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A NEW FASTENER TO ENSURE THE RELIABILITY OF A PASSENGER CAR BODY ON A TRAIN FERRY

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ABSTRACT. To ensure the strength of the passenger car bodies during transportation on train ferries, it is proposed to mount fastening elements of chain binders on the body bolster beams. The principle of such an element is based on the hydraulic damper operation. The mathematic modelling was conducted in order to determine the dynamic loading on a passenger car body during sea transportation. The study established that the improvements mentioned made it possible to reduce the dynamic loading on the body during sea transportation by 30 % in a comparison with that of a typical fastening scheme. The strength of an improved passenger car body was calculated. The maximum equivalent stresses in the body structure accounted for about 120 MPa, i.e., they did not exceed the admissible values. The conducted research may contribute to ensuring the required strength of passenger car bodies during train ferry transportation, thus leading to a higher operational efficiency of train ferry transportation within the international transportation.

KEYWORDS: Passenger car, carrying structure, dynamic loading, strength, train ferry transportation.

1. INTRODUCTION

Increased competitiveness of passenger rail traffic led to the creation of rail ferry services [1–3]. A feature of such a transportation is the ability of wagon carriage by sea on special ships that are train ferries (Figure 1). In the past, passenger cars were loaded on the deck by transferring them from the track of the loading harbour to the ferry tracks with hoisting devices. Nowadays, the cars are loaded on the train ferry by rolling over the passing (loading) ramp, which has considerably shortened the loading/unloading operations (Figure 2 [4]).

Recently, train ferries have been equipped with special fastening brackets for passenger car bodies (Figure 3). Each body is fixed with six brackets (three at each side).

The cars are fixed relative to the deck according to a standard scheme with chain binders equipped with turnbuckles and stop-jacks (Figure 4). In order to prevent cars from rolling on the tracks, brake stops are installed under the rolling surfaces of the wheels and, along the longitudinal direction, the end cars in batches are linked with buffer stops with standard SA-3 couplers. Furthermore, the car braking system is connected to special hoses to that supply compressed air for the wheel set braking [5, 6]. It is also possible to use parking brakes of wagons when transporting them by sea.

A strength analysis has been carried out in order to study the strength of a passenger car body during transportation by a railway ferry. The calculation was



FIGURE 1. Train ferry between Lithuania and Germany.



FIGURE 2. Loading of passenger cars on a train ferry over the loading ramp.



FIGURE 3. Fastening brackets for a passenger car body on the train ferry.

carried out using the finite element method in the SolidWorks Simulation software.

When compiling the finite element model, spatial isoparametric tetrahedrons were used. The optimal number of elements was determined by the graphic-analytical method. The number of nodes in the model was 183393, and the number of elements was 520475. The maximum element size was 80 mm, and the minimum element size was 16 mm. The percentage of elements with an aspect ratio of less than three was 15.1, and the percentage of elements with an aspect ratio of more than ten was 56. The minimum number of elements in a circle was 12; and the ratio of increasing the element size was 1.8.

When drawing up the design scheme, it was taken into account that the vertical static load P_v^{st} , the wind load P_w and the forces from the chain ties P_{ch} act on the car body (Figure 5). Due to the spatial arrangement of the chain ties, the force that would act on the car body through them was divided into components, which is due to the angle of inclination of the tie in space (Figure 6). The angles of the chain tie are shown in table 1.

The fixing of the model was carried out in the zones where the body is supported by bogies and in the zones of installation of the stop-jacks. Carbon steel St.3 was used as the material for the body structure.

The strength analysis of the passenger car body, taking into account its fastening relative to the deck for the attaching clamp, allowed to calculate that the maximum equivalent stresses are about 350 MPa (von Mises), that is, they exceed the permissible ones (Figure 7).

The maximum displacements were 11.8 mm; they were concentrated in the middle sections of the side walls. The maximum deformations were $1.54 \cdot 10^{-3}$.

So, to ensure the reliability of the fastening of passenger cars on train ferries, it is important to improve their load-bearing structures.

It is important to note that the existing regulatory documentation on the passenger cars' dynamic loading



(A).



(B).



(c).

