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Research Article

Strength analysis of sectional flat wagon supporting structures when transported by a railway ferry

Alyona Lovska[1], Juraj Gerlici[1], Ján Dižo[1,*], Vasyl Ravlyuk[2], Andrij Rybin[2]

[1]Department of Transport and Handling Machines, Faculty of Mechanical Engineering, University of Žilina Univerzitná 8215/1, 010 26 Žilina, Slovak Republic
[2]Department of Wagon Engineering and Product Quality, Ukrainian State University of Railway Transport, Feuerbach Square 7, 61050 Kharkiv, Ukraine
*e-mail: jan.dizo@fstroj.uniza.sk

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Abstract: The goal of the research is to present the main peculiarities, with relate with the loads of flat wagon during maritime transport. A feature of the flat wagon is that its structure consists of two sections and special nodes are provided to fasten it to the ferry deck. A derived mathematical model expresses the lateral loading of the flat wagon under the conditions of a railway ferry roll. This derived model allows to to determine the acceleration and, accordingly, the loads due to the dynamic effects, which act to the flat wagon main load-bearing structure. These loads were considered in calculations of the strength of the main load-bearing structure of the solved wagon. The calculations lead to the results, that the strength of the main load-bearing structure of the considered flat wagon is maintained under the conditions of the considered type of oscillations. The performed research will contribute to improving the safety of maritime transport.

Keywords: flat wagon; design adaptation; combined transport; maritime transport; rail-ferry crossings

I. INTRODUCTION

The development of a competitive environment in the transport services market leads to the introduction of combined transport systems. One of the most promising symbioses in this direction is container transportation and rail-ferry transportation. [1, 2]. The possibility of Ukraine entering international traffic through the waters of the Black and Azov Seas has led to its participation in transportation between Eurasian countries. Combined transport is one of the last such routes, which began to be operated at the beginning of last year and connected the countries of Europe and Asia (**Fig. 1**).

(a) (b)

Figure 1. *Transportation of flat wagons loaded with containers by railway ferries: a) rolling of flat wagons onto the railway ferry; b) placing of flat wagons on the railway ferry*

When transporting rail vehicles by maritime transport, they are subjected to the forces that are significantly different from those occur when running on rails. This can cause damage of a wagon structure and lead to reduced the safety level of their maritime transport. Therefore, it is important to adapt the wagon structure to such transportation.

The issues of designing rail vehicles for transporting heavy goods are considered in the research [3]. A FEM analysis was used to study the load on its structure. When designing the carrier structure, a study was conducted on the possibility of its execution using different types of materials. The design of the wagon for international transport are research work presented in [4]. To improve the stability of the wagon during its operation, it has a lowered center of gravity. The wagon also has a rotating platform for loading the goods. The issues of improving combined transportation, in particular container transportation, are considered in [5]. An analysis of the features of fastening containers on platform wagons is presented. To increase the technical and economic indicators of wagons when transporting containers of various sizes, a justification for improving the designs of long-wheelbase platform wagons and sectional flat wagons for these transportations is provided in the study presented in [6].

The length of the solved wagon can be adjusted according to the type of the goods, which is being transported on it. Studies of the dynamics of a flat wagon using the multibody methods are given in [7]. The calculation was performed for a flat wagon with a rotating middle part using the MSC Adams software. Improving the technical characteristics of an sectional flat wagon by improving its design is given in [8]. The theoretical calculations that were obtained are confirmed by experimental studies of the strength of this wagon type. The strength calculation of the main load-bearing structure of the flat wagon frame is presented in the article [9].

It is important to emphasize that these studies were carried out using experimental methods, in particular, electrical strain gauge testing. The results of these studies made it possible to determine the most loaded components of a flat wagon structure.

Another phenomenon that is investigated in relation to rail vehicle dynamics is the dynamic response of the railway track structure [10–13]. Further, energy consumption in the case of traction rail vehicles, like locomotives [14–16], together with energy efficiency is important [17]. Regarding maritime transport of wagons, it belongs to part of the intermodal transportation [18–20] network system, and transport means, as well as the entire system, must meet strict criteria from the safety, efficiency and reliability point of view [21–25].

