Improvements in passenger car body for higher stability of train ferry

Article *in* Engineering Science and Technology an International Journal · September 2020

DOI: 10.1016/j.jestch.2020.08.010

2 authors:

O. V. Fomin
State University of Infrastructure and Technologies, Kyiv, Ukraine

Alyona Lovska
Ukrainian State University of Railway Transport

ARTICLE IN PRESS

Engineering Science and Technology, an International Journal xxx (xxxx) xxx

HOSTED BY

ELSEVIER

Contents lists available at ScienceDirect

Engineering Science and Technology, an International Journal

journal homepage: www.elsevier.com/locate/jestch

Full Length Article

Improvements in passenger car body for higher stability of train ferry

Oleksij Fomin [a,1,*], Alyona Lovska [b,2,*]

[a] Department of Cars and Carriage Facilities, State University of Infrastructure and Technology, Kyrylivska str., 9, Kyiv 04071, Ukraine
[b] Department of Wagons, Ukrainian State University of Railway Transport, Feierbakh sq., 7, Kharkiv 61050, Ukraine

ARTICLE INFO

Article history:
Received 27 August 2019
Revised 29 July 2020
Accepted 13 August 2020
Available online xxxx

Keywords:
Passenger car
Carrying structure
Dynamic loading
Strength
Train ferry transportation

ABSTRACT

The authors suggest that the strength of passenger car bodies under train ferry transportation can be provided by mounting fastening elements of chain binders on the body bolster beams. The principle of such an element is based on the hydraulic damper operation Therefore, the authors developed a mathematical model which considered displacements of a train ferry loaded with passenger cars under rolling motion. The model was solved in Mathcad software. The mathematic modeling was conducted in order to determine the dynamic loading on a passenger car body under sea transportation. The study established that the improvements mentioned made it possible to reduce the dynamic loading on the body under sea transportation by 30% in 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. Besides, the study presents the computer modelling of dynamic loads of the carrying structure of a passenger car body under train ferry transportation. Numerical values of the accelerations and their distribution fields relative to the carrying structure of a car were determined. The adequacy of the designed models was checked with an F-test. The research and proposed engineering solutions can ensure the adequate strength of passenger car bodies under their transportation by train ferries, and also conduct efficient international rail/ferry transportation.

1. Introduction

Development of the railway industry under integration in the systems of international transport corridors requires introduction of the combined transportation. The most promising among them is the rail ferry transportation, the peculiarity of which is a possibility to transport cars by sea on special vessels – train ferries [1–3]. The train ferry is a special vessel equipped with rail tracks for location of rail cars transported by sea. At present both passenger cars and freight wagons are transported by sea. The passengers are located in cabins. Fig. 1 presents train ferries intended for transportation of passenger cars and operated in the Baltic Sea environment. And now the cars are loaded on the train ferry by rolling over the passing (loading) ramp, which has considerably shortened the loading/unloading operations (Fig. 2 [4]). The stability of cars transported by sea is provided by their fixation on the decks (See Table 1).

The cars are fixed relative to the deck according to a standard scheme with chain binders equipped with turnbuckles and stop-jacks. In order to avoid the rocking of cars on the rails, brake stops are mounted under the rolling surfaces of the wheels, and the end cars in batches are linked with buffer stops equipped with standard SA-3 couplers along the longitudinal direction Besides, the car braking system is connected to special hoses to supply compressed air for braking the wheel sets [5,6].

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

Higher stresses in the units of interaction between the passenger car body and fastening systems can cause stability loss relative to the deck and may result in sinking of a train ferry. Thus, there are known cases when ship sank during the storm due to instable fixation of cars on the deck.

For example, the MV Princess Ashika sank near the islands of Tonga in June 5, 2009. It was caused either by displacement of the freight to one side or by improper loading in the port. The ferry carried 117 passengers and freight.

* Corresponding authors.
E-mail addresses: fomin1985@ukr.net, fomin_ov@gsuite.duit.edu.ua (O. Fomin), alyonalovskaya.vagons@gmail.com (A. Lovska).

Peer review under responsibility of Karabuk University.

1 ORCID: 0000-0003-2387-9946.
2 ORCID: 0000-0002-8604-1764.

https://doi.org/10.1016/j.jestch.2020.08.010
2215-0986/© 2020 Karabuk University. Publishing services by Elsevier B.V.

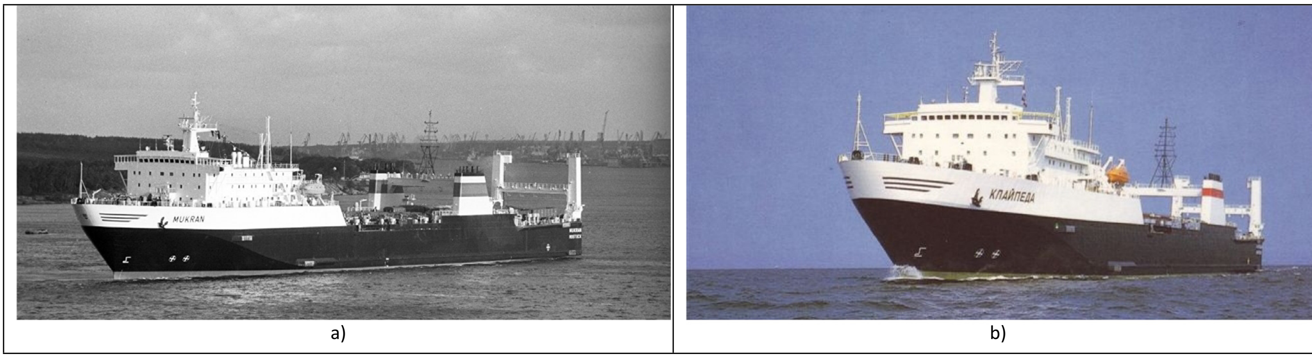

Fig. 1. Train ferries between Lithuania and Germany. a) Mukran b) Klaipeda.

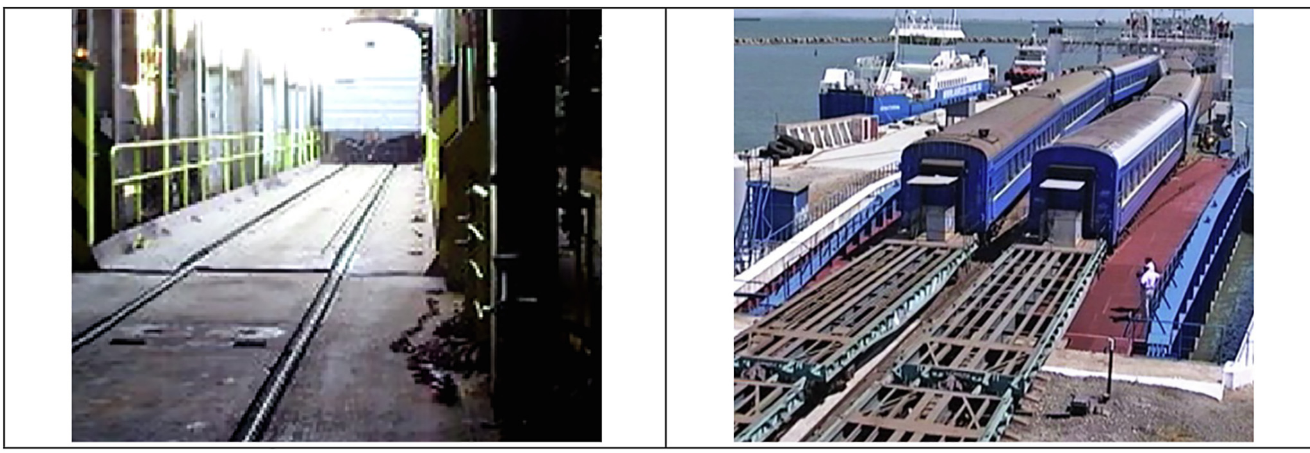

Fig. 2. Loading of passenger cars on a train ferry over the loading ramp.