FIGURE 4. Multi-turn means for wagon fastening on railway ferries a) chain tie; b) mechanical stop-jack; c) stop block.

Angle symbol	Numerical value
α	30°
β	30° – 60°
γ	60°

TABLE 1. The angles of the chain ties relative to the plane of the car body.

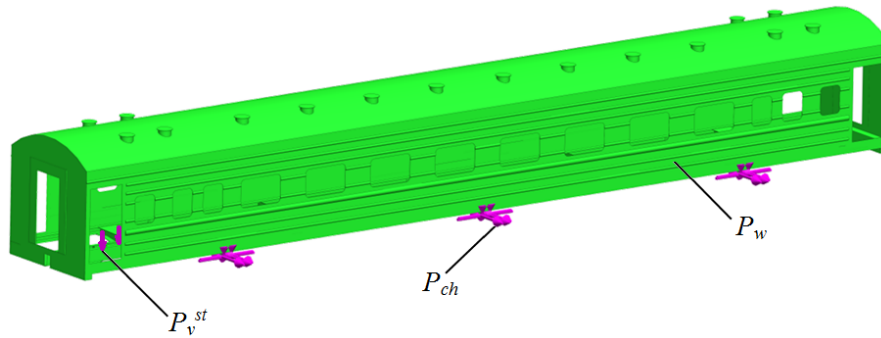


FIGURE 5. Design scheme of the passenger car body.

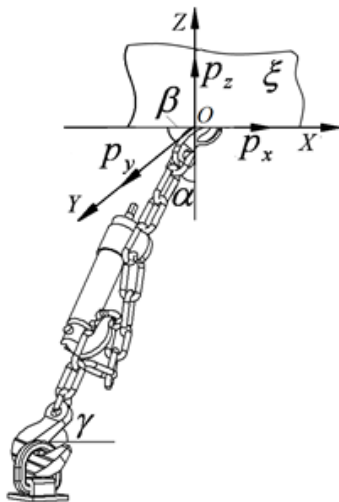


FIGURE 6. Placement of the chain tie relative to the car body p_x , p_y and p_z - are the projections of the force that acts from the chain tie and is applied to the zone of attachment to the body onto the axis of the Cartesian axes; α , β , γ - are angles of chain tie placement relative to the planes of the car body.

and strength under operational conditions does not fully cover the issues of passenger car transportation by railway ferries [7, 8].

Determination of dynamic loading on cars in train ferry transportation is given in [9–11]. The obtained dynamic loading values are considered in the strength calculation for car-carrying structures.

The studies do not provide a research of the dynamic loading on passenger cars during train ferry transportation.

Study [12] deals with the development of recommendations for a longer effective life of passenger cars. The results of the experiments demonstrate that the passenger cars with a service life of 28-30 and 33-35 years meet the requirements for strength and safe transportation in accordance with the normative documents. Therefore, their service life can be extended, provided that they meet the requirements for the impact endurance.

Study [13] presents a need to specify the terms of a longer effective life for passenger cars. It also presents

scientific methods of a service life estimate for the carrying structure of car bodies.

However, the substantiation of a longer life of cars does not consider the stress load during the train ferry transportation.

Modern requirements for carrying systems of railway cars are presented in [14]. The authors suggest that these requirements should be met in new car structure manufacturing, and also for those under modernization. However, the issues of a safe transportation of cars by train ferries are not covered.

An analysis of the literature [9–14] allows us to conclude that the issues of the passenger car dynamic loading and strength on railway ferries and the improvement of their design require closer attention at the present stage of the transport industry development.

2. MATERIALS AND METHODS

To reduce the dynamic loading of the car bearing structures, shock absorbers and damping are used. These include automatic coupler draft gears, buffer devices, vibration dampers, etc. Such devices provide a reduction in dynamic load due to the dry or viscous resistance forces. A promising direction is the use of viscous resistance, as it is the most effective one.

The authors suggest that the strength of passenger car bodies during train ferry transportation can be improved by mounting fastening units of chain binders on the body bolster beams (Figure 8). The principle of action of the unit was based on the principle of a hydraulic damper, which allowed reducing the value of dynamic loading on the body.

