INVESTIGATION OF THE STRENGTH OF A CHAIN BINDER FOR SECURING A WAGON ON THE RAILWAY FERRY DECK

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Resume

The article presents the results of the strength analysis of the chain binder components for symmetry fixing a wagon on the railway ferry deck, taking into account the actual hydrometeorological conditions of the navigation area. The simulation of the wagon dynamic load during the railway ferry rolling was carried out to determine the loads acting on the chain binder. The strength of the chain binder hook was analysed. The calculation results showed that the maximum equivalent stresses in the hook occur in the radial part and exceed the allowable ones by 23%. Therefore, to ensure the strength of the chain binder, it is necessary to comply with the appropriate roll angles of the railway ferry or create measures to reduce its load when rolling. The conducted studies will contribute to ensuring the safety of wagon transportation by sea and increasing the efficiency of rail-ferry transportation.

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1 Introduction

Ensuring the efficiency of the functioning of the transport industry leads to the need to introduce intermodal transport systems into operation. One of the most successful among these is rail-ferry transportation [1], which has become used in countries that have access to international traffic through sea areas. A feature of these transportations is the possibility of wagon transport by sea on special ships, which are railway ferries equipped with the appropriate infrastructure.

The wagon is fixed by using chain binders to ensure its stability on the railway ferry deck (Figure 1).

Eight chain binders per wagon are used. A typical design of a chain binder for fastening a wagon on the railway ferry deck is shown in Figure 2 [2].

For fastening, one end of the chain binder using a hook 2 is attached to the wagon structural element 1, and the other end is attached to the deck eye bolt (Figure 3, a). The tension of the chain binder is provided by using a pneumatic gun (Figure 3, b). The tensile force of the chain binder is about 5 tons.

In order to effectively secure the wagon on the deck, chain binders are spatially located relative to the body (Figure 4) [3].

Chain binders must meet strength conditions in order to ensure reliable fastening wagon on the deck. One of the most important components of the binder is the hook for fastening the wagon and the chain. Under the conditions of alternate stresses caused by oscillation of a railway ferry during sea disturbance, damage to the chain binder hook occurs, in particular, deformations and cracks. Mostly cracks occur in the zone of interaction between the hook eye and the shackle (Figure 5) or in the zone of the radial tide. When we speak about the chain, the most common damage is its break.

This circumstance contributes to the violation of the wagon stability on the deck and threatens the safety of the railway ferry movement. It is important to say that the violation of the vehicles fastening has repeatedly become the cause of the sea craft wreck. For example, the wreck of the railway ferry Mercury - 2 in 2002

(a)

(b)

Figure 1 *Fastening the wagon on the railway ferry deck: (a) by the bottom rail of the side wall; (b) by the towing shackle*

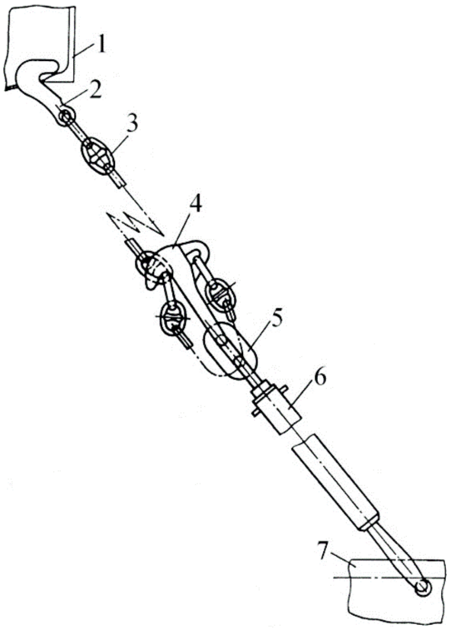

Figure 2 *Chain binder in working position: (1) is a wagon frame; (2) is a hook; (3) is a stud chain; (4) is a claw hook; (5) is an enlarged link; (6) is a turnbuckle; (7) is an eye bolt fixed on the deck*

(a)

(b)

Figure 3 *Means of fixing the lashing chain: (a) the deck pad-eye; (b) the pneumatic ratchet*

was caused by a violation of the tank wagon stability on the deck during a storm in the Caspian Sea [4]. In prior years, namely, on December 8, 1966, as a result of unreliable fastening on the Greek ferry ship Heraklion, the refrigerator trailer broke off and damaged the ferry gate, through which water began to flow onto the cargo deck. In a matter of minutes, the ship lost its stability, overturned and sank. The tragedy occurred in the Mediterranean Sea during a storm [5].