Table 1
Numerical values of the disturbing action parameters used in the mathematical model.

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

During the storm in the Caspian Sea in 2002 the Mercuri II freight and passenger ferry sank due to poor fixation of rail cars on the deck. It carried 16 rail cars, 8 passengers and 42 crew members.

So to ensure the reliability of fastening of passenger cars on railway 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 and strength under operational conditions does not fully cover the issues of transporting passenger cars carriages by railway ferries [7]. The normative document [8] presents the generalized requirements for sea transportation of rail cars and [9] gives the requirements for fastening systems including those used for train ferries. However, these requirements do not consider train ferry type, sea environment, rail car type, etc. Normative document [10] presents the requirements for loading/unloading of rail cars on/from the train ferry. These requirements are generalized, as the procedure of loading/

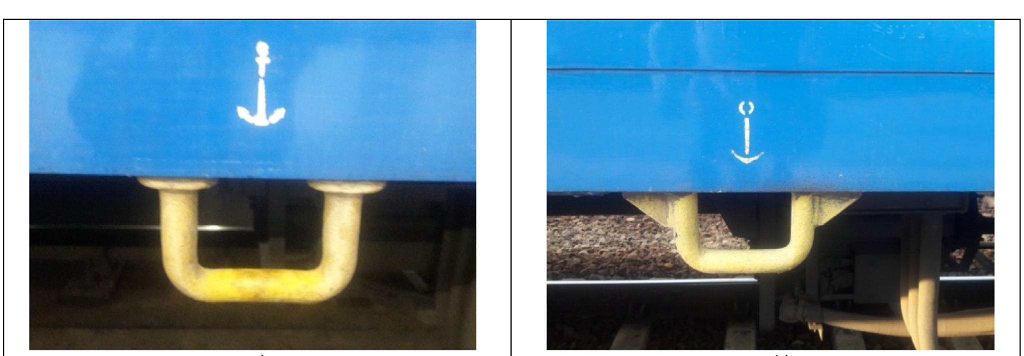

Fig. 3. Fastening brackets for a passenger car body on the train ferry. a) with increased base diameter b) with reinforced ribs.

Please cite this article as: O. Fomin and A. Lovska, Improvements in passenger car body for higher stability of train ferry, Engineering Science and Technology, an International Journal, https://doi.org/10.1016/j.jestch.2020.08.010

unloading on/from the train ferry requires consideration of actual values of inclination of the approach ramp joining the train ferry and land-base rail tracks, and also the geometrical characteristics in the joint zone between the approach ramp and the train ferry.

The research into the dynamic loading of rail cars in train ferry transportation is presented in [11–13]. The study determined peculiarities of interaction between car bodies and fastening systems relative to the deck. The authors conducted the mathematical modelling of dynamic loads and the strength calculation of the carrying structure of rail car bodies and proposed techniques to ensure safe transportation of cars by train ferries.

However, the studies do not determine the dynamic loading and the strength of passenger cars in train ferry transportation.

Some recommendations for longer effective operation of passenger cars are presented in [14]. The cars were selected through technical diagnostics of their state in order to reveal a level of corrosion and mechanical defects. The further stages included research into the strength of carrying structures of rail car bodies on the basis of experimental static and impact tests, life cycle tests in terms of longitudinal forces.

The results of the experiments conducted prove that passenger cars of 28–30 and 33–35 years of operation meet the requirements for strength and safe transportation in accordance with the normative documents, and substantiate that these cars can stay in operation provided the required impact endurance.

Study [15] gives reasons for specifying the term of a longer effective life of passenger cars. Besides, the authors conducted theoretical and experimental research into the strength of the carrying structure of a car. The strength calculation considered the loading values indicated in normative documents. The theoretically obtained results were proved by electric strain-gauging testing.

However, the substantiation of a longer effective life of cars does not consider their loading under train ferry transportation.

Some requirements for carrying systems of rail cars are presented in [16]. They refer to production of new rail car structures, and modernization of cars and wagons. The proposed methods can shorten maintenance costs of cars in operation, decrease empty runs, increase carrying capacity, prolong inter-repair-cycles and service life.

However, the study does not present requirements for the strength and safety of cars transported by train ferries, which is of primary importance for effective international transportation.

An analysis of the literature [11–16] allows us to conclude that the issues of the passenger cars dynamic loading and strength on railway ferries, as well as the improvement of their designs require closer attention at the present stage of the transport industry development.

The objective of the study is research into the dynamic loading and the strength of a passenger car body in train ferry transportation.

The following tasks were set to achieve the objective:

- to determine the dynamic loading of a passenger car body under train ferry transportation;
- to conduct strength calculation for a passenger car under train ferry transportation;
- to improve the structure of a passenger car body in order to provide reliable fixation on the train ferry;
- to determine the dynamic loading of a passenger car body with consideration of improvements under train ferry transportation;
- to make the strength calculation for an improved passenger car body under train ferry transportation; and
- to conduct the computer modelling and verification of the developed models of the dynamic loading for a passenger car body under train ferry transportation.

2. Determination of the dynamic loading on a passenger car body in train ferry transportation

q_1, q_2 – generalized coordinates corresponding to an angular displacement around the longitudinal axis of the train ferry and the car body, respectively;
D – weight water displacement;
B – width;
h – broadside height;
Λ_θ – oscillation resistance factor; z_g – center-of-gravity coordinate;
p'– wind load;
$F(t)$ – law of force action causing movement of a train ferry loaded with rail cars on the deck;
I_k– inertia moment relative to the longitudinal axis;
p_k – wind load on the sidewall;
h_k – sidewall height;
F_β – moment of force between body and deck.
a and b – horizontal and vertical coordinates of a traffic route of a train ferry with coordinates $\times$ and z at a time;
R – traffic route radius of a train ferry;
k –frequency of disturbance effect on the traffic route;
v – natural oscillation frequency of a train ferry;
β_θ – oscillation damping coefficient;
Iy – mass moment of inertia of a train ferry relative to the transverse axle.

A mathematical model was built to determine the dynamic loading on the passenger car body under sea transportation; it considered angular displacements of the train ferry relative to the longitudinal axis (careen). This oscillation type was taken as determining, because it mostly affected the strength and stability of the body relative to the deck. The calculation was made for an empty car, as far as the passengers were accommodated in the cabins during train ferry transportation.

The technical characteristics of the train ferry and passenger car bodies, as well as hydro meteorological characteristics of the cruising area 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 [17].

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

The impact action of sea waves to the train ferry loaded with rail cars on the deck was not taken into account. While designing the model the following factors were considered: the trochoidal law of motion of disturbing action (sea waves) to the train ferry with rail cars on [18], and the dissipative component occurring due to train ferry oscillations in sea rolling, the wave-to-course angle relative to the train ferry body ($\chi = 0^0 - 180^0$) and the wind force to the above-water projection of the train ferry and the car on the upper deck.

The sea wave frequency was determined with consideration of the wave angle to the train ferry body with cars on its deck [19]:

$$\omega=\frac{2\pi\cdot\upsilon}{k_\lambda\cdot L\cdot\cos\chi}, \tag{2}$$

System (1) was solved with transition from differential equations of the second order to equations of the first order (3). The calculation was conducted in program MathCad [20–24]. The initial displacements and speeds were taken equal to zero.

$$Q(t,y)=\left|\begin{matrix}\frac{p'\cdot\frac{h}{2}+\Lambda_\theta\cdot\frac{B}{2}\cdot\dot{F}(t)-\left(\Lambda_\theta\cdot\frac{B}{2}\right)\cdot y_3}{\frac{D}{12\cdot g}\cdot\left(B^2+4\cdot z_g^2\right)}\\ \frac{p_k\cdot\frac{h_k}{2}+F_\beta}{I_k}\end{matrix}\right| \tag{3}$$

$Z = rkfixed\ (Y0,\ tn,\ tk,\ n,\ Q)$.

