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DETECTING THE INFLUENCE OF UNEVEN LOADING OF THE BRAKE SHOE IN A FREIGHT CAR BOGIE ON ITS STRENGTH

The object of the study is the processes of occurrence, perception, and redistribution of loads in the brake shoe of a freight car bogie during braking. In order to ensure the safety of the movement of freight cars, a study of the uneven load on the bogie shoe of the model 18-100 freight car was carried out. A mathematical apparatus was built to determine the strength of the brake shoe, taking into account the uneven load transmitted to it from the brake pad. In this case, the brake shoe was considered in the form of a frame with variable stiffness. It was established that the stresses that occur in the shoe exceed the permissible ones. To test the proposed mathematical apparatus, a computer simulation of the strength of the brake shoe was carried out. In this case, the finite element method, which is implemented in SolidWorks Simulation, was used. The difference between the results obtained by mathematical modeling and computer simulation was 5.7 %.

A feature of the research results is that they make it possible to determine the moment of resistance, and accordingly, the stresses that act in the shoe along its length. This will make it possible to design its fundamentally new structure at the subsequent stages.

The field of practical application of the reported results is the engineering industry, in particular, railroad transport. The conditions for the practical application of the research results are to ensure the strength of the shoe during braking of the rolling stock in operation.

The study will contribute to advancements in improving the reliability of the braking systems of bogies, as well as ensuring the manufacturability and maintainability in the construction, operation, and repair of the components of the mechanical part of brakes for the new generation freight cars

Keywords: freight car, brake shoe of a car, stressed state of the shoe, transport mechanics, traffic safety

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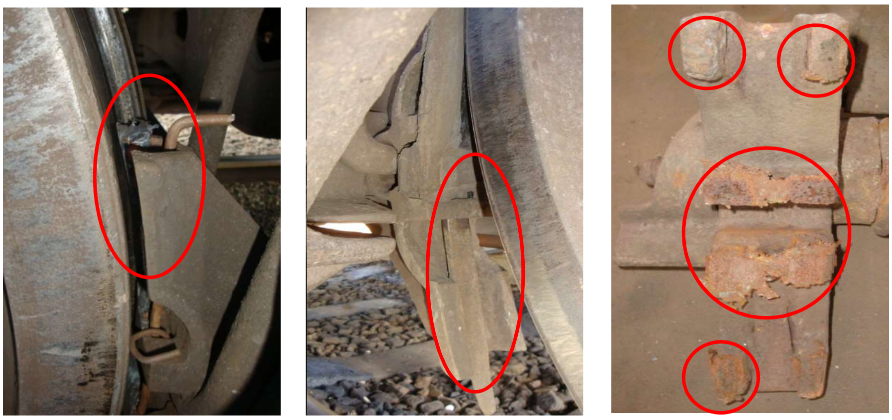
1. Introduction

The development of railroad transport under the current conditions of a competitive environment requires the creation of prerequisites for the improvement of its components [1–3]. In this case, special attention should be paid to the mechanical part of brakes, as one of the most responsible from the point of view of traffic safety. It is important to say that the uneven wear of brake pads exerts a significant impact on the efficiency of rolling stock brakes. In turn, this affects the strength of the shoes in which they are fixed.

When braking, the contact forces of pressure on unevenly worn pads are distributed eccentrically along the reduced braking friction area; because of this, significantly greater frictional forces are concentrated on unevenly worn parts of the pads and intense frictional heat generation is concentrated. This circumstance becomes the reason for the destruction of the pads under the conditions of operation of freight cars and leads to both damage to the brake shoes and the occurrence of malfunctions on the rolling surfaces of wheels due to contact with the brake shoes.

The well-known practice of operational research indicates that about 8 % of shoes have corresponding damage during operation. Some cases of destruction, which were recorded during field studies of bogies of freight cars equipped with composite pads, are shown in Fig. 1.



a *b* *c*

Fig. 1. Damage to brake shoes: *a* — the absence of a brake pad due to its destruction; *b* — shoe damage to the rolling surface of the wheel because of the destruction of the pad; *c* — destruction of the platform of the shoe to transfer the load to the pad due to its absence and contact with the wheel

In this connection, there is a threat to the safety of the movement of the carriage in the train. This can contribute to the emergence of environmental hazards in the case of transportation of hazardous goods. Therefore, there is a need to study the strength of brake shoes under uneven loading from composite pads. Thus, research into the development of innovative methods for calculating components of the mechanical part of bogie brakes is relevant.