In this regard, it is important to determine the actual conditions under which the strength of chain binders for securing wagons on railway ferries is ensured. This will help to ensure the safety of carriages by sea and increase the efficiency of rail and ferry transportation.

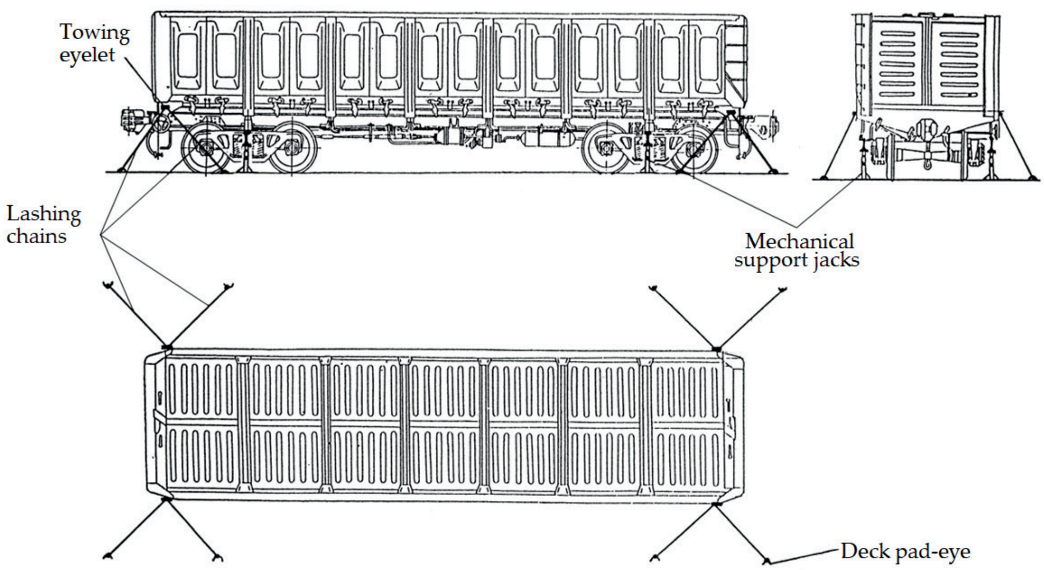

***Figure 4** Scheme of fixing the wagon on the railway ferry desk*

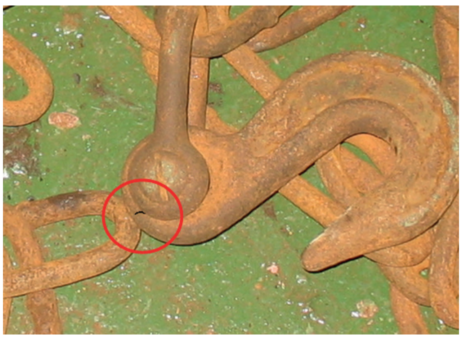

***Figure 5** Crack in chain link hook*

2 Analysis of recent research and publications

The issue of determining the load of reusable fastening means is covered in a book [2]. The author proposed a simplified method for calculating the means of fastening wagons on railway ferries. When determining the chain binder strength, classical formulas of strength of materials, which allow obtaining the stress in an uniaxial stress state, are used. It is important to say that this method is quite simplified and does not allow to investigate stress concentrators in the components of the hook of the chain binder.

In the paper [6] Zemlezin gave a method for calculating the forces acting on the wagon bearing structure during transportation by railway ferry. When doing this, the author considered the disturbing effect in the form of a plane wave, which is described by the harmonic law. However, the paper did not investigate the strength of the means of fixing the wagons on the decks.

The load of vehicle bearing structures during transportation by railway ferries are modelled in publications [7-9]. The specified value of the dynamic load acting on them during the oscillations of the railway ferry was determined. The stability of the vehicles was studied, taking into account the typical interaction with the deck. Along with this, the authors did not make the strength analysis of chain binders for securing vehicles on decks.

The results of mathematical modelling of the load of the rigging lines for containers fastening on the deck are presented in [10]. Forces at the points of their interaction with containers are calculated. Forces and moments are obtained taking into account different schemes for rigging lines. However, the above methodology applies to metal cables and cannot be used to calculate chain binders.

