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DETERMINING STRENGTH INDICATORS FOR THE BEARING STRUCTURE OF A COVERED WAGON'S BODY MADE FROM ROUND PIPES WHEN TRANSPORTED BY A RAILROAD FERRY

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Підвищення ефективності перевізного процесу через міжнародні транспортні коридори сприяє розвитку інтероперабельних систем. Успішне функціонування інтероперабельного транспорту можливе лише при надійній та злагодженій роботі окремих складових між собою. У зв'язку з цим необхідним є впровадження в експлуатацію рухомого складу нового покоління з покращеними техніко-економічними показниками. Розроблено несучу конструкцію критого вагона, особливістю якого є те, що елементи кузова виготовлені з труб круглого перерізу, а для надійності закріплення його відносно палуби залізничного порому на шворневих балках розміщуються вузли для закріплення ланцюгових стяжок. Для уточненого визначення показників міцності кузова критого вагона досліджено його динамічну навантаженість при найбільш несприятливій розрахунковій схемі – кутові переміщення залізничного порому навколо повздовжньої осі (еквівалент коливань бічна хитавиця в динаміці вагонів). Визначення максимальної величини прискорень здійснено шляхом математичного моделювання процесу коливань залізничного порому з вагонами, розміщеними на його палубах з використанням метода Лагранжа II роду. Розв'язання диференціального рівняння коливань залізничного порому з вагонами, розміщеними на ньому, проведено за методом Рунге-Кутта в середовищі програмного забезпечення MathCad. При визначенні загальної величини прискорення, яке діє на кузов критого вагона при перевезенні на залізничному поромі також враховано горизонтальну складову прискорення вільного падіння, яка обумовлена кутом нахилу (крен) залізничного порому. Отримане значення прискорення, як складова динамічного навантаження, враховане при дослідженні міцності несучої конструкції кузова критого вагона. Розрахунок проведений за методом скінчених елементів в програмному забезпеченні CosmosWorks. Для цього розроблено модель міцності несучої конструкції кузова критого вагону з круглих труб при перевезенні на залізничному поромі. Встановлено, що максимальні еквівалентні напруження не перевищують допустимі для марки сталі металоконструкції кузова та складають близько 280 МПа. Визначено проектний строк служби вузла для закріплення ланцюгових стяжок на кузові критого вагону при перевезенні на залізничному поромі. Результати досліджень можуть використовуватися при проектуванні вагонів нового покоління з покращеними техніко-економічними та експлуатаційними показниками

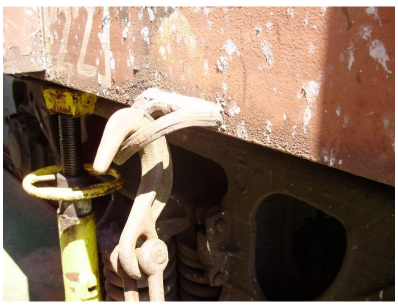
Ключові слова: критий вагон, несуча конструкція, динамічна навантаженість, залізнично-водний транспорт, залізнично-поромні перевезення

1. Introduction

Improving the efficiency of functioning of the transport industry predetermines a necessity to introduce interoperable transportation systems. One of the most promising components in the transport industry is railroad-ferry transportation. The special feature of such transportation is the possibility to transport railroad cars by sea by vessels, specifically equipped for this purpose, which are the railroad ferries. To ensure the stability of railroad cars relative to the decks of railroad ferries, the load-bearing structures are fastened using multi-turn means: chain screeds, mechanical stop-jacks, brake shoes, buffer stops.

An analysis of operating conditions for railroad carriages transported by railroad ferries across the Black Sea water area revealed that there occurs the damage to the elements of the bodies' bearing structures. This is caused by the effect of loads acting on them, which exceed their operational specifications relative to the main tracks, as well as by technical inappropriateness in terms of reliable interaction with multi-turn fastening means relative to decks.

As a result of the absence in the bearing structure of railroad cars of specialized nodes for fastening relative to decks, interaction with the chain screeds employs the body's elements, which are not designed for this purpose. This causes damage to the bearing structure of railroad cars' bodies when they are transported by railroad ferries (Fig. 1).



a

b

Fig. 1. Damaged elements of the bearing structure of a covered wagon's body: *a* – deformation of a towing bracket; *b* – deformation of a body panel

Thus, it is necessary to design and implement the fundamentally new designs of railroad cars with improved technical and economic indicators, adapted for use along international transport corridors.