When the force transfers through the eyelet 7 to the unit from the chain binder's hook, piston 5 moves together with the rod 3 relative to body 4. The operating fluid overflows through an open throttle valve and creates the resistance to motion of the piston. Brake spring 8 is pressed. Piston 5 travels to its initial position by the means of brake spring 8. At the backward travel of the piston 5 the liquid runs through the other throttle valve. And the energy dissipates in the environment.

The area where rod 3 interacts with the unit's support 1, fixed to the vertical plate of the bolster beam

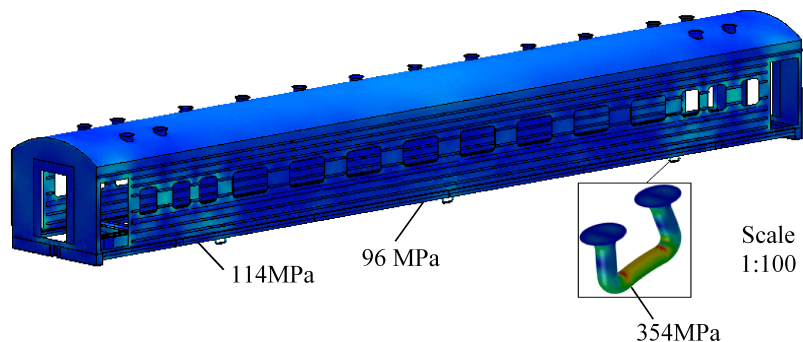


FIGURE 7. Stressed state of the passenger car body.

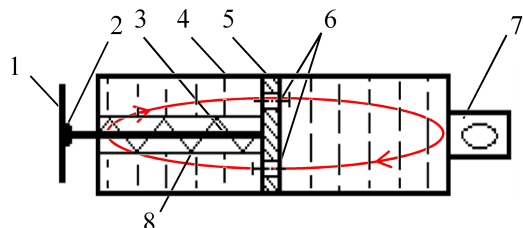


FIGURE 8. Unit for fixation of the car body relative to the deck 1 – support; 2 – hinge; 3 – rod; 4 – body; 5 – piston; 6 – throttle valve; 7 – eyelet for fixation of the hook of a chain binder; 8 – brake spring.

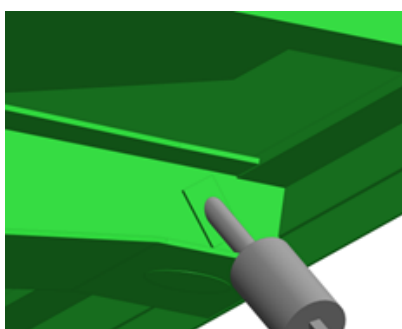


FIGURE 9. Position of the unit for car body fixation relative to the deck.

with a pivot connection 2. The unit could be moved to a horizontal position if there was no need for it (Figure 9).

3. MATHEMATICAL MODELLING

The numerical value of the dynamic loading on the car body relative to the deck in the new fixation scheme was determined with a mathematical model (1). The movement pattern of a railway ferry and a passenger car placed on it when heeled are shown in Figure 10 and Figure 11, respectively.

$$\begin{cases} \frac{D}{12 \cdot g} \cdot (B^2 + 4 \cdot z_g^2) \cdot \ddot{q}_1 + (\Lambda_\theta \cdot \frac{B}{2}) \cdot \dot{q}_1 = \\ p' \cdot \frac{h}{2} + \Lambda_\theta \cdot \frac{B}{2} \cdot \dot{F}(t), \\ I_k \cdot \ddot{q}_2 + \beta \cdot \frac{B_k}{2} \cdot \dot{q}_2 = p_k \cdot \frac{h_k}{2} + F_\beta, \end{cases} \quad (1)$$

where q_1, q_2 are the generalized coordinates corresponding to the angular displacement around the longitudinal axis X of the train ferry and the car body, respectively.

For the train ferry:

D is the weight displacement; B is the width; h is the side height; Λ_θ is the coefficient of resistance to vibrations; z_g is the coordinate of gravity centre; p' is the wind load; $F(t)$ is the law of action that makes a train ferry, loaded with cars on the deck, move.