Analysis of the works [3-25] shows that currently not enough attention has been paid to the study of the safety of maritime transport of wagons. Therefore, this direction is relevant.

II. MATERIALS AND METHODS OF THE RESEARCH

Sectional flat wagons have been used in order to achieve the higher efficiency of container transport. Due to the insignificant replenishment of the wagon fleet of Ukrzaliznytsia (Ukrainian Railways) in recent years. Therefore, it is appropriate to create a sectional flat wagon based on the 13-401 model. The wagon is assumed to have two sections. These sections interact with by means of a special device (a joint device). The sections are supported on two bogies in the cantilever parts. In the middle part, the sections are supported on one bogie.

To reduce the weight of the platform wagon, its main longitudinal beams are made of I-beam profiles, which have a constant height along the length of the frame. To increase the moment of resistance of the I-profiles, they are reinforced with vertical sheets (**Fig. 2**) [26].

It is proposed that nodes will be installed on its supporting structure to secure chain ties and enable the transportation of a sectional flat wagon on railway ferries [26], as can be seen in **Fig. 3**. On the inner parts of the main longitudinal beams of the frame, it is planned to install metal superstructures, which have a box-shaped structure. On these superstructures, nodes are welded to which chain ties are attached.

The determination of dynamic loads on the main load-bearing structure of the flat wagon was carried out by mathematical modelling. In this case, it is taken into account, that the movements of the frame of the flat wagon relative to the deck are absent because these movements will be limited by chain ties.

The calculation was performed for the roll movement of a railway ferry (**Fig. 4**). This type of oscillation is equivalent to lateral sway oscillations in the dynamics of wagons (see Eq.(1)):

$$\left(\frac{D}{12 \cdot g} \cdot \left(B^2 + 4 \cdot z_g^2\right)\right) \cdot \ddot{q} + \left(\Lambda_\theta \cdot \frac{B}{2}\right) \cdot \dot{q} = \acute{p} \cdot \frac{h}{2} + \Lambda_\theta \cdot \frac{B}{2} \cdot \dot{F}(t), \tag{1}$$

where q is a generalized coordinate corresponding to the angular displacement of the railway ferry with wagons around the longitudinal axis. The origin of the coordinate system is located at the center of gravity of the railway ferry; D is the weight displacement, B is the width of the railway ferry, h is the height of the side of the railway ferry; Λ_Θ is the coefficient of vibration resistance, z_g is the