2. Literature review and problem statement

Features and results of the cataloguing of load bearing systems at semi-wagons using the application of a given approach to an edge wall in one of the basic models of semi-wagons were reviewed in [1]. The results of research into determining the nature and degree of influence of different freight railroad cars on strength of the railroad cars' bearing systems were reported in [2]. The specified papers did not study the strength of improved structures in freight wagons when transported by a railroad ferry.

Features of the development of a technology for modernizing freight wagons during periodic repair were considered in [3]. Within the framework of the project, the authors proposed manufacturing the body of a car from composite panels, and apply color coating from anticorrosive materials. An analysis of fundamentally new designs of freight railroad cars and their manufacturing technology were specified in [4]. The authors give the requirements to the freight railroad cars at the current stage of development.

The specified papers did not investigate the dynamic loading of the reported structures of freight wagons transported by railroad ferries.

An analysis of dynamic properties of rolling stock in operation relative to rail tracks is given in [5]. The research results showed that the most sensitive inertial properties are the mass and the vertical moment of inertia, and the least sensitive are the longitudinal and lateral moments of inertia. A description of the new technique for a vehicle traveling along a curved section of the track, using the multifunctional computational software, was given in [6].

It should be noted that the issue of wagons dynamics and safety of their motion when transported by railroad ferries was not paid attention to.

The results, as well as the peculiarities, of performed theoretical and experimental research into the introduction of the joint execution of a girder beam at railroad pellet wagons, were reported in [7]. Practical implementation of the proposed solutions makes it possible to reduce the cost of manufacturing such railroad cars by 10 %. Features of the simulation of loading on the bearing structure of a wagon-platform of the joined type at combined transportation are given in [8]. The research was conducted when the wagon-platform was operated relative to the main tracks and when transported by a railroad ferry.

It is important to note that the specified papers did not perform computer simulation of the dynamic loading on the wagons' bearing structures when transported by a railroad ferry.

An analysis of the structural features of railroad cars of the new generation was given in [9]. In addition, the paper reports a study into the dynamics of these wagons when they rest on the trolleys LEILA and SUSTRAIL. The paper does not provide calculation of strength of the structural bodies of railroad cars when transported by a railroad ferry.

Features of application of the adaptive weighted amount method for multi-purpose optimization were considered in [10]. The method defines the evenly-distributed Pareto optimal solutions, solutions in not-convex regions, and neglects those optimal solutions that do not refer to Pareto. It is important to note that the paper does not address the adaptation of the specified method to the tasks related to optimal design of wagon bodies.

To ensure the strength of bearing structures of the covered wagons' bodies, it is necessary to determine the refined magnitudes of dynamic loads that act on them when transported by railroad ferries and to investigate indicators for the strength of load-bearing structures. In order to provide safety of the wagons transported by railroad ferries, it is necessary that bearing structures should securely interact with the means of their fastening to decks.

3. The aim and objectives of the study

The aim of this work is to identify special features in determining strength indicators for load-bearing structures of the covered wagons' bodies made from round pipes when transported by a railroad ferry.

To accomplish the aim, the following tasks have been set:

– to model mathematically the dynamic loading of the body of a covered wagon when transported by a railroad ferry;

– to determine the indicators of strength of the covered wagon's body when transported by a railroad ferry;

– to improve the bearing structure of the covered wagon's body to ensure its durability when transported by a railroad ferry;

– to simulate the dynamic loading of the covered wagon's body of improved design when transported by a railroad ferry;

– to verify the models of dynamic loading of the covered wagon's body;

– to determine strength indicators for the covered wagon's body of improved design when transported by a railroad ferry.

4. Mathematical modeling of dynamic loading on the covered wagon's body when transported by a railroad ferry

In order to study dynamic loading of the covered wagon's body when transported by a railroad ferry, we used a mathematical model given in [11].