For the passenger car body:

I_k is the inertia moment relative to the longitudinal axis; β is the coefficient of viscous resistance to displacements of the car body; B_k is the body width; p_k is the wind load on the side wall; h_k is the height of the side wall; F_β is the moment of forces between the body and the deck.

The technical characteristics of the train ferry and passenger car bodies and hydro-meteorological characteristics of the ship route were taken as the input parameters of the model. The calculations were made for a Mukran-type train ferry operating on the Baltic Sea. The hydro meteorological characteristics of the area were determined according to the data given in [15] and are given in the Table 2.

System (1) was solved with a transition from differential equations of the second order to equations of the first order. The calculation was conducted in program MathCad [16–19].

The trochoidal motion law of the disturbing action (sea wave) onto a railway ferry with cars placed on its decks and angles of the approaching sea waves in relation to the railway ferry hull and the wind load acting on the surface projection of the railway ferry and on cars placed on the upper deck have been taken into account when compiling the model. The frequency of the sea waves was determined taking into account the approach angle to the hull of a train ferry with cars placed on its decks [13]:

$$\omega = \frac{2\pi \cdot \nu}{k_\lambda \cdot L \cdot \cos \kappa}, \quad (2)$$

where ν is the speed of the railway ferry; k_λ is a coefficient depending on the shape of the ship lines; κ

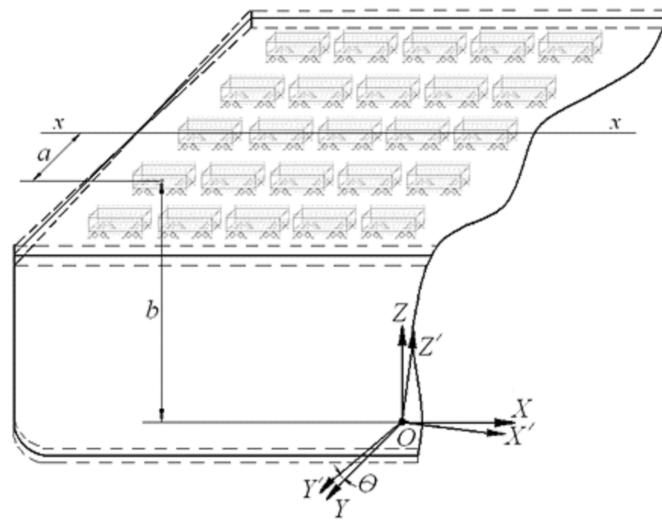


FIGURE 10. The movement pattern of a railway ferry when heeled, a and b are the horizontal and vertical coordinates of the centre of the path along which the body, having the x and z coordinates, is fighting.

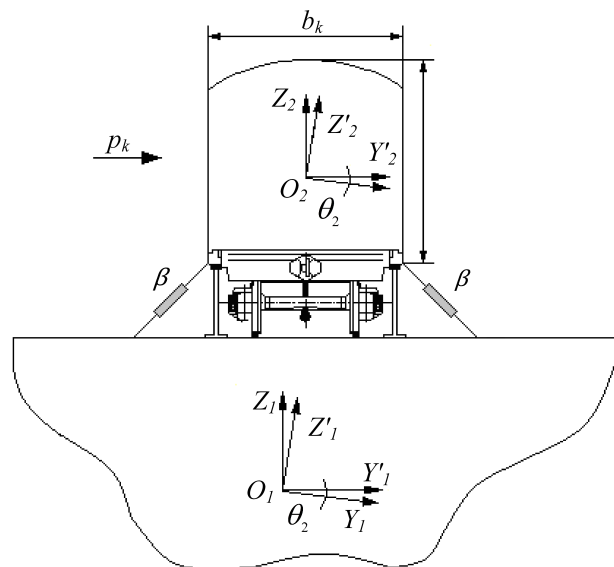


FIGURE 11. Design scheme for determining the dynamic loading of the passenger car body.

Parameter	Numerical value
Sea wave height, m	6
Wave-to-course angle, grad.	0 – 180
Wind pressure on the above-water projection of the train ferry, t/m ²	0.15

TABLE 2. Numerical values of the disturbing action parameters used in the mathematical model.