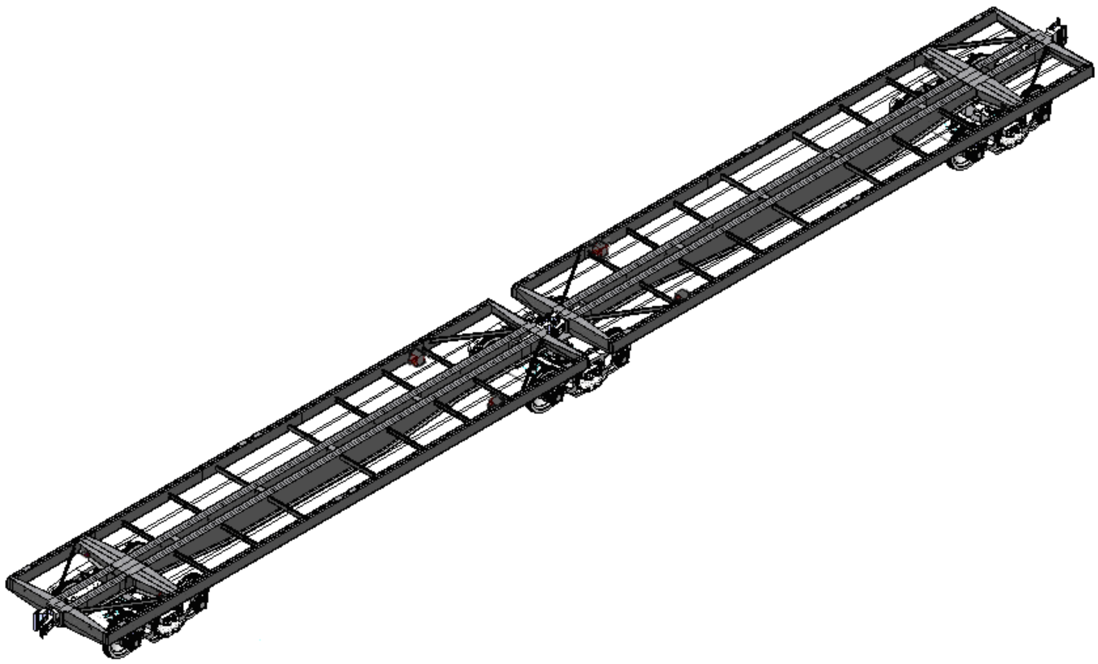

Figure 2. *An improved design of the sectional flat wagon*

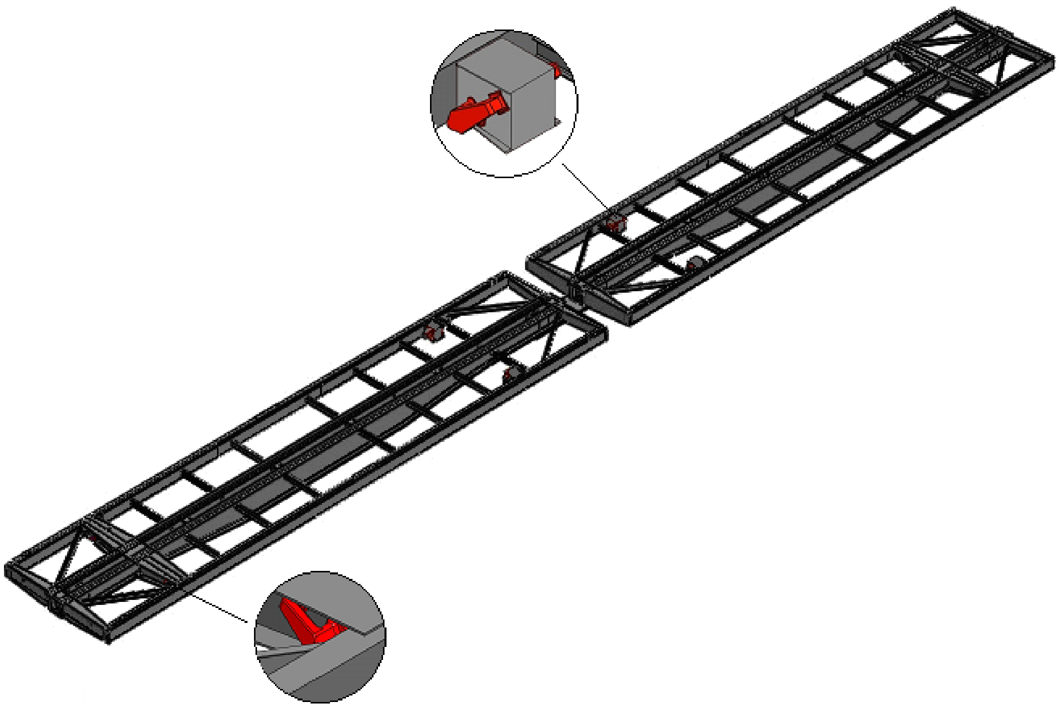

Figure 3. *A main load-bearing structure (a frame) of the solved sectional flat wagon*

coordinate of the center of gravity of the railway ferry, p' is the wind load, and $F(t)$ is the law of action of the force that disturbs the movement of the train ferry with the wagon bodies placed on its decks.