2. Literature review and problem statement

The issue of improvements to the elements of brake lever gears (BLG) to ensure traffic safety and reduce operating costs for their maintenance is considered in a significant number of scientific works. So, for example, in [4], a study of tests of industrial railroad freight rolling stock was carried out regarding the assessment of braking efficiency, as well as structural and dynamic analysis of the mechanisms of the braking system. They involved determining the empirical dependence of the friction coefficients of the tribotechnical pair "brake pad – wheel" depending on the initial parameters during braking. However, the authors did not take into account the load transfer from the brake shoe, which causes uneven wear of the brake pads of industrial railroad rolling stock. It should be noted that this phenomenon affects both the strength of the shoes and the evaluation of braking efficiency.

In [5], a study of the design features of modern rolling stock brakes was carried out. The main factors affecting the evaluation of brake performance were considered. The temperature load on the components of tribotechnical pairs during train braking was determined. However, the authors did not take into account the influence of the uneven transfer of the load from the shoe to the block, which leads to abnormal wear of blocks and causes surface defects of the wheels.

The scientific approach of experimental studies into the mechanical brake system of freight rolling stock is covered in [6]. It is proposed to apply an information model in the form of a differential equation of motion of a freight car during the study of braking processes. Mathematical models are also given that take into account the main characteristics of the braking system, which make it possible to estimate the braking efficiency of the train. However, in the cited work during the performance of brake calculations, the peculiarities of the load transfer from the shoe to the pad were not taken into account, which causes their abnormal wear.

In [7], the issue of increasing the efficiency of brakes of a hopper car is considered. The task is solved by improving the design of BLG. The measures were substantiated and optimization of the design of the lever transmission elements was carried out using the Solid Edge Siemens PLM Software complex. However, the effective operation of BLG depends on the load transfer in the kinetostatic nodes, which, depending on the amount of braking, constantly increase, which leads to an uneven transfer of the load from the shoe to the pad. It should be noted that the authors did not take this factor into account, and the calculation was performed only for the combined operation of the levers with the brake cylinder.

In studies [8, 9], aimed at the introduction of innovative materials in the structures of tribotechnical units, the effectiveness of their use in modern rolling stock is justified. Using them, one can increase the speed of the train, the load on the axle, the efficiency of the braking system, etc. But, in this case, there are a number of problematic issues related to the uneven transfer of the load from the shoe, which is caused by increased gaps in the kinetostatic nodes from wear. Thus, the problems associated with uneven wear of pads, which leads to their destruction and causes contact of the shoe with the wheel during braking, are quite important [10]. Therefore, in this area, work related to the modernization of the BLG elements of wagons is being carried out in order to guarantee the safety of traffic on railroad transport.

Paper [11] reports the results of research aimed at eliminating angular movements of the brake cylinder rod. Measures have been devised to improve the brake cylinder by changing its design, which makes it possible to prevent the movement of the rod at its maximum output. The proposed structural improvements of the brake cylinder are justified by strength calculations. However, the authors did not consider the issue of transferring the unevenly distributed force of the shoe to the pad, which causes their uneven wear and the effect of this phenomenon, both on the strength of the shoes and on the output value of the brake cylinder rod.

The research reported in [12, 13] is aimed at analyzing the operation of tribotechnical assemblies and justifying the introduction of promising materials in their structures. Due to such decisions, the speed of trains increases significantly, the load on the axle of the car increases significantly. The resource of tribotechnical parts – brake pads and linings - also improves, as well as the operation of the braking system of rolling stock. However, there are a number of problematic issues due to the strength of the brake shoes, which relate to uneven wear of composite brake pads in freight trains. Thus, the problems associated with uneven wear of elements of tribotechnical units of freight cars need to be solved [14, 15].

Our review of the literature [4–15] allows us to conclude that the issues of researching the strength of brake shoes, including taking into account their uneven load, have not been considered properly so far. Therefore, there is a need to conduct studies into this area.

3. The aim and objectives of the study

The purpose of this study is to identify the impact of uneven loading of the model 18-100 bogie shoe on its strength. This will contribute to devising the recommendations for calculating modern structures of the components of the mechanical part of brakes of freight cars and for ensuring the movement safety of trains.