The author proposed elements of calculation models for different methods of fastening cargo placed on semi-trailers in the paper [11-12]. Calculations were made in accordance with the requirements of the XL Code. The results of the analysis of transport security management are given. At the same time, the given method cannot be used to determine the strength of chain ties of railway ferries.

The issue of increasing the level of reliability of fastening military wheeled vehicles on a railway flat wagon by using improved technical means is carried out in a paper [13]. The design features of a reusable tension cable are described. However, when designing this cable, the loads that may act on it during the transportation

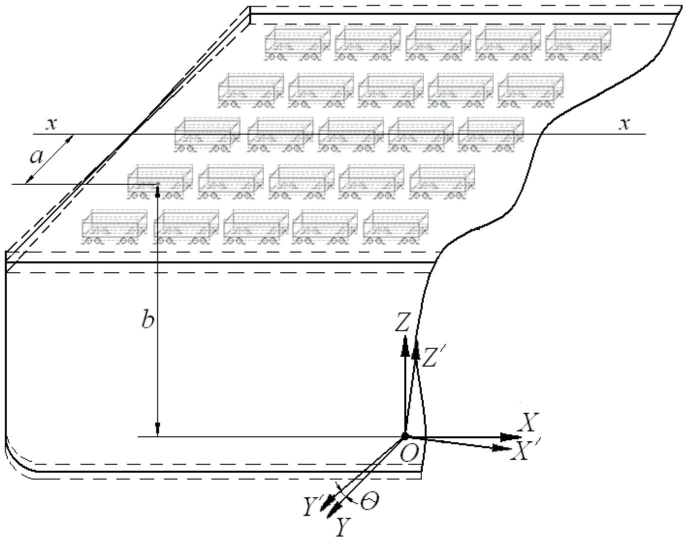

Figure 6 *Movement of a railway ferry with wagons during rolling motion*

of goods by rail are taken into account. That is, it is not suitable for securing cargo on decks during sea transportation.

Calculation of marine fastenings of a container crane for the transportation of heavy cargo is carried out by the authors in [14]. The highest stress fields in the crane structure are determined and, taking this into account, the places of its fastening are chosen. The calculations confirmed the possibility of its fastening, taking into account the proposed scheme. However, the authors focused on determining the strength of the crane, and not the means of its fastening.

The publication [15] presents the results of determining the forces acting on the container and means of securing during maritime transportation. Solutions are proposed for optimal fastening of containers on deck in terms of ensuring the safety of their transportation by sea. At the same time, certain forces are not taken into account for strength calculation of the means of securing containers on the deck during vessel oscillations.

The dynamic load of the wagon bearing structures during transportation on rail ferries was determined in papers [16-17]. The main strength characteristics of wagon bodies are determined in the course of their interaction with the fastening means on the decks. It is proposed to improve the wagon bearing structures to ensure the reliability of their fastening. At the same time, the author did not calculate the strength of the fastening means, taking into account their interaction with improved wagon designs during railway ferry oscillations.

The manuals [18-21] contain features of the placement, fastening and loading of car-goes on the railway ferry decks, which are operated in the Black Sea. Possible schemes of cargo fastenings are given. The strength conditions of reusable fasteners are mentioned. However, these regulatory documents do not provide methods for strength calculation of the fastening means in the conditions of railway ferry rolling.

An analysis of literature sources [2-21] allows us to conclude that the issues of strength calculation of the means of wagon fastening on the railway ferry decks have not been given due attention. Therefore, there is a need for research in this direction.

3 The aim and main objectives of the article

The aim of the article is to determine the strength of the main components of a chain binder for symmetry fastening a wagon on the railway ferry deck, taking into account the actual hydrometeorological conditions of the navigation area. To achieve the goal, the following tasks are defined:

- to investigate the dynamic load of the wagon during transportation by rail ferry to determine the actual loads acting on the chain binder;
- to conduct the strength analysis of the chain binder hook;
- check the strength of the binder chain.

4 Investigation of the dynamic load of a wagon during its transportation by the railway ferry

To determine the actual values of the loads perceived by the chain binder in storm conditions, mathematical modelling of the dynamic load of the wagon during the railway ferry rolling motion has been carried out in the case of the highest load of its structure (Figure 6) [22].

