The object of research is strength indicators of load-bearing structures of special rolling stock (dump cars). The research problem is the appearance of the same type of cracks in the girder beams of dump cars, the repair of which is not provided for by the current repair documentation. Malfunction analysis, control tests, strength studies by calculation and experiment were carried out.

The analysis of malfunctions of cars in operation helped prove the place of occurrence of fatigue defects – the girder beam. This made it possible to determine specific zones of load-bearing elements, in which during control tests of cars, on the basis of taking into account data on fatigue defects, it is necessary to measure stress parameters.

The results of the control tests showed that the lowest value of the fatigue resistance reserve factor n=1.6 for the dump car is found in the zone on the girder beam in the area of the pivot beam. The value of n is within acceptable limits.

Normative calculations were carried out and a separate calculation (emergency) mode was additionally defined in the SolidWorks Simulation 2019 software package (France). Based on the results of the dump car stress calculations, it was established that the maximum equivalent stresses in the load-bearing structures of the car occur during its unloading due to twisting, and the stress vectors are at an angle of 45°. During the calculation of individual load modes, the stresses exceed the permissible values.

In order to ensure the necessary strength conditions, it is proposed to introduce a reinforcing pad into the girder beam of the dump car, due to which the calculated stresses are within the permissible limits.

The research will contribute to devising the recommendations for the restoration of dump cars, for designing modern structures of special rolling stock, and for improving strength determination processes

Keywords: car, dump car, girder beam, dump car strength, calculated loads

UDC 629.463.66:629.463.67
DOI: 10.15587/1729-4061.2023.285894

REVEALING PATTERNS IN THE STRESSED-STRAINED STATE OF LOAD-BEARING STRUCTURES IN SPECIAL ROLLING STOCK TO FURTHER IMPROVE THEM

Oleksii Koshel
Corresponding author
Postgraduate Student*
E-mail: koshela1520mm@gmail.com
Svitlana Sapronova
Doctor of Technical Sciences, Professor*
Serhii Kara
PhD, Head of Department
Department of Engineering
Branch of Science-Research and Design-Engineering
Institute of Railway Transport
of the JSC "Ukrainian Railways"
Ivana Fedorova str., 39, Kyiv, Ukraine, 03038
*Department of Railway Carriage
and Railway Carriage Property
State University of Infrastructure and Technologies
Kyrylivska str., 9, Kyiv, Ukraine, 04071

Received date 22.05.2023
Accepted date 31.07.2023
Published date 31.08.2023

How to Cite: *Koshel, O., Sapronova, S., Kara, S. (2023). Revealing patterns in the stressed-strained state of load-bearing structures in special rolling stock to further improve them. Eastern-European Journal of Enterprise Technologies, 4 (7 (124)), 30–42. doi: https://doi.org/10.15587/1729-4061.2023.285894*

1. Introduction

Railroad companies of European countries (Romania, Lithuania, Latvia, Moldova), as well as Georgia, Kazakhstan, and Ukraine, are interested in reducing costs for maintenance and repair of railroad rolling stock. In addition, different economic and technical development of countries forces to look for opportunities to use railroad rolling stock whose service life established by the manufacturer has expired. This is possible due to the increase in the service life of metal load-bearing structures, which are subject to aging processes during operation. To this end, it is important to have a residual resource in the rolling stock.

Determining the residual resource of the rolling stock after long-term operation requires a set of measures to control the technical condition of the load-bearing structures. The set of such measures includes the analysis of malfunctions, conducting control tests and periodic technical diagnostics, researching the stress-deformed state of load-bearing structures and strength by calculation. Such rolling stock research could contribute to devising new maintenance and repair technologies, to the design of modern structures, and the improvement of strength characteristics research methods [1, 2].

Therefore, scientific decisions and approaches to conducting such research must be substantiated for this.

Studies on increasing the service life of load-bearing structures of cars were conducted on the example of dump cars of the Ukrainian Railroads.

The analysis of the structure of the fleet of special rolling stock (dump cars) according to the Guide of the GIOC UZ 2066 VU reveals that the service life of the vast majority of cars exceeds the service life designated by the manufacturer. The share of dump cars that have reached the end of their service life is 99 %. The rate of renewal of Ukrzaliznytsia's car fleet in recent years has been insignificant, which makes it necessary to look for ways to extend the service life of the existing car fleet. On the railroads of Ukraine, it was decided to partially abandon the ban on operation after the end of the designated service life of those rolling stock units whose residual resource allows for further accident-free operation. For this purpose, the Order of the Ministry of Infrastructure of Ukraine dated November 30, 2021, No. 647 on the extension of the period of operation of freight cars beyond the specified period was implemented.