To achieve this goal, the following tasks are set:

– to build a mathematical apparatus for determining the strength of a brake shoe when it is unevenly loaded;

– to investigate stress distribution fields in the brake shoe when it is unevenly loaded.

4. The study materials and methods

The object of our study is the processes of occurrence, perception, and redistribution of loads in the brake shoe of a freight car bogie.

The main hypothesis of the study assumes that the uneven wear of brake pads of freight cars affects the strength of the brake shoes during braking [16].

The following hypotheses and simplifications were formulated to determine the main indicators of shoe strength:

1. The effort from the shoe to the pad when calculating its strength is transmitted in the form of a concentrated force applied in the middle of the contact between the shoe and pad.

2. Since the stiffness of the shoe is high, it can be assumed that the pressure from the shoe on the pad coincides with the directions of the radii of the pad at the points of contact between the shoe and pad.

3. The extreme supports of the shoe are represented in the form of hinged movable supports.

4. Since the cross-section is not constant along the length of each side of the frame, the cross-section with minimum stiffness is used for the calculation.

5. Since the slight curvature of the shoe is less than 0.2, the calculation is performed similarly to an ordinary flat frame.

6. At the moment of braking, the shoe turns into a statically indeterminate system.

In accordance with the "Instructions for the operation of rolling stock brakes on the railroads of Ukraine. TST-TSV-TSL-0015 (Department of locomotive management-department of wagon management-department for organization of domestic and international passenger transportation-0015)", effort from the triangle to the shoe is transmitted in the form of a concentrated force equal to F=41.7 kN at an angle of 10° to the axis of symmetry of the shoe. The effort from the shoe to the pad, in accordance with hypothesis 2, is transmitted in the form of concentrated forces at the points of contact between the shoe and pad (points A, B, C, D) (Fig. 2). The frame is a doubly statically indeterminate system (Fig. 3) [17]. In this case, the main system is shown in Fig. 4.

It is taken into account that the direction of the frame racks in the direction of the radii at the contact points of the shoe and pad corresponds to the pressure of the shoe on the pad.

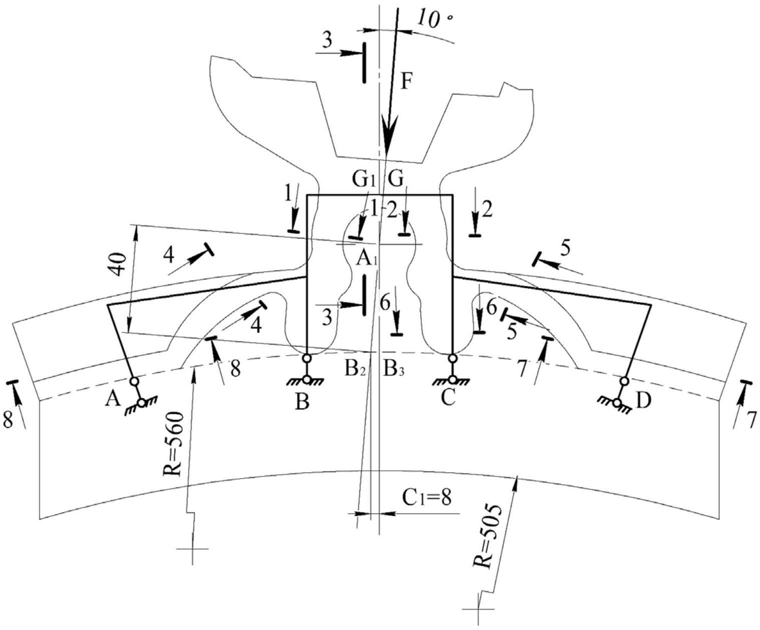


Fig. 2. Shoe-to-pad load transfer diagram (mm)