We took into consideration the displacements of a railroad ferry with railroad cars lined up on its decks around the longitudinal axis (heeling), that being the case of the largest dynamic loading on railroad cars when transported by sea (1).

$$I_\theta \cdot \ddot{q} + \left(\Lambda_\theta \cdot \frac{B}{2}\right)\dot{q} = p' \cdot \frac{h}{2} + \Lambda_\theta \cdot \frac{B}{2} \cdot \dot{F}(t), \tag{1}$$

where q is the generalized coordinate, which corresponds to the angular displacement around the longitudinal axis. The coordinate system origin is at the center of mass of a railroad ferry.

I_Θ is the moment of inertia of a train ferry with railroad cars placed relative to its decks; B is the width of the train ferry; h is the depth of the railroad ferry; Λ_Θ is the coefficient of resistance to oscillations; p' is the wind load; $F(t)$ is the law of action of the effort, which disturbs the motion of a train ferry with railroad cars' bodies lined up on its decks.

We determined a coefficient of resistance to oscillations of the train ferry according to [12]

$$\Lambda_\theta = \omega_0{}' \sqrt[8]{\frac{(I_\theta + \lambda)g}{D \cdot h^2}} (1 + 2Fr + 10Fr^2), \tag{2}$$

where λ is the connected fluid mass moment of inertia; Fr is the Froude's number that depends on motion speed; ω_0' is the coefficient, which is determined from a special nomogram and depends on the ratio B/T, where T is the railway ferry draft, m.

When constructing a model, we took into consideration a trochoidal law of the disturbing action movement (a sea wave) on a railroad ferry with bodies of railroad carriages placed on its decks. The profile of such a wave is described by equations [13]

$$x = a + \mathrm{R}e^{kb}\sin(ka + \omega t),$$

$$z = b - \mathrm{R}e^{kb}\cos(ka + \omega t), \tag{3}$$

where a and b are the horizontal and vertical coordinates of the trajectory's center, along which a particle rotates that has current coordinates x and z; R is the radius of the trajectory, along which is a particle rotates; ω is the frequency of a sea wave; k is the frequency of trajectory of the disturbing effort.

The model takes into account that a railroad car is rigidly fixed relative to the deck and displaces along with it. We disregarded the impact action of sea waves on the railroad ferry's body with railroad cars lined up aboard it. It was taken into consideration that a train ferry is loaded with covered wagons utilizing their full capacity.

Our research was conducted for the case when railroad cars were transported by the railroad ferry "Geroi Shipki" along the Black Sea water area.

Differential equation (1) was solved applying the programming environment Mathcad [14, 15] by using a Runge-Kutta method.

It was established that at angular displacement of a train ferry with railroad cars lined up on its decks around the longitudinal axis, the maximal magnitude of acceleration was about 0.24 g. The magnitude of acceleration is given for the wagon, placed next to a gunwale, at the upper deck of the train ferry.

5. Determining strength indicators for the covered wagon's body when transported by a railroad ferry

To determine strength indicators of the covered wagon's body when transported by a railroad ferry, we built a spatial model in the programming environment SolidWorks. We selected as the basic structure a covered wagon of model 11-217. When building a model, we took into consideration elements of the body that rigidly interact, that is, the model disregarded mobile self-closing doors.

Calculation of strength was performed using a finite element method in the software package CosmosWorks.

The optimum number of elements in the finite-element model was determined using a graphic-analytical method. In this case, the number of grid elements amounted to 637,520, nodes – 225,092. The maximum size of the grid's element equals 100.0 mm, minimum – 20.0 mm, the maximum ratio between the sides of the elements is 525.19, the percentage of elements with the ratio of sides less than three is 11.1, exceeding ten – 46.7. The minimum number of elements in the circle is 22, the ratio of increasing the size of the element is 1.8, a model simplification factor in the regions where roundings and openings are located is 0.4.

Computer model of strength of the bearing structure of the covered wagon's body at angular displacements of the train ferry relative to the longitudinal axis is shown in Fig. 2.

When constructing a model of strength, we took into consideration the following loads: vertical static P_v^{st} and dynamic loads, a wind load on the lateral surface of the car's body, as well as loads that act on the body of the car through chain screeds P_{ch}. Because chain screeds have a spatial arrangement, the effort that will be transmitted to the bearing structure through them was then divided into three parts, with respect to the angles of location in space [16]. The model accounted for the fact that the body of the wagon is loaded with a conditional load using the full loading capacity.