Therefore, studies that consider comprehensive measures to increase the service life of special rolling stock are relevant. The solutions that can be obtained owing to such studies could also be applied to rail rolling stock (metro, trams, etc.).

2. Literature review and problem statement

Modern methods of estimating the residual resource of load-bearing structures of rolling stock of railroads are considered in paper [3]. The principles of building regulations for the operation of rolling stock beyond the designated service life are proposed. At the same time, in the study, the authors considered the change in the endurance limit of the structure under the action of multi-cycle loads, which leads to a loss of load-bearing capacity. Primary defects that arise as a result of episodic emergency loads with exceeding permissible stresses were not considered.

Work [4] examines the influence of long-term operation of railroad rolling stock on the performance of its load-bearing structures. The stages of fatigue failure of low-carbon, carbon, and low-alloy steels, from which the load-bearing structures of rolling stock are made, their welded joints, and modern possibilities of calculating the probability of occurrence of fatigue cracks in them were studied. It is important to say that when the study was conducted, the issue of fatigue failure of other parts of the elements except for welded joints was not considered.

Issues related to the creation of a complex bench for carrying out tests of cars for fatigue life are considered in paper [5]. In order to evaluate the accumulated fatigue stresses, a test of the equivalent mileage of the car of 3.125 million kilometers or 25 years was carried out. However, carrying out fatigue tests of cars in the proposed way requires a significant amount of time.

Paper [6] examines the issues of experimental and theoretical studies of the strength of new and modernized dump cars. Analysis of the occurrence of damage to such cars shows that the main part of the damage occurs during the loading process, in the case when the car body is subjected to deep impacts of a large mass from a height. A reduction in the level of stress that occurs during an impact is possible when a protective layer of bulk cargo is sprinkled on the floor of the car. The question of the strength of the girder beam (lower frame) of the cars is not considered.

The set of studies of modern models of dump cars for mainline railroad transport with a gauge of 1520 mm, which were created and put into mass production in recent years, is reported in [7]. According to the results of a comparative analysis of the characteristics of dump cars, it was established that the main advantages of modern ones are a reduction in the weight of the container, an increase in the carrying capacity and volume of the body, and an increase in the strength of individual nodes. At the same time, optimization of the load-bearing structures of the dump car was not carried out, taking into account the experience of malfunctions in operation.

The ratio of the test trip of a freight car to bench tests is considered in [8]. The error of the obtained stresses on the test bench was between 16.03 % and 27.14 %. In addition, research was conducted on replaceable elements that are subject to replacement during scheduled repairs.

The analysis of the maintenance management system on European railroads is carried out in work [9]. The proposed method of determining the critical elements of the rolling stock design is determined by the manufacturer of the rolling stock and the certified organizations responsible for maintenance. When considering critical elements, cars with unloading mechanisms (unloading mode) were not taken into account.

The issue of modernization of freight cars using composite materials is considered in [10]. The main direction of using such materials is the car body, which implies increasing the anti-corrosion characteristics. At the same time, it is considered that corrosion processes cause the greatest impact on the body of the car, the question of the processes of the occurrence of defects in other ways was not considered.

In work [11], studies performed using mathematical modeling methods are considered. These methods make it possible to consider the behavior of the rolling stock of significant costs. At the same time, a simplified version of process modeling is considered, not taking into account the temporal changes that occur with the rolling stock during operation.

Work [12] analyzed the types of failures and their critical levels of running parts of railroad rolling stock. However, the analysis concerned only the running parts, the failure of the load-bearing structures was not taken into account, the failure of which can lead to the exclusion of the entire unit.

The aabove review of literary sources [3–12] allows us to state that the issue of researching the stressed-strained state of load-bearing structures of special rolling stock remains unresolved. Determining the features of such a state could contribute to the improvement of the supporting structures of the special rolling stock, which would make it possible to improve the strength characteristics and contribute to the extension of the service life of the special rolling stock after the end of the period defined by the manufacturing plant.

3. The aim and objectives of the study

The purpose of this study is to identify the features of the stressed-strained state of load-bearing structures of special rolling stock using the example of a dump car. This will make it possible to determine ways to restore the existing fleet of rolling stock and improve new designs in the future.

