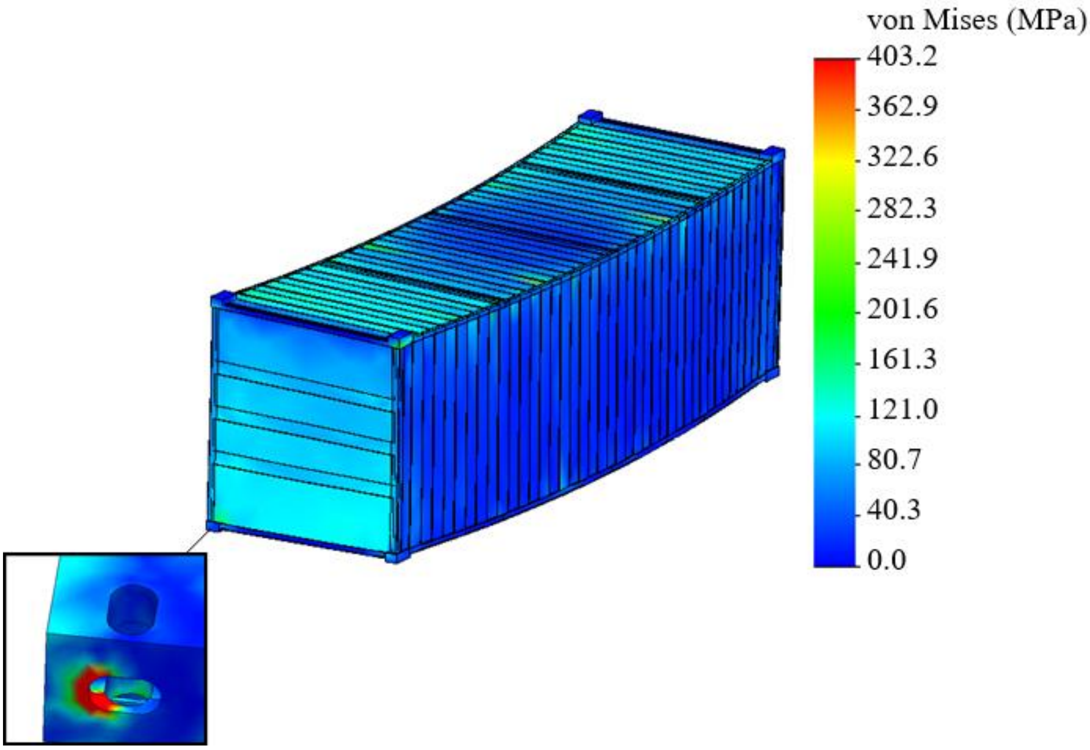

Figure 6. The stressed state of the analyzed container (a deformation scale 20:1)

The maximum equivalent deformations in the container structure are 3.24×10^{-6}, and the displacements in the nodes are 3.5 mm. There is no structural safety margin. In the case of placing the container on the flat wagon, which is located on the second and third tracks from the bulwark, its strength is ensured.

Future development of this research involves conducting an experimental study of container strength during transportation on a railway ferry. Improved container fastenings on flat wagons also require performing the research. This is crucial, as the existing container-to-flat wagon interaction system is unreliable under elevated rail ferry tilt angles (greater than 10°). This situation poses a significant risk to container tipping and the overall environmental impact of transportation. Therefore, the authors plan to devote special attention to this issue.

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The conducted research will not only contribute to improved container shipping safety by sea, but also to the sustainable development of rail and ferry transportation as a segment of the transport industry. The research will also allow for the development of recommendations for the design of modern container structures with improved technical and economic characteristics.

6. Conclusions

The conducted studies on the strength of the supporting structure of a universal container when it is fixed to a flat wagon of an improved design showed that the maximum equivalent stresses do not exceed the permissible ones in the case of its location on the second track from the bulwark and the middle track of the railway ferry. In the case of placing the flat wagon with a container on the outermost track from the bulwark track, the stresses in its structure exceed the permissible ones by 23%.

Studies of the stability of the container relative to the flat wagon frame showed that, under the existing conditions of fixing the container to the flat wagon on the track farthest from the bulwark, the container's resistance against overturning is not ensured. This may compromise the stability of the whole mechanical system "flat wagon – railway – ferry". Therefore, it is proposed that, on a railway ferry navigating in conditions of large heel angles of, flat wagons loaded with containers should not be placed on the tracks farthest from the bulwark.

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