The model was fastened in the zones where a bearing structure of the wagon rests against the running part, as well as bearing surfaces of mechanical stop-jacks. The material of the bearing structure of the wagon that we used was steel of grade 09G2S; values for its strength limit σ_L=490 MPa and yield strength σ_Y=345 MPa.

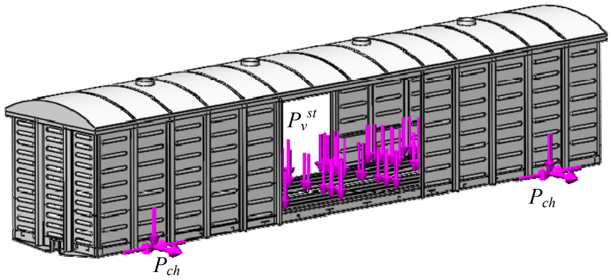


Fig. 2. Model of strength of the bearing structure of a covered wagon when transported by a railroad ferry

The results of calculating the strength of a covered wagon's bearing structure are shown in Fig. 3. Maximum equivalent stresses arise in the zones of interaction between the body (towing brackets) and chain screeds, and amount to about 360 MPa. That is, they are higher than the admissible for the grade of metallic structures' steel [17, 18].

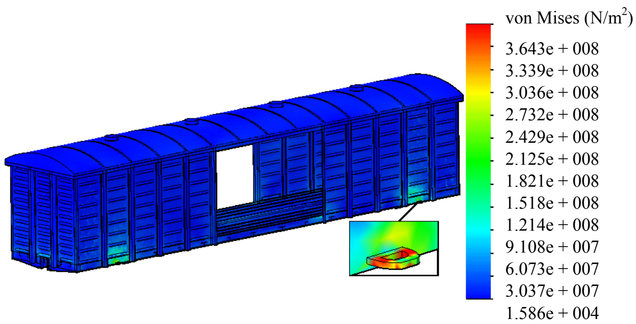


Fig. 3. Stressed state of the covered wagon's bearing structure when fixed relative to the deck using towing brackets

The maximum displacements amounted to about 11 mm, deformations – $1{,}196\cdot10^{-2}$.

That necessitates the improvement of the covered wagon body's bearing structure in order to ensure strength when transported by a railroad ferry.

6. Improvement of the covered wagon body's bearing structure in order to ensure strength when transported by a railroad ferry

To improve the efficiency of operation of railroad transport, we have developed a new design of the covered wagon, whose special feature is that the bearing elements are made from pipes of round section (Fig. 4). Such a technical solution made it possible to reduce the mass of the covered wagon tare by 4 % in comparison with a car-prototype while maintaining requirements for strength under conditions of operational loads [19]. In order to transport a covered wagon at a rail ferry, we propose the placement of nodes on its pivot beams for fixing it atop the deck (Fig. 5).

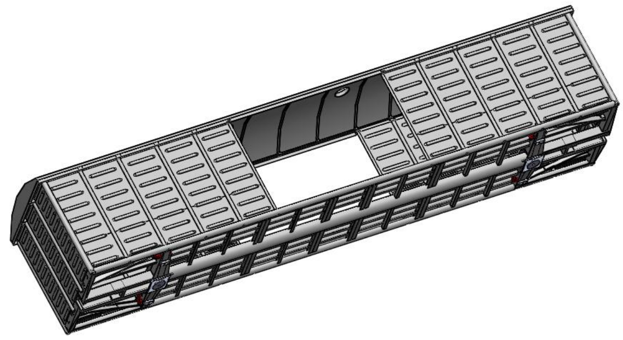
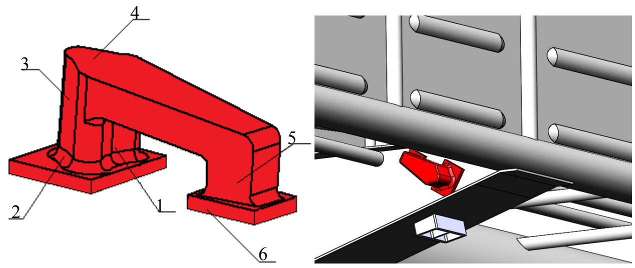