And the analytical expression for determination of train ferry accelerations has the form

$$\begin{aligned} q_R = &\Big[-\frac{R\cdot e^{kb}\omega\beta_\theta}{2I_y v}\Big[\Big(-\frac{1}{\omega-v}\cos(t(\omega-v)+ka)\\ &+\frac{1}{\omega-v}\cos ka-\frac{1}{\omega+v}\cos(t(\omega+v)+ka)+\frac{1}{\omega+v}\cos\kappa a\\ &-\frac{1}{\omega-v}\sin(ka-t(\omega-v))+\frac{1}{\omega-v}\sin ka-\frac{1}{\omega+v}\sin(ka+(t(\omega+v))\\ &++\frac{1}{\omega+v}\sin ka)\Big]+\frac{1}{\omega+v}\sin ka)\Big]+\frac{p'\frac{h}{2}}{I_y v^2}(\cos vt+1)\Big]\cos vt+\frac{1}{\omega+v}\sin ka)\Big]\\ &++\frac{p'\frac{h}{2}}{I_y v^2}(\cos vt+1)\Big]\cos vt+\frac{p'\frac{h}{2}}{I_y v^2}(\cos vt+1)\Big]\cos vt\\ &++\Big[\frac{R\cdot e^{kb}\omega\beta_\theta}{2I_y}\times\Big(\frac{1}{\omega-v}\sin(ka+t(\omega-v))-\frac{1}{\omega-v}\sin ka\\ &+\frac{1}{\omega+v}\sin(ka+t(\omega+v))-\frac{1}{\omega+v}\sin ka-\frac{1}{\omega-v}\times\cos(ka+t(\omega-v))\\ &+\frac{1}{\omega-v}\cos ka-\frac{1}{\omega+v}\cos(ka+t(\omega+v))++\frac{1}{\omega+v}\cos ka\Big)+\frac{p'\frac{h}{2}\sin vt}{I_y v}\Big]v\sin vt \end{aligned} \tag{4}$$

With consideration of (4) the authors defined the force moment between the body and the deck.

The results of the calculation made it possible to determine numerical values of accelerations as components of the dynamic loading on the passenger car body in train ferry transportation. And the maximum acceleration affecting the car body at a ratio of the wave angle to the train ferry body 60° and 120° accounted for about 1.9 m/s^2. The acceleration value obtained is given with consideration of the horizontal component of free fall acceleration conditioned by the rolling angle of a train ferry, and directed perpendicular to the sidewall of a passenger car body.

3. Strength calculation for a passenger car under train ferry transportation

The accelerations obtained in Section 2 were considered in the strength calculation for the carrying structure of a passenger car body. A spatial model of the carrying structure of a passenger car body was built in SolidWorks (Fig. 4). A 61-836 passenger car model was taken as the prototype. The design length of the model was 23.976 m, and the width – 3.225 m. The empty weight of the car body was 33.4 tons. The model considered elements rigidly joint by welding or riveting.

The strength calculation was realized with the finite element method in CosmosWorks software [25–27]. The finite element model (Fig. 5) was built with spatial isoparametrical tetrahedrons. The optimal number of elements was determined with the graph-analytical method. The model consisted of 183.393 units and 520.475 elements. The maximum size of an element was 80 mm, and the minimum – 16 mm. The percentage of elements with a ratio of sides less than three was 15.1, and more than ten – 56. The minimum number of elements in the circle was 12, and a ratio of an increase in the size of an element was 1.8.

The design model considered the vertical static loading P_v^{st}, the wind load P_v, and also the forces of chain binders P_f (Fig. 6). Owing to a spatial layout of the chain binders, the forces on the car body through them were decomposed. Besides, the vertical displacements of the car body relative to the deck were not considered, as far as the assumption was taken that mechanical support jacks completely unloaded the car spring suspension. The car body was fixed relative to the deck with chain binders of lashing ropes tighten up with air wrenches and had pre-tension of five tons (See Fig. 7).

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 support jacks were installed. Carbon steel (St.3) was used 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,

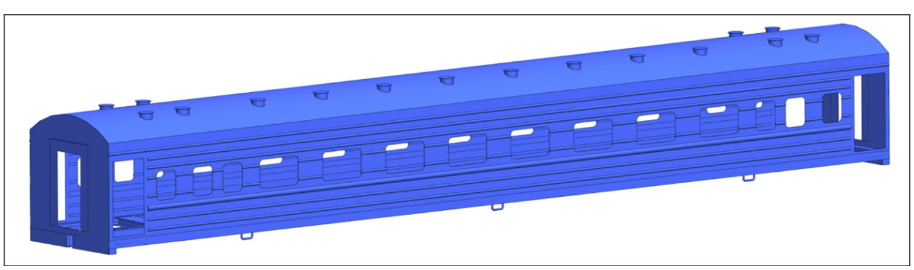

Fig. 4. Spatial model of a passenger car body.

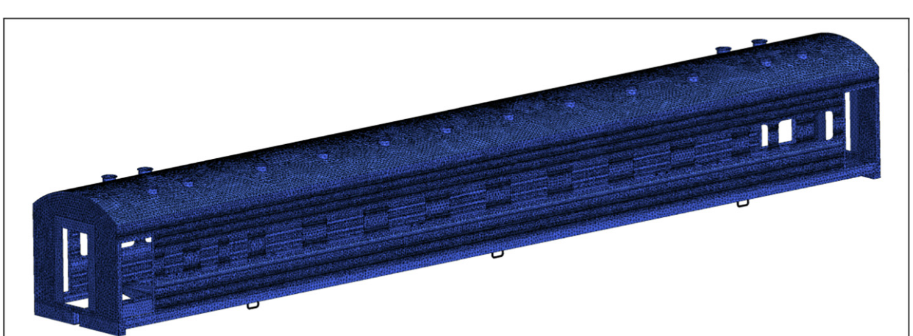

Fig. 5. Finite element model of a passenger car body.

Please cite this article as: O. Fomin and A. Lovska, Improvements in passenger car body for higher stability of train ferry, Engineering Science and Technology, an International Journal, https://doi.org/10.1016/j.jestch.2020.08.010

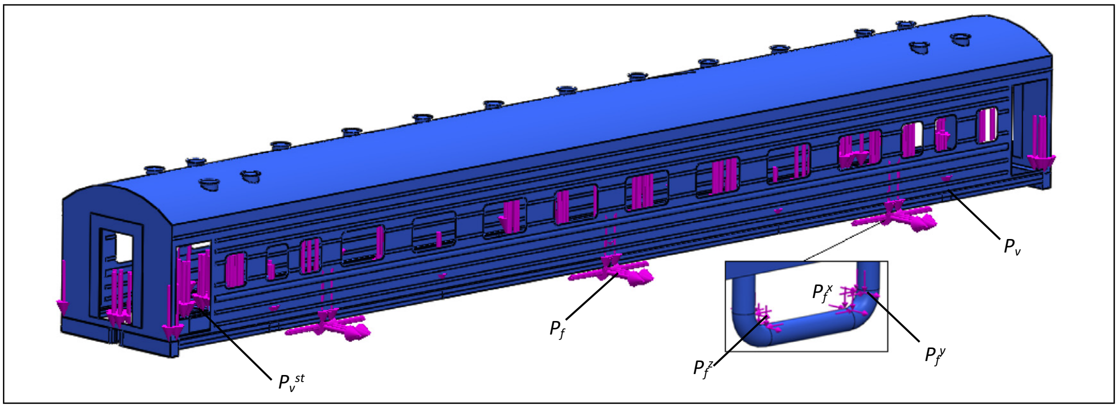

Fig. 6. Design model of a passenger car body.

allowed to conclude that the maximum equivalent stresses are about 350 MPa, that is, exceed the permissible ones (Fig. 7). The stresses in the interaction zone between the fixing clam and the car body were about 310 MPa.