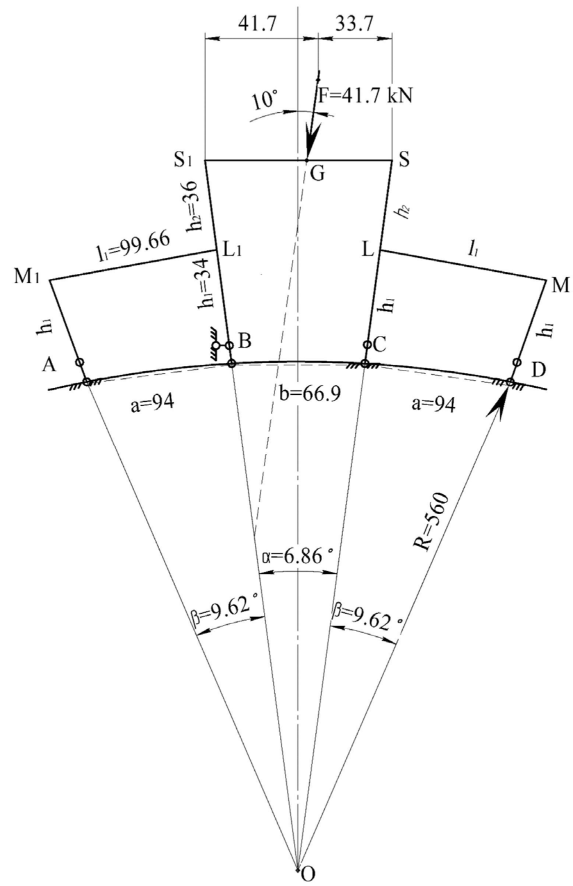


Fig. 3. Estimated shoe diagram (mm)

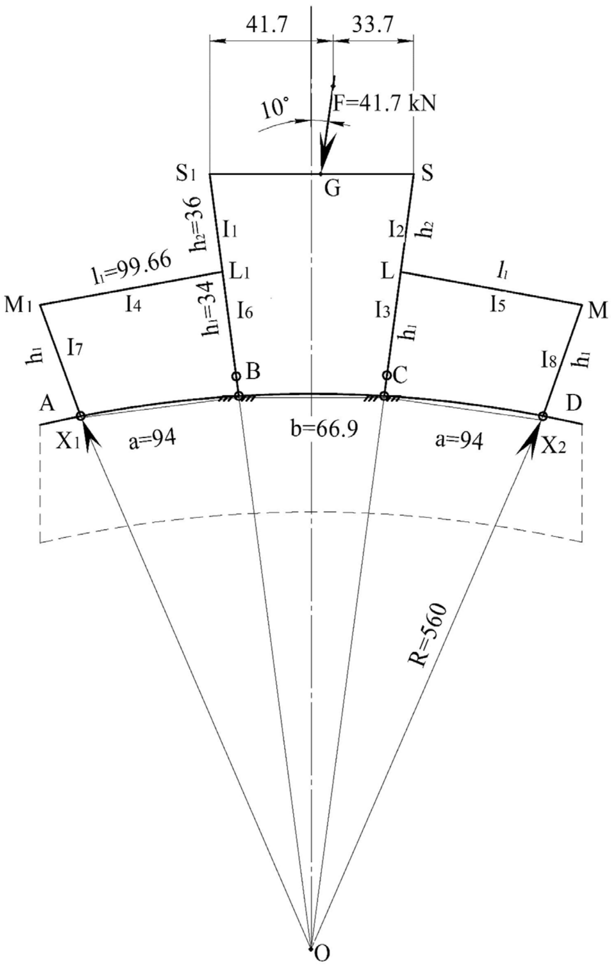


Fig. 4. Core system (mm)

The shoe is a frame with variable stiffness. Therefore, the minimum stiffness is adopted in each section of the calculation scheme [17, 18].

This system is statically indeterminate. The force method was used to solve the static uncertainty.

For a doubly statically indeterminate system, the canonical equations are:

$$\delta_{11}X_1+\delta_{12}X_2+\Delta_{1F}=0, \quad (1)$$

where δ_{ik} is the unit coefficient of the canonical equation, which determines the movement in the direction of the i-th unknown caused by the k-th unknown; ΔiF – movement in the direction of the i-th unknown caused by the action of an external load:

$$\delta_{21}X_1+\delta_{22}X_2+\Delta_{2F}=0. \quad (2)$$

The coefficients of the canonical equations are determined by the Mohr integral as follows:

$$\delta_{ik}=\sum\int\frac{\bar{M}\cdot\bar{M}_k}{EI}\mathrm{d}x, \quad (3)$$

$$\Delta_{iF}=\sum\int\frac{\bar{M}\cdot M_F}{EI}\mathrm{d}x. \quad (4)$$

It is convenient to determine these integrals in a graphoanalytical way, without using the Simpson-Kornaukhov rule. For this purpose, it is necessary to construct the curves of the bending moments from the unknowns, equal to unity and the external load.