It was considered for the derived mathematical model that the wagon body is rigidly fixed relative to the reference plane (deck) and moves together with it. The impact of sea waves on the railway ferry body side, where the wagons are placed on, is not considered.

The model takes into account the wave angles χ relative to the ferry, which are considered in the range of 0° to 180°. These angles were embedded in the frequency of the sea wave, which is considered in the law of action of the disturbing force, which is described in the form of a trochoid (see Eq.(2)):

$$F(t) = a + R \cdot e^{k \cdot b} \cdot \sin(k \cdot a + \omega \cdot t) + b - R \cdot e^{k \cdot b} \cdot \cos(k \cdot a + \omega \cdot t) \qquad (2)$$

where a and b are the coordinates of the center of the principle's trajectory in the horizontal and vertical direcitons, respectively, R is the radius of the principle's trajectory; ω is the wave frequency, k is the wave trajectory frequency.

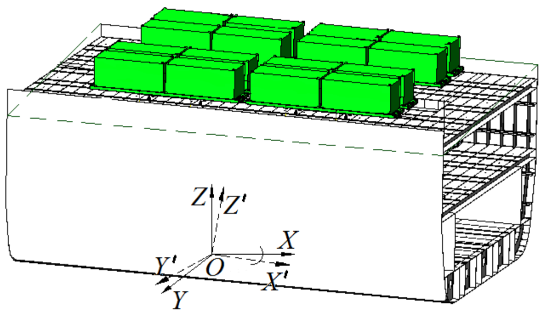

Figure 4. *Schemes of movements of railway ferry fragments during roll movement*

Input parameters to the derived model (1) are the technical parameters of the considered railway ferry [27], parameters of the sea area [28–30], coordinates of the location of the wagons' bodies relative to the center of oscillations of the ferry deck.

III. RESULTS AND DISCUSSION

A calculation program was developed in the Mathcad package [31–33] to solve the derived differential equation of motion (1). These equations were reduced for this software to the normal Cauchy form. Subsequently, they were integrated using the Runge-Kutta method. The achieved results are shown in **Fig. 5**.

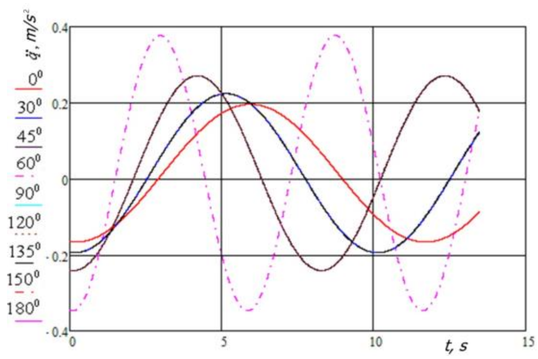

Figure 5. *Accelerations acting on the main load-bearing structure of a sectional flat wagon during oscillations of a railway ferry*

In this case, the duration of the oscillatory process was taken equal to the wave period, the nature of the disturbance was trochoidal, the amplitude was equal to the maximum wave height for the given sea area, and the frequency was determined by the course angle of the wave in relation to the railway ferry hull.

Fig. 5 shows the acceleration of platform wagons placed on the track of the railway ferry upper deck furthest from the bulwark during angular movements around the longitudinal axis. The most significant acceleration of the wagons occurs at a course angle of the wave in relation to the railway ferry hull of 0.40 m/s^2.

The magnitude of the accelerations is given without the g, i.e. without gravitational acceleration.

The results were used in calculations to determine the strength of the main load-bearing structure of the frame of the sectional flat wagon. The calculation was carried out using the finite element method in the CosmosWorks software environment.

A calculation scheme takes into account the vertical loads in the areas of container support on the fitting stops, as well as forces from the chain ties on the fastening nodes relative to the deck (**Fig. 6**). The component forces, which arise from the chain ties and which are determined by the angles of their placement in a space, are listed in **Table** 1.