The differential equation, which describes the movement of a wagon placed on the deck of a railway ferry during its roll, has the form in Equation (1)

$$\left(\frac{D}{12\cdot g}\left(B^2+4z_g^2\right)\right)\cdot\ddot{q}+\left(\Lambda_\theta\cdot\frac{B}{2}\right)\cdot\dot{q}= p'\cdot\frac{h}{2}+\Lambda_\theta\cdot\frac{B}{2}\cdot\dot{F}(t), \tag{1}$$

where $q=\theta$ is a generalized coordinate corresponding to the angular movement of a railway ferry with wagons around the longitudinal axis. The origin of the coordinate system is located at the mass center of the railway ferry.

D is weight water displacement; *B* is the width of the railway ferry; *h* is the height of the railway ferry board; Λ_θ is a coefficient of resistance to of the railway ferry motion; z_g is a coordinate of the railway ferry gravity center; *p'* is a wind load; and *F(t)* is the law of action of the force that disturbs the motion of a railway ferry with wagons placed on its deck.

Equation (1) is a second order equation for non-conservative systems.

When doing this, the law of a sea wave motion is considered in the form of a trochoidal curve [23]:

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

where *a* and *b* are the horizontal and vertical coordinates of the center of the trajectory along which the particle rotates, which currently has x and z coordinates; R is the radius of the trajectory along which the particle rotates; ω is the sea wave frequency; k is the frequency of the disturbing force trajectory.

When compiling the mathematical model, it was taken into account that the wagon body is rigidly and symmetry fastened on the deck and moves with it. The shock effect of sea waves on the hull of a railway ferry with wagons placed on its board was not taken into account [24].

Input parameters to the mathematical model are geometric characteristics of the railway ferry and hydrometeorological characteristics of the Black Sea water area. The model also took into account different angles on the bow of the wave χ in relation to the railway ferry body [18].

To solve the mathematical model, a calculation program was created in the environment of the Mathcad, for what it was reduced to the Cauchy normal form, and then integrated according to the Runge-Kutta method [25-28]. The initial conditions were assumed to be zero [29-30]. The obtained results are given in Figure 7.

The largest acceleration, which acts relative to the standard place of the wagon on the deck, occurs at χ° and is 0.4 m/s². Accelerations are given for wagons placed on the last track from the bulwark of the railway ferry upper deck.

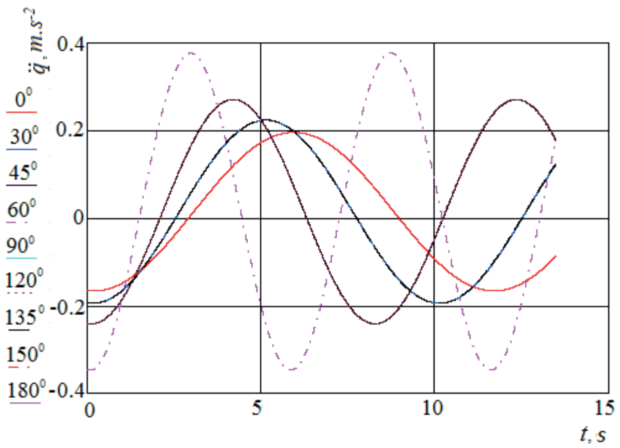

Figure 7 *Acceleration of the wagon during railway ferry rolling motion*

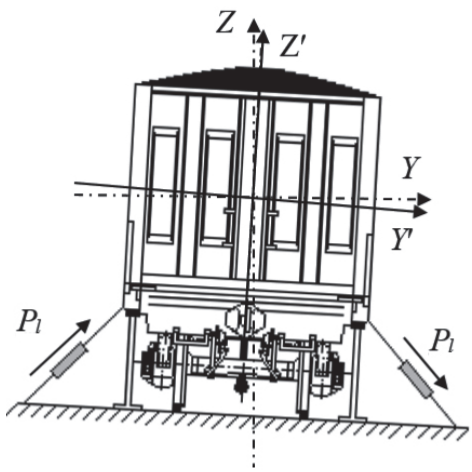

Figure 8 *The scheme of chain binder operation in the case of railway ferry rolling motion*

The total amount of acceleration acting on the wagon is the sum of the accelerations on its regular place on the deck, as well as the horizontal component of the acceleration of free fall due to the railway ferry roll angle. The roll angle was 12.2° based on the manual [3], for the case of static wind action on the surface projection of a railway ferry with wagons placed on its upper deck and the hydrometeorological conditions of the Black Sea water area. Taking this into account, the total acceleration acting on the wagon farthest from the bulwark is equal to 2.47 m/s^2 (0.25g). The obtained acceleration value is considered when determining the dynamic loads acting on the chain binder. The calculation was carried out under the condition of fixing the open wagon model 12-757 with chain binders. The total value of the dynamic load acting on it is equal to 208.96 kN. Therefore, 52.24 kN falls on one binder during the railway ferry rolling motion.