5. Results of detecting the impact of uneven shoe loading on its strength

5. 1. Construction of a mathematical apparatus for determining the strength of the brake shoe when it is unevenly loaded

Based on our calculations, single diagrams were constructed, shown in Fig. 5.

In order to determine the load coefficients of the canonical equations, the diagrams of bending moments from the external load F=41.7 kN were constructed (Fig. 6).

According to the diagrams $\bar{M}_1$ and $\bar{M}_1$ the coefficients of the canonical equations are equal to:

$$\delta_{11}=\sum\int\frac{\bar{M}_1^2}{EI}\mathrm{d}x=\frac{591252}{I}, \quad (5)$$

$$\delta_{12}=\frac{14067}{I}, \quad (6)$$

$$\delta_{22}=\frac{250755}{I}. \quad (7)$$

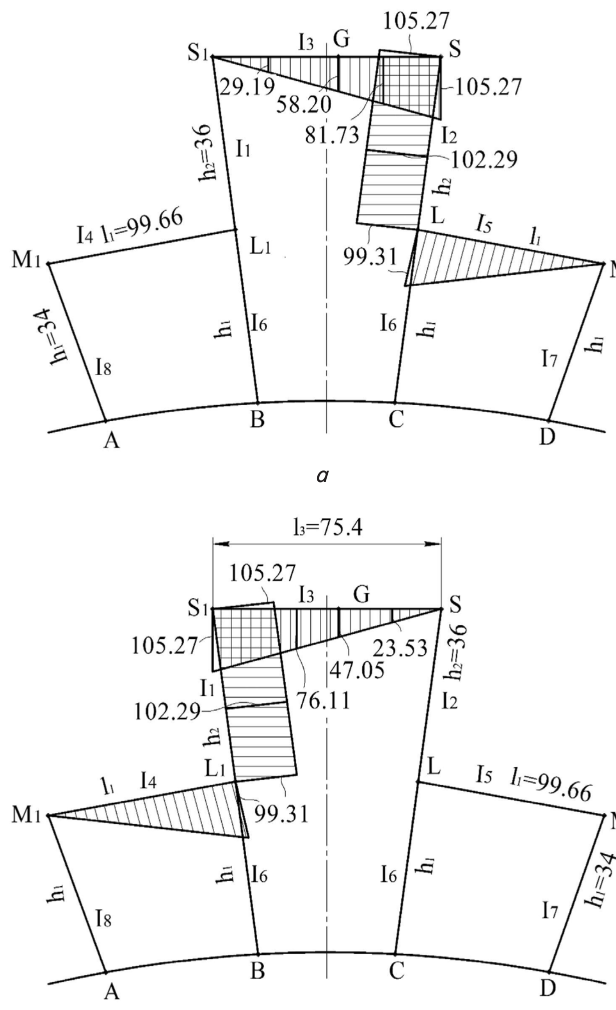


Fig. 5. Single moment diagrams: *a* – $\bar{M}_1$; *b* – $\bar{M}_2$

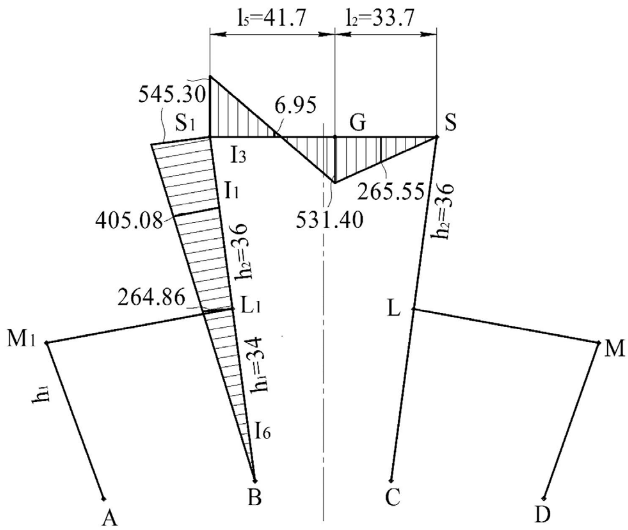


Fig. 6. Loading diagrams

By substituting the corresponding values into the system of canonical equations (1), (2), we have:

$$\left.\begin{aligned} 59{,}1522X_1+1{,}4067X_2-933997=0 \\ 2{,}4067X_1+25{,}0755X_2+8{,}9107=0 \end{aligned}\right\}. \quad (8)$$

Taking this into account, we obtain $X1=1.58$ and $X2=-0.55$.