The maximum displacements were 11.8 mm; they were concentrated in the middle sections of the side walls (Fig. 8). The maximum deformations were $1.54 \cdot 10^{-3}$.

Besides, the authors researched into the dynamic loading of a car running over the zone of interaction between the approaching ramp and the train ferry. The mathematical model used for it was presented in a scientific publication of one of the co-authors [28]. The calculation was made for the approach ramp of the train ferry complex "Port of Chernomorsk" (Ukraine).

It was established that the vertical acceleration on the carrying structure of a passenger car over the approach ramp was about 1.5 m/s^2. The acceleration value was admissible in accordance with the normative documentation and indicated a satisfactory run of the car.

4. Structural improvements in a passenger car body for rigid fixation on the train ferry

The authors suggested fixation units installed on the bolster beam for rigid fixation of passenger car bodies on the train ferry (Fig. 9). Unlike clamps used for fixation of a car body on the deck, such a unit can soften the load action transferring to the deck through the chain binders. The principle of action of such a unit is based on operation of a hydraulic damper, which reduces the dynamic loading on the body.

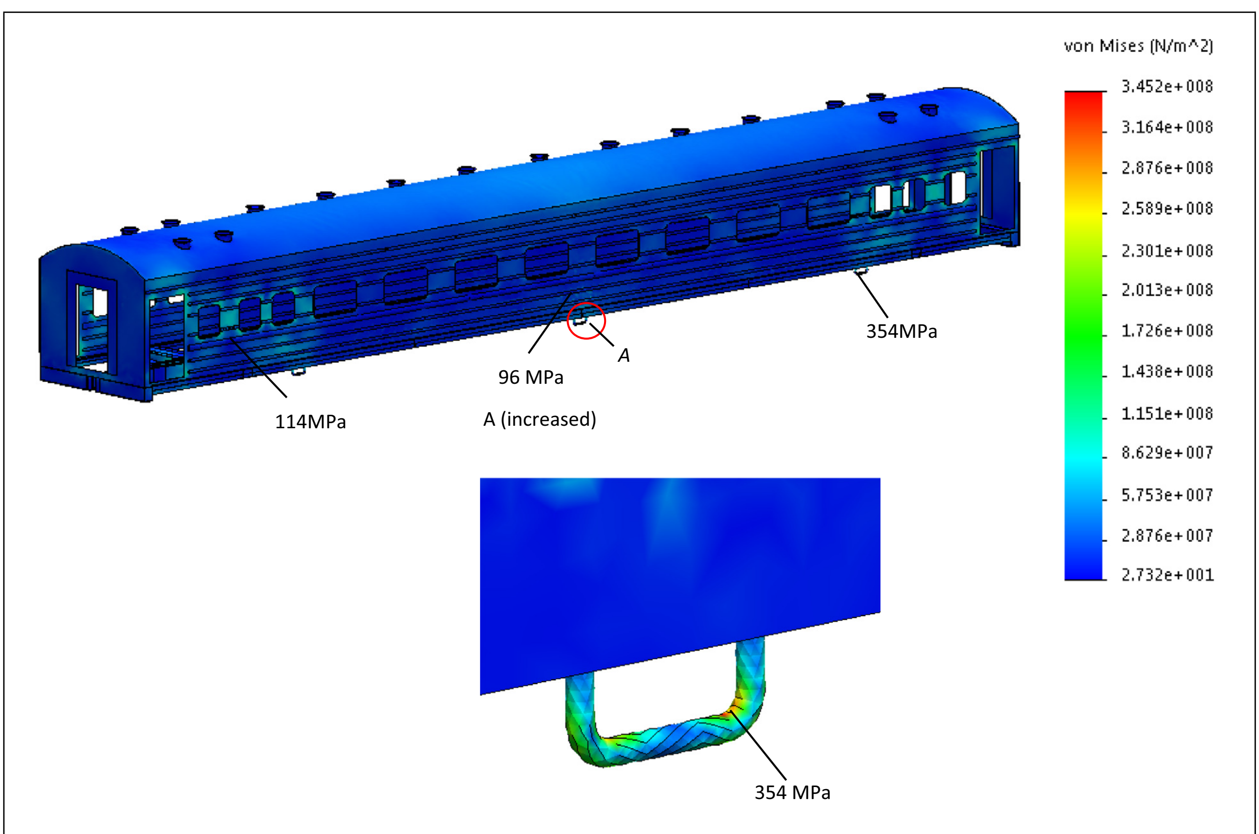

Fig. 7. Stressed state of the passenger car body.

Please cite this article as: O. Fomin and A. Lovska, Improvements in passenger car body for higher stability of train ferry, Engineering Science and Technology, an International Journal, https://doi.org/10.1016/j.jestch.2020.08.010

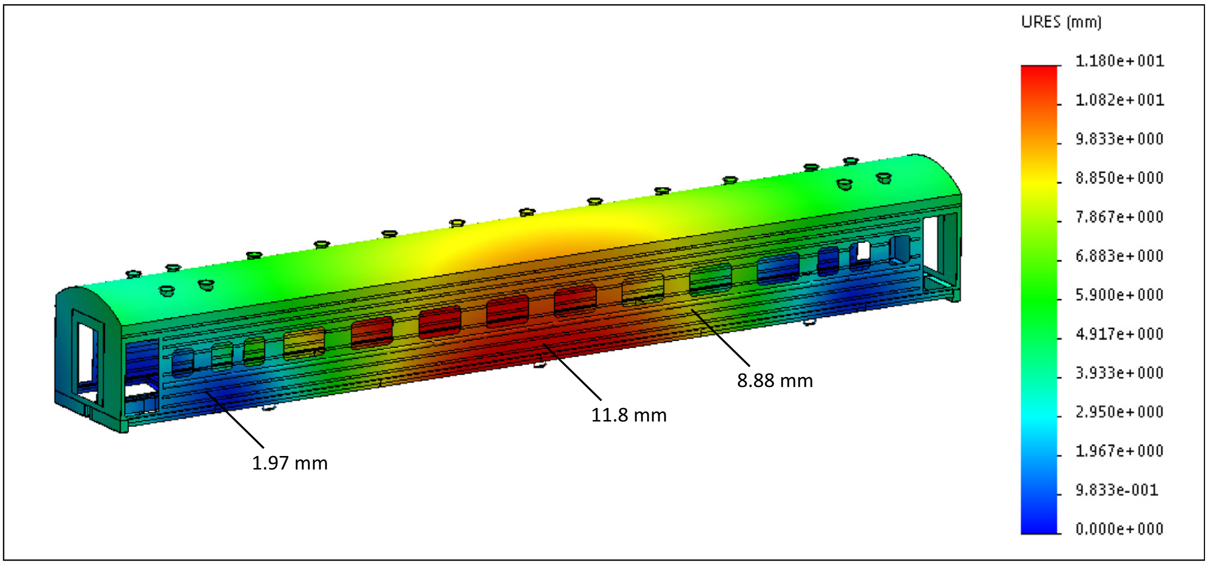

Fig. 8. Moving in the nodes of the passenger car body structure.

While transferring the loading P through eyelet 7 on the unit from the hook of a chain binder, piston 5 transferred together with piston rod 3 relative to body 4. And the operating fluid overflowed through an open throttle valve and created resistance to the piston movement. Brake spring 8 was pressed. The travel of piston 5 to the initial position was made with brake spring 8. At the backward run of piston 5 the overflow process took place through another throttle valve. And the energy dissipated in the environment.