Fig. 4. Improved bearing structure of the covered wagon



a *b*

Fig. 5. A node to fix the hook of a chain screed: *a* — structural features; *b* — placement on the wagon; 1 — hook guide; 2 — radial rush; 3 — cylinder part; 4 — prismatic part; 5 — strengthening; 6 — supporting part

7. Computer simulation of the dynamic loading on a covered wagon's body when transported by a railroad ferry

In order to test the obtained magnitudes of accelerations, we performed computer simulation of the dynamics of the bearing structure of a covered wagon's body made from round pipes when transported by a railroad ferry. The study was conducted in the programming software CosmosWorks, version 2015. The calculation was performed using a finite element method.

When constructing a finite-element model, we used spatial isoperimetric tetrahedra. The finite elements used were the isoperimetric tetrahedra, whose optimal number was determined applying a graphic-analytical method. The number of the grid's elements was 1,723,354, nodes – 574,624. The maximum size of the grid's element equals 80.0 mm, minimum – 16.0 mm, the maximum ratio between the sides of the elements is 1,523.8, the percentage of elements with the ratio of sides less than three is 32.4, more than ten – 21.7. The minimum number of elements in the circle is 22, the ratio of increasing the size of the element is 1.8, a model simplification factor in the regions where roundings and openings are located is 0.4.

The model of strength of the covered wagon's bearing structure at angular displacements around the longitudinal axis is given in Fig. 6.

The model accounted for the load specified when calculating a standard structure of the covered wagon's body with respective numerical values.

The results of our study have shown that the maximum accelerations of the covered wagon's body occur in the middle parts of main longitudinal beams of the frame and amount to about 0.11 m/s^2 (Fig. 7, 8). Taking into consideration the component of a free fall acceleration, the maximal acceleration that acts on the covered wagon's body was 2.18 m/s^2 (0.22g).

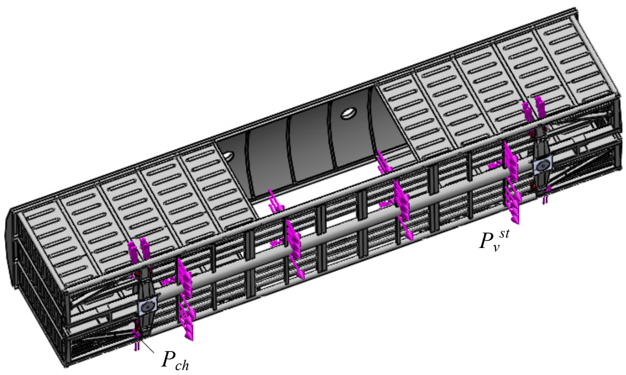


Fig. 6. Model of strength of the covered wagon's bearing structure

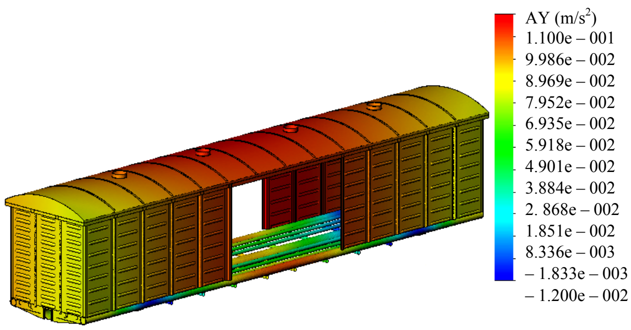


Fig. 7. Distribution of acceleration fields that act on the covered wagon body's bearing structure made from round pipes when transported by a railroad ferry (side view)

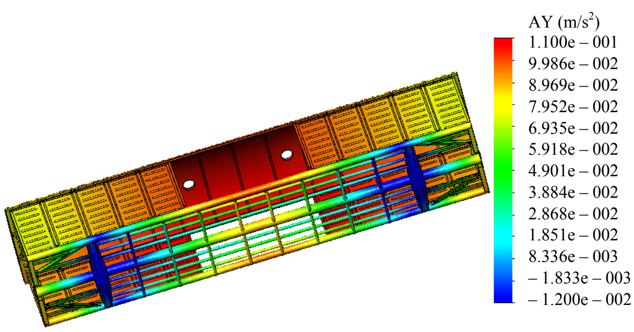


Fig. 8. Distribution of acceleration fields that act on the covered wagon body's bearing structure made from round pipes when transported by a railroad ferry (bottom view)

In the middle of a girder of the wagon's frame, the acceleration is about 0.1 m/s^2. The lowest acceleration magnitude was observed in regions where a body's bearing structure rests against the running part.