Based on the calculations, the diagrams of bending moments and transverse forces were constructed, shown in Fig. 7, 8.

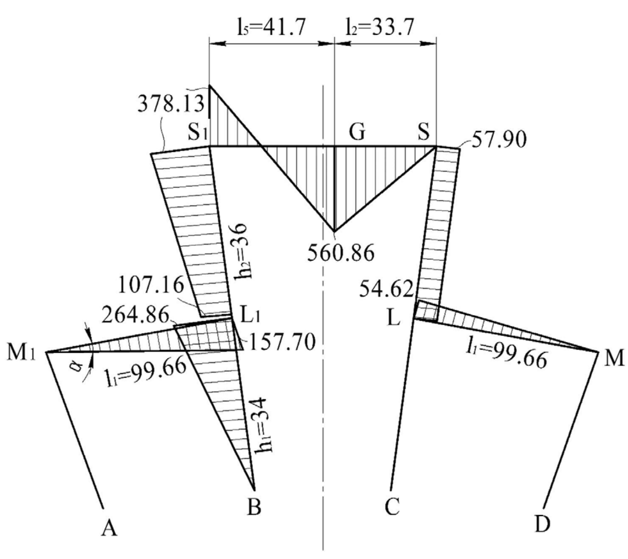


Fig. 7. Estimation diagram of bending moments *MX*

Hence, taking into account that the shoe works both for bending and compression, the stresses in it are determined by the following expression [17, 18]:

$$\sigma=\frac{M}{W}+\frac{Q}{F}, \quad (9)$$

where W is the axial moment of inertia of the shoe cross-section; F is the cross-sectional area of the shoe.

Then the stresses acting in the shoe are 491.6 MPa. These stresses exceed the allowable ones, which are 145 MPa for St3 steel. This stress value *was* established in accordance with DSTU 7598:2014. Freight cars. General requirements for calculations and design of new and modernized wagons of 1520 mm gauge (non-self-propelled). The foreign analog of this standard is EN 12663-2. Railroad applications – structural requirements of railroad vehicle bodies – Part 2: Freight wagons.

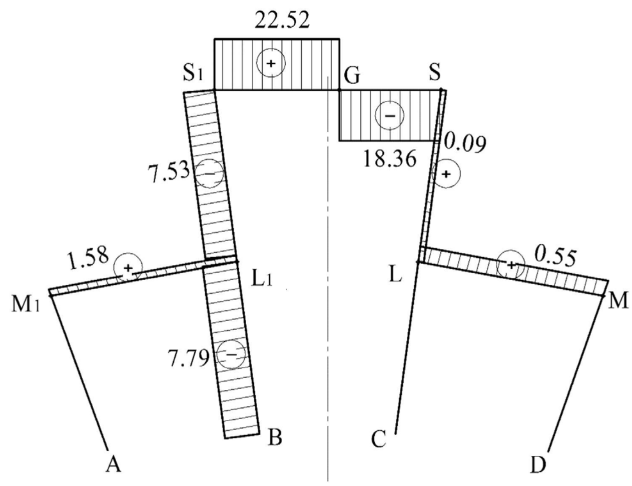


Fig. 8. Diagram of shear forces *QX*

In order to test the proposed mathematical apparatus, a computer simulation of the strength of the brake shoe was carried out at the next stage.

5. 2. Investigating stress distribution fields in a brake shoe under its uneven load

To determine the stress distribution fields in the shoe, its spatial model was built in the SolidWorks software package (Fig. 9) [19, 20].