The total load perceived by the binder also takes into account the load from its tension. That is, in the case of rolling motion of the railway ferry, the chain binders will tense on one side of the wagon, and will be destressed on the other side (Figure 8).

Then the total value of the load on the chain binder from the side of its tension is equal to 101.3 kN.

Table 1 *The main technical characteristics of the hook*

Parameter	Value
Allowable load (kN)	80
Material of manufacture	Steel 20MnCr5
Diameter of the hole for the bracket (mm)	25
Mass (kg)	1.3

Table 2 *The main properties of the hook material*

Parameter	Value
Modulus of elasticity (Pa)	$2.1 \cdot 10^{11}$
Poisson‘s ratio	0.28
Shear modulus (Pa)	$7.9 \cdot 10^{10}$
Mass density (kg.m^{-3})	7800
Tensile strength (Pa)	1100825984
Yield strength (Pa)	750000000

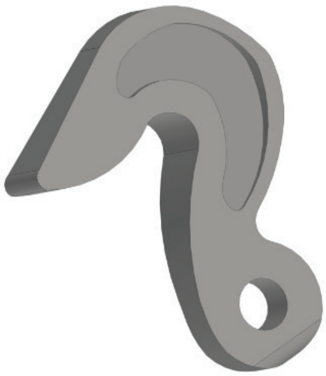

Figure 9 *Spatial model of the chain binder hook*

Figure 10 *Finite element model of the hook*

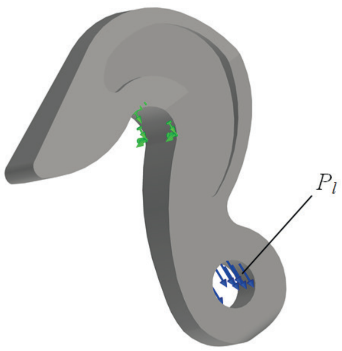

Figure 11 *Calculation scheme of the hook*

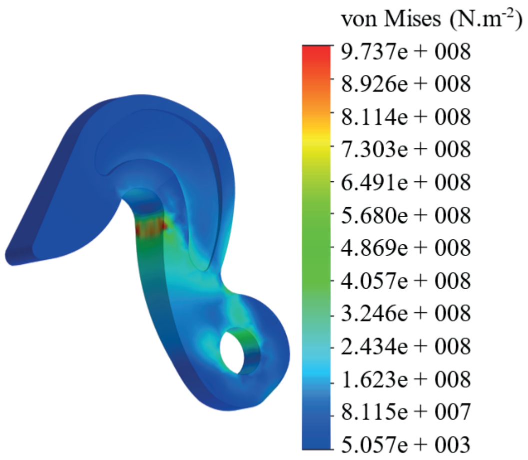

Figure 12 *The stress state of the hook*

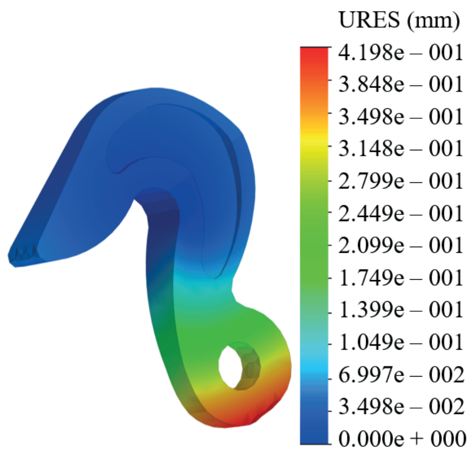

Figure 13 *Displacements in hook nodes*

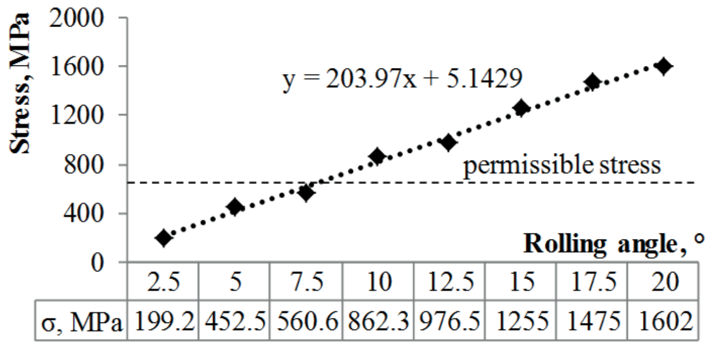

Figure 14 *Dependence of stresses in the hook of the chain tie on the railway ferry rolling angle*

5 The strength calculation of the chain binder hook

The load obtained in the previous section of the article is considered when calculating the strength of the chain binder hook. The calculation was carried out using the finite element method in the SolidWorks Simulation software.