The area where rod 3 interacted with the unit's support 1, fixed to the vertical plate of the bolster beam, had pivot connection 2. The unit could be moved to a horizontal position if there were no need for it (Fig. 10). The unit had two positions: "off" (horizontal) and "on" (angular). The unit began working under an effort of 5 tons, i.e. at the forces exceeding pre-tension of chain binder.

5. Determination of the dynamic loading and the strength of an improved passenger car body in train ferry transportation

q_1, q_2 – the generalized coordinates corresponding to the angular displacement around the longitudinal axis of the train ferry and the car body, respectively;
D – the weight displacement;
B – the width;
h – the side height;
Λ_θ – the coefficient of resistance to vibrations;
z_g – the coordinate of gravity center;
p' – the wind load;
$F(t)$ – the law of action exiting the motion of the train ferry loaded with cars on the deck.
I_k – the inertia moment relative to the longitudinal axis;
β – the coefficient of viscous resistance to displacements of the car body;
$в_k$ – the body width;
p_k – the wind load on the side wall;
h_k – the height of the side wall;
F'_β – moment of force between the body and the deck with consideration of interaction through the fixation unit;
σ_s – stresses in welded joint;
M – torque moment in welded joint section;
β' – weld penetration depth coefficient which depends on the welded joint form and welding method;
l_s – design length of welded joint;
N – design force impacting the welded joint;
F – welded joint area;
R_{ys} – design resistance of the welded joint.

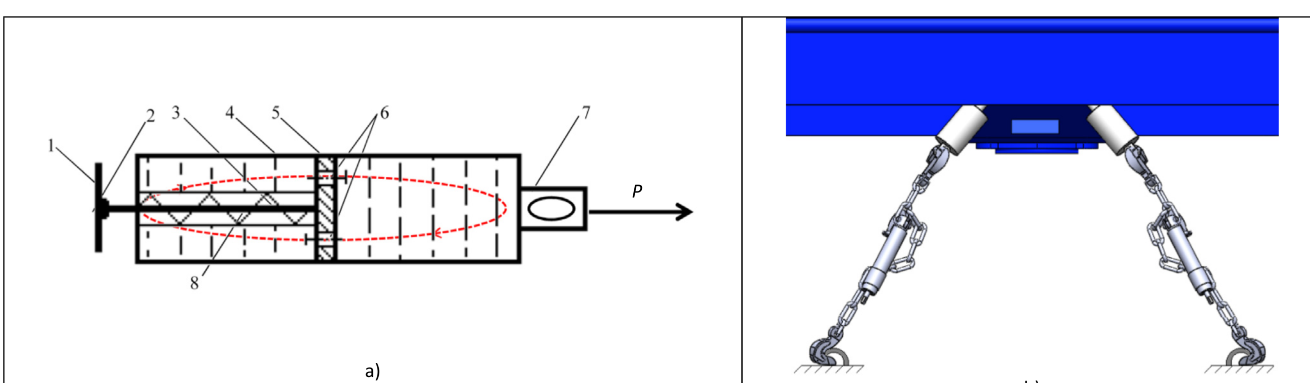

Fig. 9. Unit for fixation of the car body relative to the deck. a) unit structure; b) body fixation scheme. 1 – support; 2 – hinge; 3 – rod; 4 – body; 5 – piston; 6 – throttle valve; 7 – eyelet for fixation of the hook of a chain binder; 8 – brake spring.

Please cite this article as: O. Fomin and A. Lovska, Improvements in passenger car body for higher stability of train ferry, Engineering Science and Technology, an International Journal, https://doi.org/10.1016/j.jestch.2020.08.010

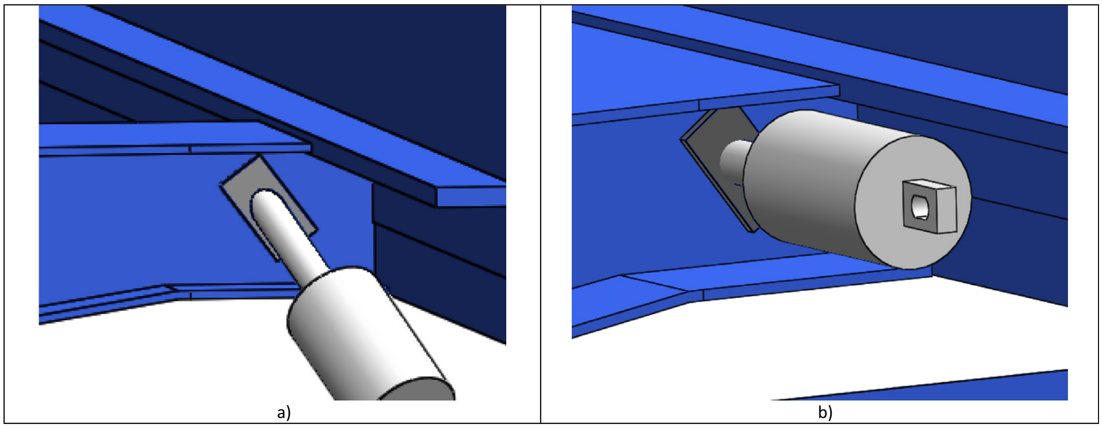

Fig. 10. Position of the unit for car body fixation relative to the deck. a) with car body fixation; b) without fixation.

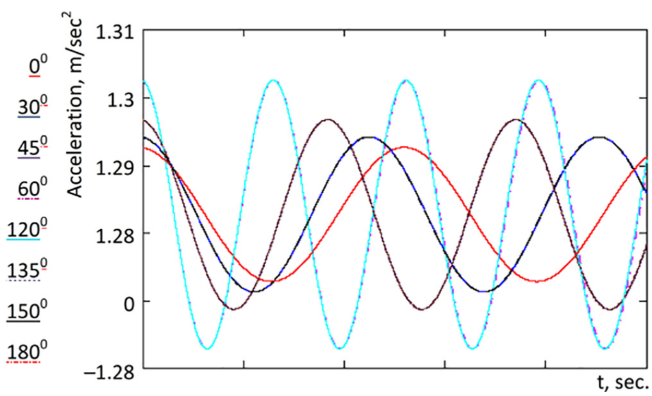

Fig. 11. Accelerations on the car body under viscous interaction with the deck.

The mathematic modelling substantiated the use of a fixation unit for the car body on the train ferry. Thus a mathematical model was built (4). The calculation was conducted in program MathCad [20 –24]. The accelerations on the car body with consideration of the new fixation method relative to the deck are given in Fig. 11.

$$\begin{cases} \frac{D}{12\cdot g}\cdot\left(B^2+4\cdot z_g^2\right)\cdot\ddot{q}_1+\left(\Lambda_\theta\cdot\frac{B}{2}\right)\cdot\dot{q}_1=p'\cdot\frac{h}{2}+\Lambda_\theta\cdot\frac{B}{2}\cdot\dot{F}(t) \\ I_k\cdot\ddot{q}_2+\beta\cdot\frac{\beta_k}{2}\cdot\dot{q}_2=p_k\cdot\frac{h_k}{2}+F'_\beta \end{cases} \tag{5}$$

The study established that the maximum accelerations on the car body at the relative bearings to the train ferry body 60^0 and 120^0 accounted for about 1.3 m/s^2. The acceleration value obtained considered the horizontal component of free fall acceleration.

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 kN·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 scheme of fixation relative to the deck.

6. Results and discussion

In order to determine the strength of the improved passenger car body the authors conducted the calculation by the finite element method in CosmosWorks software suite [25,26].

The model considered the elements rigidly connected by welding or riveting.