Table 1. *Forces acting on the main load-bearing structure of the frame of a sectional flat wagon through chain ties*

Acting force **[kN]**		
F_x	F_y	F_z
92.94	129.96	160.98

Rigid connections were installed in areas, where the frame rests on mounts.

A graph-analytical method was used to determine the optimal number of grid elements. The number of grid nodes was 148,723, and the number of elements of the finite element mesh was 462,131 with the largest size being of 200 mm and the smallest being of 40 mm. Such element sizes are determined by variational calculations. In this case, the dependence of stresses on the number of finite elements was constructed. When this dependence took the form of a horizontal straight line, it meant that this number of elements is sufficient to obtain reliable calculation results. The results of the calculation of the main load-bearing structure of the flat wagon are presented shown in **Fig. 7**.

The maximum equivalent stresses in the supporting structure of the flat wagon are concentrated in the zone of interaction of the pivot beam with the main longitudinal beam. The maximal value of the stress was 215.4 MPa. However, this value does not exceed the permissible value for the grade of steel of the metal structure [34].

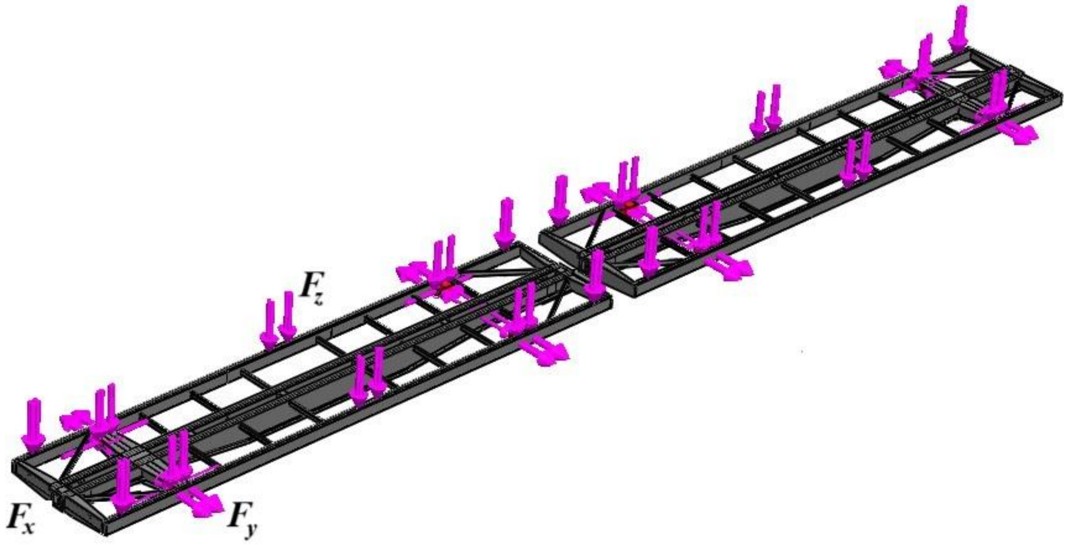

Figure 6. *A calculation diagram of the solved sectional flat wagon frame*

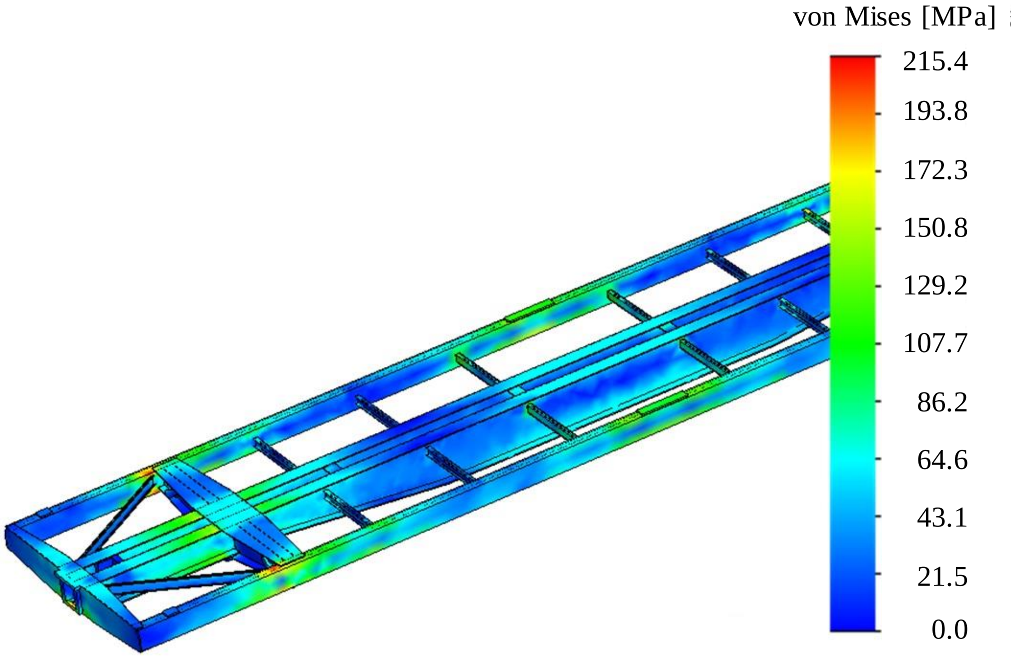

Figure 7. *A stress distribution in the solved sectional flat wagon frame*

The permissible values of stresses are considered of 310.5 MPa. There is an analogue of this normative document [35]. However, it contains other values permissible stresses. As the study was conducted on the example of a 1520 mm gauge wagon, the document [34] was considered as the basic source.

The further research in this area will be devoted to determining the loading of a flat wagon under other calculation schemes, i.e. rolling onto the ferry (rolling off the ferry), loading during vertical and keel roll of the ferry, the research on the stability of the wagon on the deck, etc. The authors also plan to investigate the fatigue strength of the frame of the flat wagon during transportation by a ferry. A mandatory stage of these studies is also the study of the loading of 1435 mm gauge wagons during maritime transport.