8. Verification of models of the dynamic loading on the covered wagon's body

In order to verify the models reported here, we used a Fisher criterion. The input variable in the mathematical and computer models of dynamic loading of the covered wagon's body when transported by a railroad ferry is the heeling angle in the interval from 5° to 20°; the output variable is the accelerations that occur in the covered wagon body's bearing structure.

It was established that the model under consideration is linear and describes a change in the accelerations of the covered wagon body's bearing structure made from round pipes due to a heeling angle of the train ferry (Fig. 9).

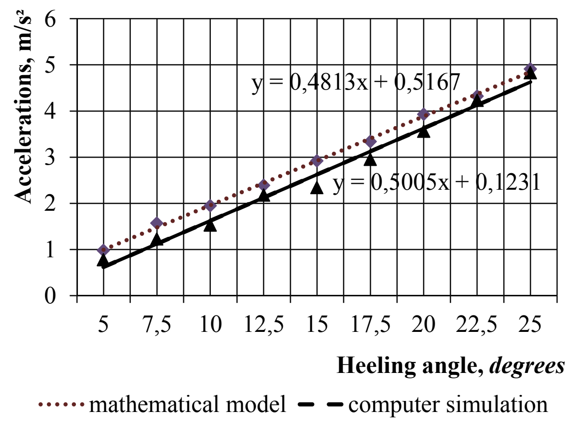


Fig. 9. Dependence of accelerations that act on the covered wagon's body on heeling angle of a train ferry

Results from determining the accelerations that are derived by simulating the dynamic loading on the covered wagon's body are given in Table 1.

Table 1

Numerical values for accelerations that act on the covered wagon body's bearing structure at oscillations of a train ferry

Heeling angle	Acceleration magnitude, m/s^2	
	Mathematical model	Computer simulation
5	0.98	0.78
7.5	1.57	1.23
10	1.95	1.53
12.5	2.39	2.18
15	2.92	2.34
17.5	3.34	2.95
20	3.93	3.56
22.5	4.32	4.23
25	4.91	4.83

In this case, the number of degrees of freedom at N=9 will equal f_1=7.

Calculation results have shown that at reproducibility variance S_r^2=2.48 and adequacy variance S_{ad}^2=7.94, the actual value for the Fisher criterion F_p=3.2, which is smaller than the tabular value for the criterion F_t=3.29. Thus, the hypothesis about the adequacy of the developed model is not challenged. An error of approximation in this case was 10.6 %.

9. Determining the strength of the covered wagon's body when transported by a railroad ferry

To determine the strength of the covered wagon's body made from round pipes, we used a finite element method.

The features related to constructing the model of the body's strength were specified above. Calculation results of strength are shown in Fig. 10, 11. The research conducted has made it possible to conclude that the maximum equivalent stresses arise in the zones of interaction between pivot beams and a girder and amount to about 280 MPa, which does not exceed the permissible ones in accordance with [17, 18].

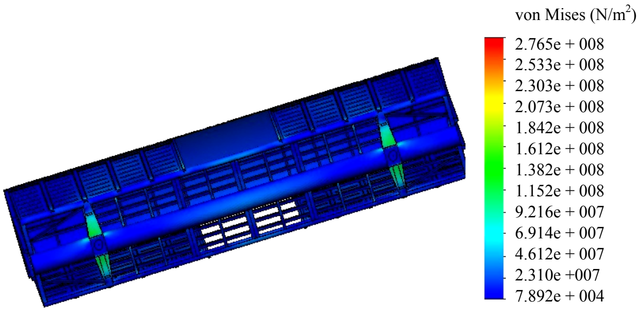


Fig. 10. Stressed state of the covered wagon's bearing structure at angular displacements around the longitudinal axis (bottom view)

Maximum displacements occur in the middle part of the main longitudinal beam of the frame from the side where chain screeds are placed, which pull under an angular displacement of the wagon's bearing structure and amount to 25.4 mm. Maximum deformations equaled $3.15 \cdot 10^{-3}$.