The finite element model was built with spatial isoparametrical tetrahedrons. The optimal number of elements was determined with a graph-analytical method. The model consisted of 152.967 units and 434.641 elements. The maximum size of an element was 80 mm, and the minimum – 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 also forces from the chain binders $P_{ch.b.}$ (Fig. 12). Due to a spatial layout of the chain binders the force on the car body through them was decomposed and applied to the unit's support part located on the vertical plate of the bolster beam.

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. Steel was used as material for the body structure.

The results of the calculation are given in Fig. 13. 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 stresses in the interaction zone between the lining and the bolster beam's vertical sheet were about 95 MPa. The maximum displacements were fixed in the center sill of the car and accounted for 6.47 mm (Fig. 14). The maximum deformations were $1.01\cdot10^{-3}$.

It should be mentioned that, as far as the proposed units are intended only for fixation of a car on the train ferry, the other loading modes intended for other different purposes were not considered by the authors.

The research made it possible to conclude that the proposed improvements decreased the maximum equivalent stresses in the carrying structure elements by more than 60% in comparison with those of standard fixation systems (Table 2).

The authors made strength calculation for a welded joint in the interaction zone between a unit and the bolster beam's vertical sheet.

It was considered that the welded joint are affected by bending and tensile deformations. And the strength condition has the form

$$\sigma_r=\frac{3\cdot M}{(\beta_r h_r)\cdot l_r^2}+\frac{N}{F}\leqslant R_y^r. \tag{6}$$

It was established that at M = 0.49 N•m, β_r = 1, h_r = 0.8, l_r = 0.56 m, N = 196.0•103 N, F = 0.003 mm^2, the value σ_r = 653.3•10^5-Pa, which was lower than the design joint resistance (R_y^r = 1.96•10^8-Pa). Therefore, the strength of the welded joint was ensured.

Besides, within the research the authors calculated fatigue of the carrying structure of a car. The calculation was made in CosmosWorks software according to the design diagram presented in Fig. 12. The test base consisted of 10^7 cycles. The fatigue curve was obtained by dividing each stress value

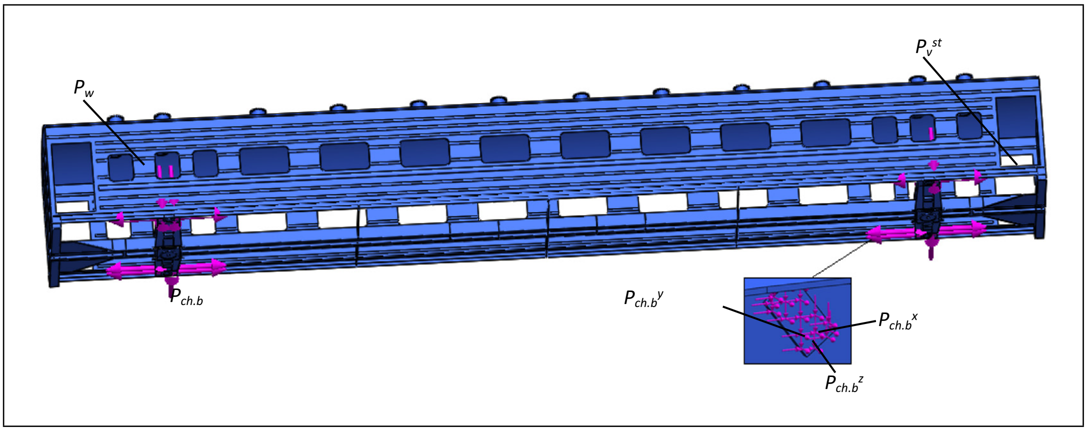

Fig. 12. Strength modelling for the passenger car body.

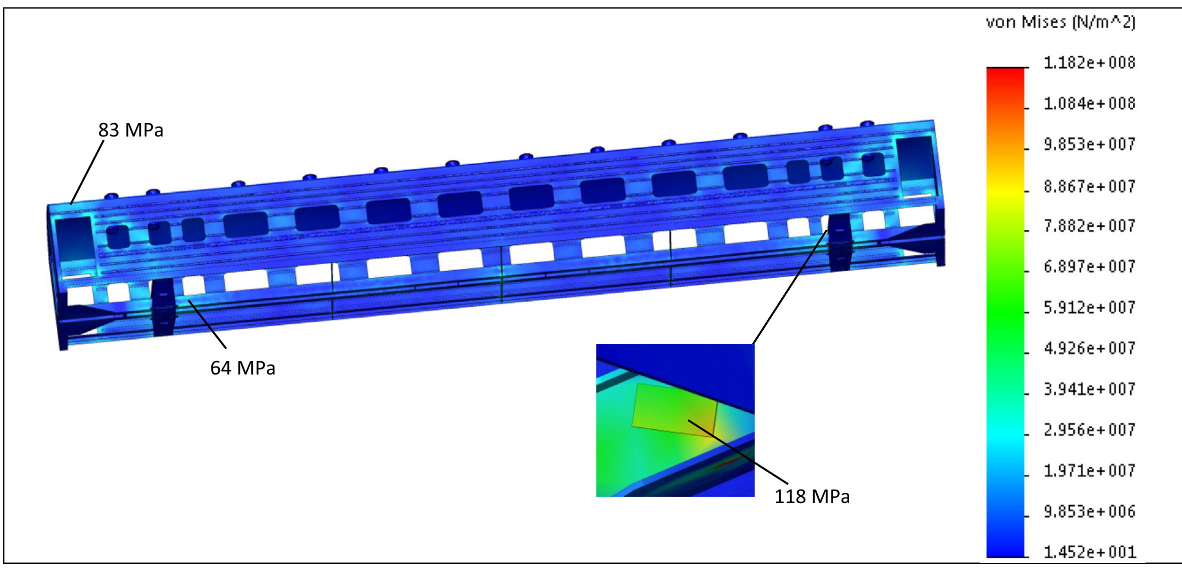

Fig. 13. Stressed state of the passenger car body.

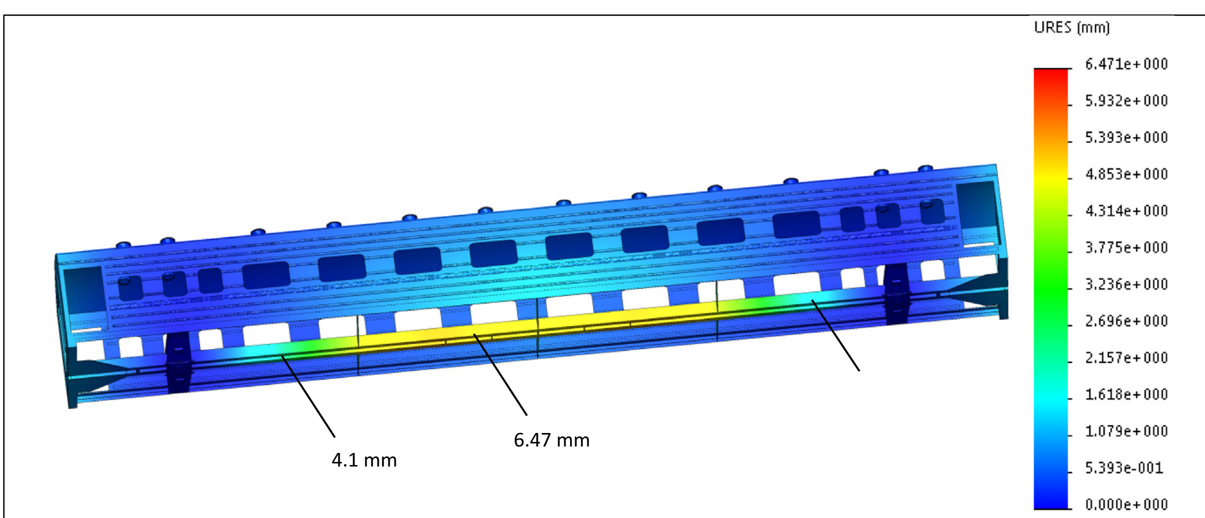

Fig. 14. Moving in the nodes of the passenger car body structure.