IV. Conclusions

1. It is proposed that nodes be installed on their supporting structures for securing chain ties to increase the reliability of securing flat wagons on railway ferries.

2. A mathematical model was developed to determine the numerical values of accelerations as components of the dynamic load acting on the main load-bearing structure of a sectional flat wagon during transportation on a railway ferry. It was established that in the absence of the flat wagon's

movements relative to the deck, the acceleration acting on its supporting structure during angular movements around the longitudinal axis is about 0.40 m/s^2.

3. The magnitudes of the forces acting on the solved sectional flat wagon frame through the means of securing relative to the decks were determined.

4. The strength of the frame of the sectional flat wagon type during transportation by a rail ferry has been calculated. The maximum equivalent stresses distributed in the frame of the solved wagon do not exceed the permissible ones, and the maximal calculated values are 215 MPa.

5. The conducted research will contribute to improving the safety of maritime transport of wagons.

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Author Contributions

A. Lovska: Software, Formal Analysis, Investigation, Data curation, Visualisation, Project Administration.

J. Gerlici: Conceptualization, Methodology, Formal analysis, investigation, Writing – original draft preparation.

J. Dižo: Methodology, Validation, Investigation, Data curation, Writing – review and editing, Project Administration.

V. Ravlyuk: Software, Formal Analysis, Investigation, Resources, Data curation, Visualisation.

A. Rybin: Validation, Investigation, Supervision, Writing – review and editing, Visualisation, Project administration.

Disclosure Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

ORCID

A. Lovska http://orcid.org/0000-0002-8604-1764

J. Gerlici https://orcid.org/0000-0003-3928-0567

J. Dižo http://orcid.org/0000-0001-9433-392X

V. Ravlyuk https://orcid.org/0000-0003-4818-9482

A. Rybin https://orcid.org/0000-0001-7546-0077

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