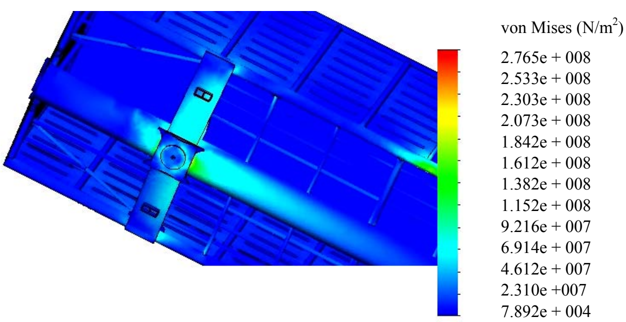


Fig. 11. Stressed state of the covered wagon's bearing structure in the zone of interaction between a girder and a pivot beam

Taking into consideration the fixation of the covered wagon's bearing structure relative to the deck by using the nodes that interact with the chain screeds, it becomes possible to reduce the maximum equivalent stresses in the zones where a body is fixed by nearly 20 %, compared with the case when it is fixed by towing brackets (Fig. 12).

To determine a projected term of service life of nodes for fastening chain screeds on a covered wagon when transported by a railroad ferry, we used a procedure described in [20]:

$$T_{dp} = \frac{\left(\sigma_{-1D} / [n]^m\right) \cdot N_0}{B \cdot f_d \cdot \sigma_{ds}^m}, \tag{4}$$

where σ_{-1D} is the average value for the limit of endurance in a part, MPa; n is the permissible coefficient of reserve strength; m is the indicator for a degree of the curve of fatigue; N_0 is the test base; B is a coefficient that characterizes duration of the object's continuous work in seconds; f_d is the effective frequency of dynamic stresses, s^{-1}; σ_{ds} is the amplitude of equivalent dynamic stresses, MPa.

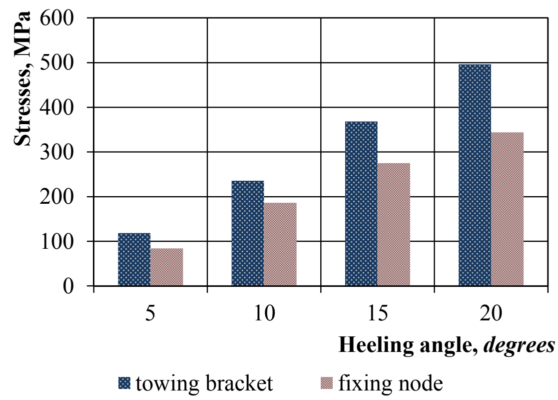


Fig. 12. Dependence of maximum equivalent stresses arising in the structural elements of the wagon's body that are used for fixing it relative to the deck on the heeling angle of a train ferry

During calculation, the average value for the limit of endurance in a node was determined to be $0.5\sigma_T$ of material (steel grade 09G2S). The test base was 10^7 cycles (a recommended test base for steel). Duration of continuous work of the node was $1.5 \cdot 10^6$ s. Effective frequency of dynamic stresses was determined based on the parameters for a disturbing action (a sea wave); for waves with a period of 9 s, it amounted to 0.1 s^{-1}. The accepted ratio of reserve strength is equal to 2. An indicator for a degree of the fatigue curve was accepted to be 4. The amplitude of equivalent dynamic stresses was determined based on the performed calculations for strength; it was about 150 MPa in accordance with [18, 19].

Based on the performed calculations, a projected service life of the node is about 5 years.

It should be noted that the determined term of service life of the fixing node would under actual conditions be longer because it is to be exposed to loading when a train ferry runs into a storm. Under normal conditions (movement in calm or at small waves), the node that fixes a railroad car relative to the deck would be loaded only by the effort related to pulling the chain screeds, which is about 54 kN.