The spatial model of the hook was built in accordance with the album of drawings of reusable railway ferry fastening means (Figure 9). Solid modeling was made in the SolidWorks software [31-34].

The main technical characteristics of the hook are summarized in the Table 1.

It is important to note that the load on one binder, which is equal to 80 kN, is determined from the strength conditions of the wagon frame items.

Isoparametric tetrahedrons were used in the building of the hook finite element model (Figure 10). The mesh was created based on curvature. The optimal number of tetrahedrons was calculated by using the graphic and analytic method [35-37]. The mesh contained 74647 elements and 14985 nodes. The maximum size of the mesh element is 3.2 mm, and the minimum size is 1.1 mm. The number of elements in the circle was 8. The ratio of the increase in the element size is 1.5.

The calculation scheme of the hook is shown in Figure 11. The longitudinal load P_l was applied to its bridge. Its fastening was carried out behind the work surface. In this case, hard clamping was used. The main properties of the hook material, steel 20MnCr5, are given in Table 2. The material was considered as linear isotropic.

The calculation was made according to the Mises criterion (energy theory of strength). The calculation results are shown in Figures 12 and 13.

The obtained results allow us to conclude that the maximum equivalent stresses in the hook occur in the radial part and amount to about 973.7 MPa. That is, they exceed the allowable ones by 23%. In this case, the allowable stresses for a hook made of 20MnCr5 steel are 750 MPa. This stress value is taken from the technical data sheet for the chain binder.

The maximum displacements in the hook take place in the zone of the bridge and are equal to 0.4 mm.

On the basis of variational calculations, the permissible rolling angle of the railway ferry has been determined from the point of view of ensuring the hook strength (Figure 14). This angle is about 9°.

Table 3 *The main technical characteristics of the binder chain*

Parameter	Value
Diameter of the ring bar (mm)	14
Manufacturing material	Steel 20MnCr5
Total length including hook (m)	2.5
Allowable load (kN)	80
Weight (kg)	11

6 The binder chain strength test

To ensure the strength of the chain, the condition [38] must be satisfied:

$$n = \frac{S_{cr}}{S_c} \geq [n], \quad (3)$$

where S_{cr} is the critical load of the chain, kN; S_c is the calculated chain load, kN; *[n]* is the safety factor of the chain.

The main technical characteristics of the chain are listed in Table 3.

Taking into account the fact that S_c = 101.3 kN and S_{cr} = 80 kN, the safety margin of the chain is less than 1. Therefore, the strength of the binder chain is not provided.

Therefore, in order to ensure the strength of the chain binder, it is necessary to comply the appropriate rolling angles of the railway ferry or to create measures to reduce its load during rolling motion.

The conducted studies will contribute to ensuring the safety of wagon transportation by sea and increasing the efficiency of railway and ferry transportation.

7 Conclusions

1. The dynamic loading of the wagon during its transportation by railway ferry was studied to determine the actual loads acting on the chain binder. It has been established that the total value of the acceleration acting on the wagon furthest from the bulwark is equal to 2.47 m.s^{-2} (0.25g). The obtained acceleration value was taken into account when determining the dynamic loads acting on the chain binder. Taking into account the calculations, the total value of the load acting on the chain binder from the side of its tension is equal to 101.3 kN.
2. The strength of the chain binder hook has been calculated. The maximum equivalent stresses in the hook occur in the radial part and are about 973.7 MPa, which exceed the permissible ones by 23%. The maximum displacements in the hook occur in the zone of the bridge and are equal to 0.4 mm. The admissible railway ferry rolling angle at which the chain binder strength is ensured has been determined. This angle is about 9°.
3. The strength of the binder chain was tested by comparing its critical load with the calculated one. In this case, the safety margin of the chain is less than 1. Therefore, the binder chain strength is not observed.

In order to ensure the strength of the chain binder, it is necessary to comply the appropriate railway ferry rolling angles or to create measures to reduce its load in the case of rolling motion.

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Conflicts of 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.

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