To achieve the goal, the following tasks were solved:

– to analyze the malfunctions of dump cars in operation;

– to determine the margin of safety of the load-bearing structures of the dump car during control tests in accordance with the current normative values;

– to develop an estimated strength model of the load-bearing structures of the dump car, taking into account the above-standard loads;

– to propose ways to eliminate the main malfunctions of dump cars' load-bearing structures.

4. The study materials and methods

The object of our research is temporal changes in the strength state of load-bearing structures of dump cars after long-term operation.

The main hypothesis of the research assumes that the cause of fatigue cracks are primary defects that could have arisen during episodic emergency loads with exceeding permissible stresses in non-standard situations.

To determine and analyze malfunctions of dump cars in operation, the method of mathematical statistics was used [13, 14]. To conduct experimental research, control tests were conducted, which included dropping from wedges and collision of cars [15].

The scheme for installing strain gauges during control tests is shown in Fig. 1.

The test for collision of cars was carried out under the following modes (Table 1):

– bouncing – wedges are installed under all wheels;

– twisting – wedges are installed under the wheels of one side of one bogie and the other side of the second bogie;

– galloping – wedges are installed under all wheels of one bogie;

– side pitching – wedges are installed under the wheels of one side of the car.

Collision tests were performed under the action of a limited series of impact loads and resource. During the tests, a one-impact and a two-impact arrangement of cars was used.

Table 1

The scheme of installing wedges under the wheels of cars during testing

No.	Oscillation mode	Side of the car	Wheelset number			
			1	2	3	4
1	Bouncing	L	●	●	●	●
		R	●	●	●	●
2	Twisting	L	●	●	–	–
		R	–	–	●	●
3	Galloping	L	●	●	–	–
		R	●	●	–	–
4	Side pitching	L	●	●	●	●
		R	–	–	–	–

Note: ● – the side of the car and the number of the wheelset where the wedge is installed; – – the side of the car and the number of the wheelset where the wedge is not installed

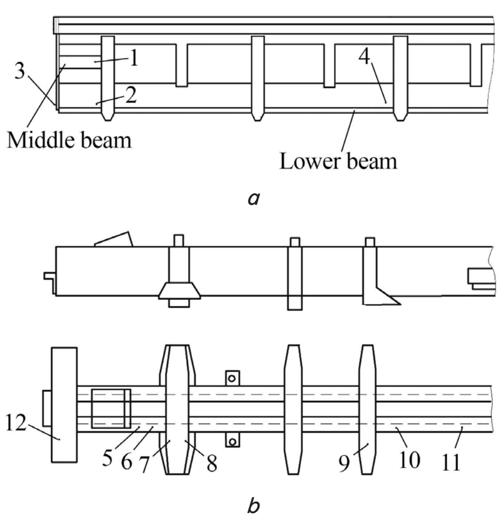

Fig. 1. The diagram of the installation of strain gauges on the load-bearing structures of the dump car: *a* – the upper frame and the side wall of the car; *b* – the girder beam of the car

The number of collisions and the rolling speed of the striker under the action of a limited series of impact loads were performed in accordance with DSTU 7598:2014 "Freight cars. General requirements for calculations and design of new and modernized railcars of 1520 mm gauge (non-self-propelled)" (hereinafter – DSTU 7598), on the resource – before the appearance of defects on load-bearing structures. The foreign analog of this standard is "EN 12663-2. Railroad applications – structural requirements of railroad vehicle bodies – Part 2: Freight cars. B., 2010. 54 p.".

The following measuring equipment was used for control tests:

– tensor resistors, type BF200-10AA-A(11)-BX30, with size 10×10 mm, resistance range R=200.0±0.5Ω;

– an automatic recorder based on the CompactRIO-9012 controller, which includes a GPS speed measurement channel, a cRio-GPSIB module, a cRio GPS satellite navigation systems GPS receiver, and a 4-channel NI 9237 analog-to-digital converter with a strain measurement range of ±2000 million;

– auto-coupling dynamometer with a measurement range of 0...3.5 MN – determination of the longitudinal forces that acted on the test car at the time of collisions. The auto-coupling dynamometer was equipped with strain gauges and pre-graded with a static load on the bench.

The equipment used during the research was in good technical condition and had calibration certificates.

The uncertainty of relative deformation measurements was 2.1 %.

The strain gauges are installed in accordance with Fig. 1.

The material of the load-bearing structure of the dump car is 09G2S steel. The mechanical characteristics of the material of the girder beam of the lower frame of the dump car are given in Table 2.