In compliance with the appropriate system of maintenance and diagnosing, the established service life may be extended.

10. Discussion of results of determining the strength of a covered wagon's body when transported by a railroad ferry

The research that we conducted has made it possible to determine the refined value for a dynamic load acting on the bearing structures of covered wagons' bodies when transported by a railroad ferry. The resulting magnitude for the dynamic load is greater than the one that acts on railroad cars in operation along main tracks. This is explained by that the parameters for a disturbing action (a sea wave) on wagons' bodies when they are transported by a railroad ferry significantly exceed those that apply when they move along rails.

The development of a competitive environment in the market of transportation services predetermines the need for implementing highly effective rolling stock, which could be operated at interoperable transportation. In this case, the rolling stock that operates in the international railroad-water transportation, which is an important segment of interoperable deliveries, is not adapted to the assigned loading operational modes. That causes damage to its load-bearing structures and necessitates non-regular repair. Therefore, at the stage of wagon design, it is necessary to take into consideration the loads and schemes of their application, which are characteristic not only of basic operational conditions for loading, but that apply when transporting by railroad ferries. In addition, to ensure the safety of operation of the interoperable rolling stock, it is important to adapt it to the reliable interaction with the means of fixing it atop the decks of railroad ferries.

Given this, we performed mathematical modeling of the dynamic loading of a covered wagon body's bearing structure made from round pipes when transported by a railroad ferry. A special feature of the applied mathematical model is a possibility to determine dynamic loads that act on rolling stock during its transportation by railroad ferries with different technical characteristics. In addition, the model makes it possible to take into consideration different meteorological characteristics of railroad ferries water area, as well as the course angles of a wave relative to their bodies.

It is important to note that the proposed mathematical model does not account for possible own displacements of structural bodies of railroad cars relative to decks. Therefore, in the future, it is necessary to undertake an appropriate research with clarifications. In addition, an important stage in the development of research into this area is to take into consideration the meteorological characteristics for other water areas of railroad ferries, as well as their parameters.

Our research will contribute to the improvement of energy efficiency in the manufacture of covered wagons at railroad car production facilities, in order to reduce the costs of operation and maintenance, as well as to improve efficiency in the operation of covered wagons for international transportation.

11. Conclusions

1. We have developed an improved bearing structure of the covered wagon. A special feature of the wagon is that the bearing elements of the body are made from pipes of round cross section, which made it possible to reduce the mass of the covered wagon's tare by 4 %. To transport a wagon by a railroad ferry, it is provided with nodes for fixing the chain screeds.

We have determined the maximum acceleration magnitude that acts on the covered wagon body's bearing structure when transported by a railroad ferry. It was established that at angular displacement of a train ferry with railroad cars aboard it around the longitudinal axis, as the case of the largest loading of the structure, for a wagon, placed next to the gunwale, at upper deck, the magnitude of acceleration amounted to 2.4 m/s^2 (0.24g).

2. We have determined the maximum equivalent accelerations acting on the covered wagon body's bearing structure by using computer simulation. It was established that the maximum accelerations of the covered wagon's body occur in the middle parts of main longitudinal beams of the frame and amount to about 0.11 m/s^2 (0.01g); taking into consideration the component of a free fall acceleration, 2.18 m/s^2 (0.22g).

3. We validated the developed models using a Fisher criterion. Calculation results have shown that at reproducibility variance S_r^2=2.48 and adequacy variance S_{ad}^2=7.94 the actual value for a Fisher criterion F_p=3.2. Thus, the hypothesis about the adequacy of the developed model is not challenged. An error of approximation in this case was 10.6 %.

4. We have determined the maximum equivalent stresses arising in the covered wagon body's bearing structure when transported by a railroad ferry. It was established that the numerical value for stresses does not exceed the permissible and is about 280 MPa. The maximum magnitude of displacements at nodes of the wagon body's bearing structure car was 25.4 mm, deformation – $3.15\cdot10^{-3}$. It was found that by taking into consideration the fixation of the covered wagon's bearing structure atop the deck when using nodes that interact with chain screeds it becomes possible to reduce the maximum equivalent stresses in zones where the body is fixed by nearly 20 % compared with the case when it is fixed by towing brackets.

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