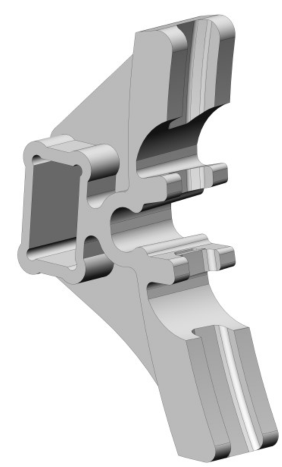


Fig. 9. Spatial model of the brake shoe

The strength calculation was implemented using the finite element method in the SolidWorks Simulation software package (France) [21–25]. The finite element model was built using isoparametric tetrahedra [26–29]. Their number was determined by the graphoanalytical method [30–34]. In this case, the number of nodes of the model was 7017, and elements – 28970, with the maximum size of 15 mm and the minimum size of 3 mm. The shoe is fastened in the area of its interaction with the triangle of the bogie. In this case, hard pinching was used. The calculation was performed for the loaded mode of operation of the air distributor, which corresponds to the maximum external load on the shoe. The calculation scheme of the shoe is shown in Fig. 10.

The calculation results are shown in Fig. 11, 12. The maximum stresses occur in the reinforcing rib and are equal to 465.1 MPa, which is much higher than permissible (Fig. 11).

In this case, the most loaded zone of the brake shoe is the lower reinforcing rib (Fig. 12). This is due to the uneven application of the load to it.

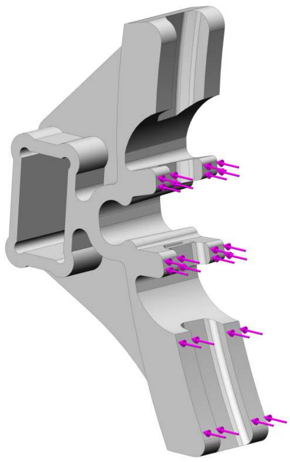


Fig. 10. Shoe calculation scheme

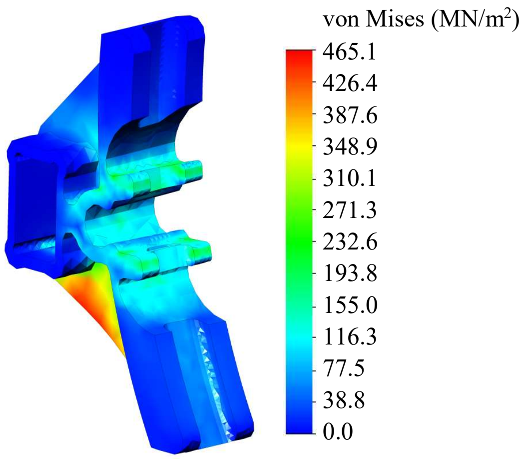


Fig. 11. The stressed state of the shoe

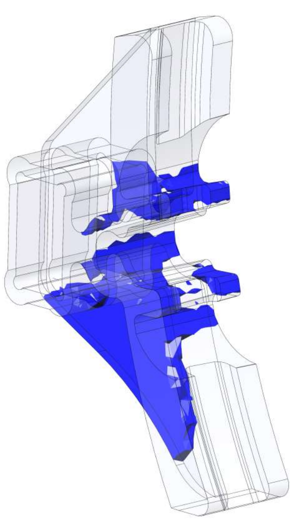


Fig. 12. Zones of the greatest load on the brake shoe

The maximum displacements were 0.8 mm and occurred at the bottom of the shoe (Fig. 13).

The discrepancy between the results obtained by mathematical modeling and computer simulation was 5.7 %.

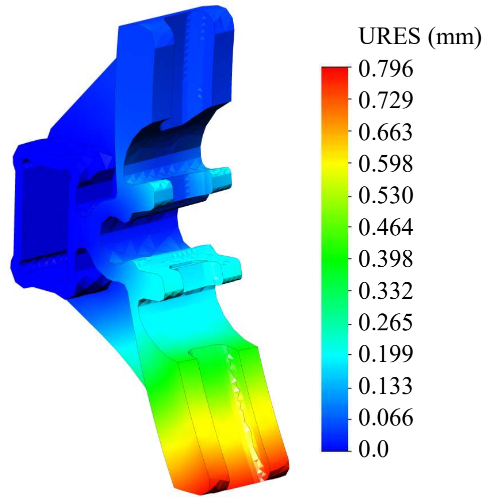


Fig. 13. Shoe displacement

6. Discussion of results related to the effect of uneven brake shoe load on brake shoe strength

In order to ensure the movement safety of trains, the strength of the brake shoe of the freight car bogie was determined, taking into account its uneven load. At the first initial stage of the research, the strength of the brake shoe was determined using the force method. It was taken into account that the shoe receives an external load F=41.7 kN, which is applied at an angle of 10° to its axis of symmetry. It was established that the stresses arising in it amount to 491.6 MPa. These stresses exceed the permissible ones.