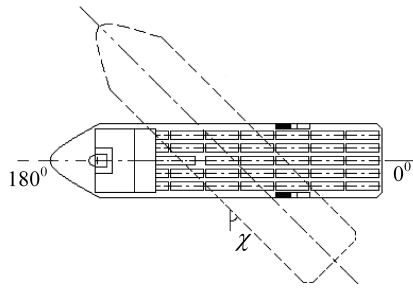


FIGURE 12. Design scheme for determining the dynamic loading of the passenger car body.

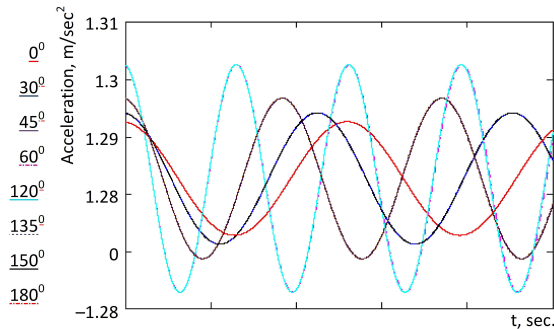


FIGURE 13. Accelerations acting on the car body under viscous interaction with the deck.

is the wave approach angle in relation to the railway ferry body (Figure 12).

The accelerations acting on the car body, considering the new fixation method relative to the deck, are given in Figure 13. In this case, each colour of the curve in Figure 13 corresponds to the value of the acceleration obtained for a certain angle of an approaching wave with respect to the body of the train ferry with the cars placed on it (the angle labels are shown on the side of the ordinate axis).

The study found that the maximum accelerations on the car body were at wave angles of 60° and 120° and accounted for about 1.3 m/s^2 .

It should be mentioned that the coefficient of viscous resistance of the working fluid creating viscous resistance between the body and the deck should be within a range of $2 - 4.2 \text{ kN}\cdot\text{s/m}$. This difference is explained by the fact that a decrease in the dynamic load of the car body when using the new fastening scheme occurs when the viscous resistance coefficient is more than $2 \text{ kN}\cdot\text{s/m}$. When the viscous resistance coefficient is more than $4.2 \text{ kN}\cdot\text{s/m}$, the proposed solution is ineffective. Thus, considering the proposed solution, the maximum accelerations acting on the car body were reduced by 30% in comparison with those in a typical scheme of fixation relative to the deck (1.83 m/s^2).

4. RESULTS AND DISCUSSION

In order to determine the strength of the improved passenger car body, the authors carried out a calcu-

lation using the finite element method in SolidWorks Simulation (CosmosWorks) software suite [20, 21].

The model considered the elements rigidly connected by welding or riveting. This method is used for calculations of wagons at the leading car-building plants in Ukraine.

The finite element model was built with spatial isoparametrical tetrahedrons. The optimal number of elements was determined with a graph-analytical method [22–24]. The model consisted of 152967 nodes and 434641 elements. The maximum size of an element was 80 mm, and the minimum one was 16 mm. The percentage of elements with a ratio of sides less than three was 12, and more than ten – 59.9. The minimal number of elements in the circle was 10, and a ratio of an increase in the size of an element was 1.8.

The strength model considered vertical static load P_v^{st} , wind load P_w and forces from the chain binders P_{ch} (Figure 14). Due to a spatial layout of the chain binders, the force on the car body through them was divided and applied to the unit's support part located on the vertical plate of the bolster beam. In this case, the load that acts on the car body through the fastening nodes was determined taking into account the found acceleration value (Figure 13), as a component of the dynamic load.

The model was fixed in the areas where the body rested on the running gears of the car, and also in the areas where the stop-jacks were mounted. Carbon steel St.3 was used as material for the body structure.

The results of the calculation are given in Figure 15. The maximum equivalent stresses were in the lining which simulated the unit's support; they accounted for 120 MPa, thus they did not exceed the admissible values [7, 8]. The maximum displacements were noted in the centre sill of the car and accounted for 1.47 mm.

The maximum deformation was $1.01 \cdot 10^{-3}$.