Please cite this article as: O. Fomin and A. Lovska, Improvements in passenger car body for higher stability of train ferry, Engineering Science and Technology, an International Journal, https://doi.org/10.1016/j.jestch.2020.08.010

Table 2
Strength values of the carrying structure of a passenger car under train ferry transportation.

Parameter	Without improvements	With improvements
Maximum equivalent stresses, MPa	354	118
Displacements, mm	11.8	6.47

of the SN curve into the elasticity modulus of the reference material ASME, and multiplying the obtained value by the elasticity modulus of the set material. The calculation considered the cumulative damage theory which assumes that the stress cycle, the stress variables of which are higher than the fatigue limit, causes damage. The total damage consisted of the sum of damages caused by isolated stress cycles. It was established that the load cycle 10^7 applied to the design model did not manifest any damage.

The design diagram built in Section 5 was used for the computer modelling of dynamic loads of a passenger car body under train ferry transportation. The distribution fields relative the carrying structure and their numerical values were determined.

The results of the calculation are given in Figs. 15 and 16. The maximum accelerations emerging in the middle of the center sill of a car were 1.8 m/s^2. In the extension parts the acceleration values were about 0.7 m/s^2.

The designed models of the dynamic loading of a passenger car body under train ferry transportation were verified with an F-test. The optimal sample size was defined by a T-test. Table 3 presents the accelerations of a passenger car body, obtained by mathematical and computer modelling.

It was established that at the dispersion adequacy $S^2_{ad} = 1.26$ and the error mean square $S^2_y = 1.22$ the actual criterion value equalled $F_p = 1.03$, which is lower than the tabulated value ($F_t = 3.29$). Therefore, the hypothesis on adequacy was not rejected.

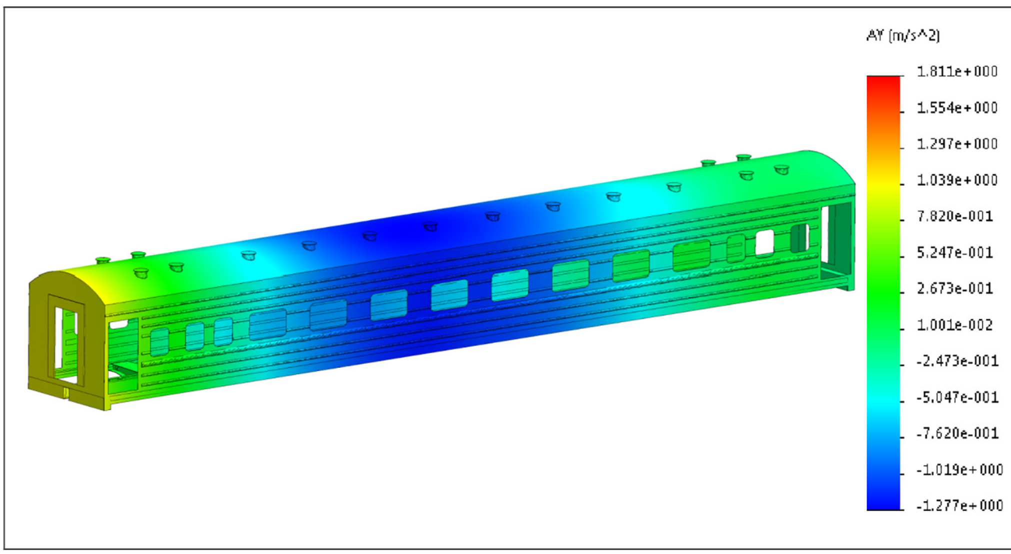

Fig. 15. Distribution of accelerations relative to the carrying structure of a passenger car (side view).

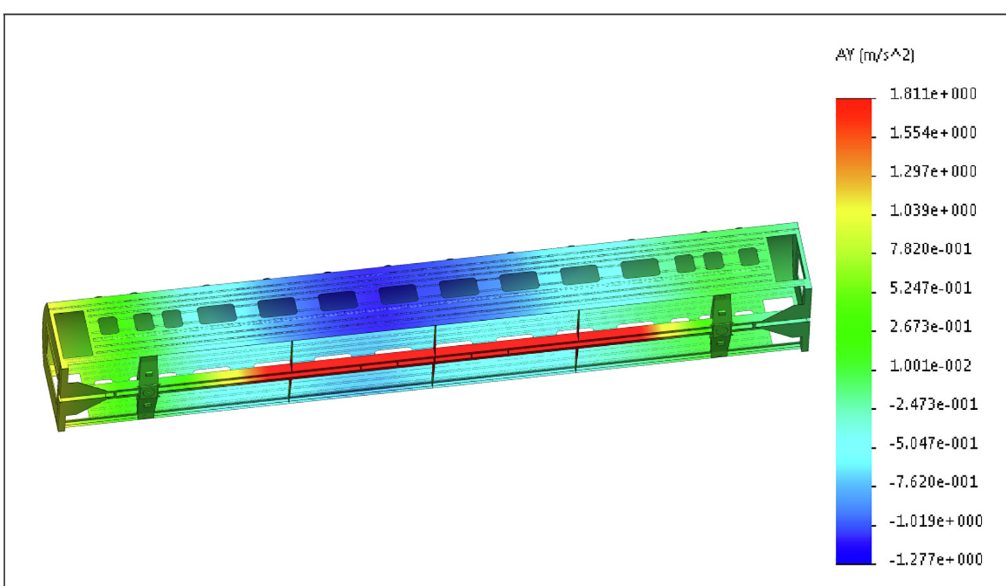

Fig. 16. Distribution of accelerations relative to the carrying structure of a passenger car (bottom view).

Table 3
Results of mathematical and computer modelling of dynamic loads on passenger car body.

Angle of roll, deg.	Accelerations, m/sec^2	
	Mathematical modelling	Computer modelling
5	0.4	0.9
7.5	0.8	1.2
10	1.3	1.8
12.5	1.7	2.3
15	2.2	2.8
17.5	2.5	3.1
20	2.9	3.4
22.5	3.2	3.7
25	3.6	4.0

For further research into the dynamic loading of a passenger car body under train ferry transportation, there is a need to consider stochasticity of the oscillation process conditioned by random parameters of a sea wave. An important stage in this research is making a physical experiment in terms of determination of the strength values of a passenger car body under sea transportation. The authors have experience in such research; however it dealt with a freight open wagon transported by the train ferry in the Black Sea environment. And the authors are going to conduct similar research for a passenger car.

The results may encourage engineers to work out recommendations in terms of safe operation of passenger cars in international rail/sea transportation. Besides, they may encourage manufacturers to develop modern structures of passenger cars.