In order to test the proposed mathematical apparatus, computer simulation of the strength of the brake shoe was carried out at the next stage. The results of our calculations showed that the maximum stresses occur in the reinforcing rib of the shoe and are equal to 465.1 MPa, which is much more than permissible ones (Fig. 11). The maximum movements in the shoe were 0.8 mm and occurred in the lower part of the shoe (Fig. 13). The difference between the results obtained by mathematical modeling and computer simulation was 5.7 %.

The advantage of our research in comparison with [4–6, 15] is that we have considered the load of the brake shoe in operation, and not only the pad located in it. In comparison with [7], uneven loading of the shoe as a power device, and not a vertical lever, which is a transmission element of BLG, was determined. In [8, 9, 12–14], the main attention was paid to the application of promising materials of tribotechnical units. In those cases, in contrast to this study, the stressed state of the BLG elements was not considered. The advantage of our study in comparison with [10] is that the unevenness of the shoe load in operation, which significantly affects the safety of train movement, was considered. In contrast to [11], the load of one of the most responsible nodes of BLG was considered, which was not given due attention before. Therefore, the current research contributed to the creation of a scientific approach to determining the strength of the brake shoe under uneven loading.

The limitation of this study is that it is focused on determining the load capacity of a shoe with composite pads.

Currently, cast iron pads are also used on railroads, which also requires appropriate research. Also, a limitation of this study is that it is specific to freight cars with a gauge of 1520 mm. That is, for European cars that are operated on 1435 mm tracks, it is necessary to take into account the relevant conditions of operation of freight cars. An equally important aspect that must be taken into account in this study is that it was conducted under the condition of using the air distributor No. 483-000 on a freight car, which has certain load modes of pads in operation.

A drawback of this study is that we investigated the load on the shoe only under the load mode of the air distributor.

The practical significance of the work is the advancements to improve the reliability of the braking systems of bogies, as well as ensuring the manufacturability and maintainability in the manufacture, operation, and repair of components of the mechanical part of brakes for the new generation of freight cars. Our results will contribute to designing modern structures of components for the mechanical part of brakes with improved strength and performance indicators.

The further development of the current study is the optimization of the geometric parameters of the brake shoe. Also, one of the options for advancing our research is the use of new grades of steel for the manufacture of a shoe, which could ensure both its strength indicators and manufacturability and maintainability during manufacture, operation, and repair.

The results of the research reported here indicate that exceeding the allowable stresses with uneven loading of brake shoes can cause their destruction during braking, which can lead to incidents on railroad transport. Therefore, the key to a successful solution to this problem is the introduction of progressive solutions for the design and development of lever transmission parts of the brake system of the bogie, which will satisfy the strength requirements. The use of modern approaches will solve the problems with the destruction of shoes and reduce the operational costs of maintaining the car fleet, as well as guarantee the safety of train movement.

7. Conclusions

1. A mathematical apparatus has been built for determining the strength of the brake shoe under uneven loading. It was taken into account that the shoe is a frame with variable stiffness, so the minimum stiffness corresponding to its actual operation was adopted at each section of the calculation scheme.

The results of our calculation of the brake shoe at the values of the external load F=41.7 kN, which is applied at an angle of 10° to the axis of symmetry, showed that the stresses arising in it amount to 491.6 *MPa*. That is, they exceed the permissible ones by three times. This proves that when the set force is transmitted from the triangle to the shoe during braking, its strength is not ensured.

2. The field of stress distribution in the brake shoe of a freight car, taking into account its uneven load, was studied by means of computer simulation. The calculation was performed for the loaded mode of operation of the air distributor, which corresponds to the maximum external load. In this case, the maximum stresses occur in the reinforcing rib of the shoe and are equal to 465.1 *MPa*. Based on the calculations, it was established that the discrepancy between the results obtained by mathematical modeling and computer simulation was 5.7 %.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

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