Based on the calculation model (Figure 14), a computer simulation of the dynamic loading of the passenger car body during its transportation by a train ferry was carried out. In this case, the maximum value of acceleration that acted on the passenger car body was 1.54 m/s^2 . Consequently, the discrepancy between the results obtained by the mathematical and computer simulation is about 15%.

According to preliminary calculations, the cost of one device for car securing on the deck is about \$300. In this case, the economic effect is achieved by reducing the costs of unscheduled repairs.

5. CONCLUSIONS

The following conclusions can be made from the research:

- (1.) The structure of the passenger car body was improved in terms of the strength and fixation on the train ferry. The authors proposed a fixation technique of the body with special units mounted on the bolster beams. The principle of the action of

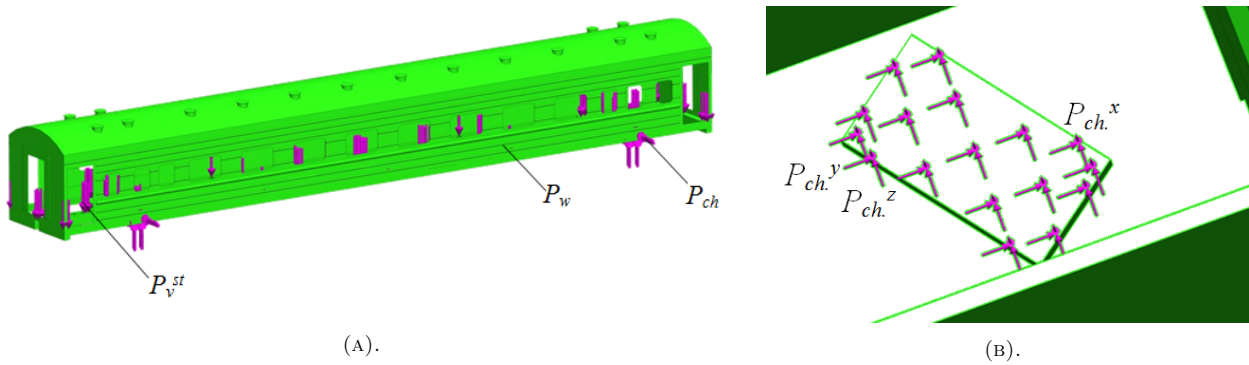


FIGURE 14. Strength modelling for the passenger car body.

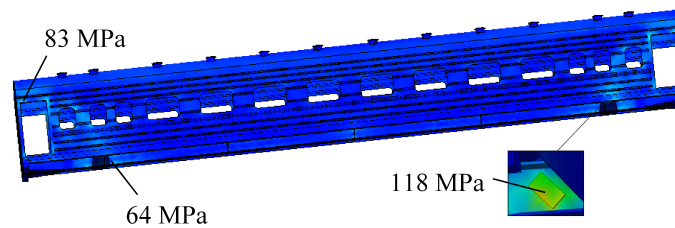


FIGURE 15. Stressed state of the passenger car body.

the unit was based on the operation of a hydraulic damper, which allowed reducing the value of the dynamic load on the body under sea transportation.

(2.) The dynamic load on the improved passenger car body under train ferry transportation was determined. The study found that the maximum accelerations, as a dynamic loading component, on the car body were at wave angles of 60° and 120° , and they accounted for about 1.3 m/s^2 . The working fluid created the viscous resistance between the body and the deck, the coefficient of viscous resistance was in a range from $2 \text{ kN}\cdot\text{s/m}$ to $4.2 \text{ kN}\cdot\text{s/m}$.

Thus, considering the proposed solution, the maximum accelerations on the car body were reduced by 30% in comparison with that in a typical fixation scheme relative to the deck.

(3.) The strength calculation for the improved passenger car body under train ferry transportation was made. The maximum equivalent stresses accounted for 120 MPa and were concentrated in the lining, which simulated the unit's support part. The maximum displacement was in the centre sill of the car and accounted for 1.47 mm, and the maximum deformation was $1.01 \cdot 10^{-3}$.

The research conducted may contribute to ensuring the required strength of passenger car bodies under train ferry transportation, thus leading to a higher operational efficiency of train ferry transportation within the international transportation.

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