7. Conclusions

The following conclusions can be made from the research:

1. The study determined the dynamic loading of a passenger car body under train ferry transportation. A mathematical model, which considered displacements of the train ferry relative to the longitudinal axle (careen), was built. This type of oscillation was chosen as determining, as it mostly affected the strength and stability of the body relative to the deck. The model was solved in Mathcad software. The results of the calculation made it possible to determine numerical values of accelerations as components of the dynamic loading on a passenger car body in train ferry transportation. The maximum acceleration affecting the car body at the wave-to-course angle relative to the train ferry body 60° and 120° accounted for about 1.9 m/s^2;
2. The authors conducted the strength calculation for a passenger car body under train ferry transportation. The finite-element method in CosmosWorks was used as a calculation method. The study determined the basic strength parameters of a passenger car body under train ferry transportation. It was established that the maximum equivalent stresses occurred in the fixating clamps on the deck, and accounted for about 350 MPa thus exceeding the admissible values. The maximum displacements were 11.8 mm; they were concentrated in the middle sections of the sidewalls. It can result in stability loss for the passenger car body relative to the deck, and endanger the safety of train ferry transportation;
3. The structural improvements for a passenger car body are aimed at ensuring reliable fixation on the train ferry. The authors propose to fasten the body with special units installed on the bolster beams. The principle of action of such a unit is based on operation of a hydraulic damper, which reduces the dynamic loading of the body under sea transportation;
4. The dynamic loading of the improved passenger car body under train ferry transportation was determined. The study established that the maximum accelerations as a dynamic loading component on the car body occurred at the wave angle to the train ferry body 60° and 120°, and accounted for about 1.3 m/s^2. The working fluid, which creates viscous resistance between the body and the deck, should have the coefficient of viscous resistance from 2 kN·s/m to 4.2 kN·s/m. Thus, considering the proposed solution, the maximum accelerations on the car body are reduced by 30% in comparison with that in a typical fixation scheme on the deck;
5. The strength calculation for an improved passenger car body under train ferry transportation was conducted. The maximum equivalent stresses accounted for 120 MPa and were concentrated in the lining which simulated the support part of the unit. The maximum displacements emerged in the center sill of a car and accounted for 6.47 mm, and the maximum deformations were $1.01 \cdot 10^{-3}$. The research made it possible to conclude that considering the proposed improvements it is possible to decrease the maximum equivalent stresses in the carrying structure elements of a car by more than 60% in comparison with that of standard fixation schemes;
6. The study deals with the computer modelling and verification of the developed models of the dynamic loading of a passenger car body under train ferry transportation. The distribution fields of accelerations relative to the carrying structure and their numerical values were determined. The maximum accelerations in the middle of the center sill of a car were 1.8 m/s^2. The acceleration values of the extension parts were about 0.8 m/s^2. The developed models of the dynamic loading of a passenger car body were verified with an F-test. The actual criterion value was defined by correlating the dispersion of adequacy and the error mean square. When the dispersion of adequacy $S_{ad}^2 = 1.26$ and the error mean square $S_y^2 = 1.22$, the actual value of the criterion was $F_p = 1.03$, which is lower than the tabular value ($F_t = 3.29$). Therefore, the hypothesis on adequacy was not rejected.

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

Declaration of Competing Interest

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.

References

[1] https://az.sputniknews.ru/economy/20151214/403031044.html.
[2] http://forums.airbase.ru/2008/04/t58887–paromy.html.
[3] N. Klochenko, Parom, "Klaypeda", Morskoy flot. 5 (1988) 27–31.
[4] http://primavera.msk.ru/image/1407-0-3.html.
[5] A.E. Sukolenov, E. Zahariev, I.G. Gutin, Mezhdunarodnaya paromnaya pereprava Illichevsk –, Varna (1989).
[6] M.G. Shmakov, Spetsialnyie sudovyie ustroystva (1975).
[7] Vagonyi passazhirskie lokomotivnoy tyagi. Trebovaniya k prochnosti i dinamicheskim kachestvam, GOST 34093-2017, 2017.
[8] Railway applications – Structural requirements of railway vehicle bodies - Part 1: Locomotives and passenger rolling stock (and alternative method for freight wagons), EN 12663-1:2010, 2010.
[9] Standardisation and positioning on wagons of steps, end platforms, gangways, handrails, tow hooks, automatic coupler (ac), automatic draw-on coupling and brake valve controls on the uic member rus and osjd member rus, UIC 535-2:4ED, 2005.
[10] Wagon stresses, UIC 577:5ED, 2012.
[11] A. Lovskaya, A. Ryibin, The study of dynamic load on a wagon-platform at a shunting collision, East.-Eur. J. Enterp. Technol. 3 (2016) 4–8.

[12] Fomin Oleksij, Lovska Alyona, Kulbovskyi Ivan, Holub Halyna, Kozarchuk Ihor, Kharuta Vitalii, Determining the dynamic loading on a semi-wagon when fixing it with a viscous coupling to a ferry deck, East.-Eur. J. Enterp. Technol. 2/7 (98) (2019) 6–12, https://doi.org/10.15587/1729-4061.2019.160456.
[13] Fomin Oleksij, Lovska Alyona, Píštěk Václav, Kučera Pavel. Research of stability of containers in the combined trains during transportation by railroad ferry, MM Sci. J. (2020), 3728–3733.
[14] S.V. Myamlin, O.G. Reydemeyster, A.L. Pularlya, V.O. Kalashnik, Rozrobka rekomendatsIy Iz prodovzhennya termInu korisnoYi ekspluatatsIYi pasazhirskih vagonIv, Nauka ta progres transportu, VIsnik DnIpropetrovskogo natsIonalnogo unIversitetu zalIznichnogo transport. 6 (60) (2015) 118–126.
[15] I. Klimenko, L. Černiauskaite, L. Neduzha, O. Ochkasov, Mathematical simulation of spatial oscillations of the "Underframe-Track", System Interaction, in: Proc. Of 12th Intern. Conf. «Intelligent Technologies in Logistics and Mechatronics Systems – ITELMS'2018», 2018, pp. 105–114.
[16] O. Fomin, A. Lovska, V. Píštěk, P. Kučera, Dynamic load computational modelling of containers placed on a flat wagon at railroad ferry transportation, Vibroengineering Proc. 29 (2019) 118–123.
[17] Veter i volnyi v okeanah i moryah: spravochnyie dannyie, 1974.
[18] V.V. Lugovskiy, Dinamika morya: Izbr. voprosyi svyaz. s ucheniem morehodnosti korablya, 1976.
[19] Yu. L. Makov, Kachka sudov, 2007.
[20] V. Tkachenko, S. Sapronova, I. Kulbovskiy, O. Fomin, Research of resistance to the motion of vehicles related to the direction by railway, East.-Eur. J. Enterp. Technol. 5, 7 (89) (2017) 65–72. doi:10.15587/1729-4061.2017.109791.
[21] G. Vatulia, A. Falendysh, Y. Orel, M. Pavliuchenkov, Structural Improvements in a Tank Wagon with Modern Software Packages, Proc. Eng.. 187 (2017) 301–307, https://doi.org/10.1016/j.proeng.2017.04.379.
[22] V. Dyakonov, MATHCAD 8/2000: spetsialnyiy spravochnik, 2000.
[23] D.V. Kiryanov, Mathcad 13, 2006.
[24] F. Oleksij, A. Lovska, R. Valentyna, H. Anatoliy, S. Inna, G. Olga, The dynamic loading analysis of containers placed on a flat wagon during shunting collisions, ARPN J. Eng. Appl. Sci. 14 (21) (2019) 3747–3752.
[25] P. Kucera, V. Pistek, Testing of the mechatronic robotic system of the differential lock control on a truck, Int. J. Adv. Robotic Syst. 14 (5) (2017), https://doi.org/10.1177/1729881417736897.
[26] A.A. Alyamovskiy, SolidWorks/COSMOSWorks 2006–2007. Inzhenernyiy analiz metodom konechnyih elementov, 2007.
[27] A.V. Kondratiev, V.E. Gaidachuk, M.E. Kharchenko, Relationships between the ultimate strengths of polymer composites in static bending, compression, and tension, Mech. Compos. Mater. 55 (2) (2019) 259–266.
[28] A.O. Lovska, Doslidzhennya dinamichnih navantazhen, sho diyut na kuzov napivvagona pri zavantazhenni na zaliznichnij porom, Zbirnik naukovih prac Derzhavnogo universitetu infrastrukturi ta tehnologij Ministerstva osviti i nauki Ukrayini: Seriya «Transportni sistemi i tehnologiyi». 29 (2016) 72–78.