Table 2

Mechanical characteristics of the material of the girder beam of the lower frame of the dump car

Steel grade	Thickness, mm	σ_T, MPa	σ_{YS}, MPa	δ_S, %
09G2S	to 10	480	345	21

Note: σ_T is the temporary resistance; σ_{YS} – yield strength; δ_S – relative elongation

In order to determine the margin of safety of dump car structures, their spatial model was built. In this case, the SolidWorks Simulation 2019 software package was used. The strength calculation was carried out using the finite element method [16, 17].

Spatial tetrahedra are taken into account when compiling the finite-element model of the spinal beam. The number of nodes of the model was 576075, elements – 2266538. The maximum size of the element was 30 mm, and the minimum – 6 mm [18, 19]. When creating a finite element model, a grid with curvature was used. The minimum number of elements in a circle was 10, the ratio of the increase in the size of the elements was 1.4. Fixing of the model took place in the places where the car rested on the bogie (heel). The minimum size of the elements was chosen according to the smallest size of the weld leg (6 mm) according to the recommendations of the International Institute of Welding (IIW document IIW-1823-07 ex XIII-2151r4-07/XV-1254r4-07. Recommendations for fatigue design of welded joints and components).

5. Results of the study on determining the strength indicators of load-bearing structures of special rolling stock

5. 1. Analysis of malfunctions of dump cars in operation

According to [20], malfunctions of freight cars are divided into the following groups:

1 – malfunction of the wheelset;
2 – bogie malfunction;
3 – failure of automatic coupling equipment;
4 – failure of automatic braking equipment;
5 – failure of the car body;
6 – failure of the car frame;
8 – malfunction of the car body, which leads to the exclusion of the car from the inventory;
9 – service codes not related to the technical condition of the car.

A selection of malfunctions of the fleet of special rolling stock in the property of JSC "Ukrzaliznytsia" was formed in accordance with the information certificate from the UZ GIOC 2020 VU for the period from 01.05.2020 to 30.04.2022. The formed data of malfunctions according to the certificate are given in Table 3.

Table 3

Malfunctions of special rolling stock according to maintenance data for the period from 01.05.2020 to 30.04.2022

Group code	Total quantity, units
1xx – wheelset	44
2xx – bogie	26
3xx – automatic coupling equipment	31
4xx – autobrake equipment	17
5xx – body	292
6xx – frame	148
8xx – malfunction leading to shutdown	11
9xx – service codes	0

From the point of view of reliability, special rolling stock cars are a complex structure consisting of many elements (nodes) that interact with each other and influence each other. During operation during repairs, certain elements (assemblies) installed on cars are subject to replacement, which is provided for in the repair documentation. Therefore, for an objective analysis of the technical condition of special rolling stock cars, structural elements that remained unchanged throughout the entire operation of the cars were selected and analyzed in more detail – the body and frame of the cars.

An in-depth analysis of body faults is given in Table 4, frames – in Table 5.

Table 4

Malfunctions of the body of cars of special rolling stock

Fault code	Malfunction name by classifier	Total quantity, units
504	Broken welded joint brace	13
506	Damage to strapping bars	4
532	Floor damage	26
549	Malfunction of loading/unloading mechanisms	129
550	Damage to overhead lines of loading/unloading	98
553	Damage (breakage) of stairs/handrails/footboards	22
Total		292

Table 5

Malfunctions of the frame of cars of special rolling stock

Fault code	Malfunction name by classifier	Total quantity, units
601	Breakage of welded joints	47
603	Crack at the junction of the girder and pivot beams	31
610	Longitudinal crack in frame beams over 300 mm	7
612	Vertical/longitudinal crack that passes through more than one bolt mounting hole	5
614	Welding breakage, pad break	8
616	Fracture/crack of intermediate beams	16
618	Breakdown/crack/brace break	7
621	End beam crack	23
622	Fracture of end beams	4
Total		148

The results of the study allowed us to determine the places of occurrence of the largest number of faults on the body and frame of cars of special rolling stock.

5. 2. Determination of the safety margin of load-bearing structures during control tests

Parts of cars that work under conditions of long-term intensive action of dynamic loads must be calculated on fatigue resistance in the case of multi-cycle loading. During the calculation, the likely dispersion of the fatigue resistance characteristics of the part and the random nature of its dynamic load are taken into account.

Fatigue resistance is calculated taking into account the coefficient of fatigue resistance reserve according to the formula in line with DSTU 7598:

$$n = \frac{\sigma_{a,N}}{\sigma_{a,e}} \geq [n], \tag{1}$$

where $\sigma_{a,N}$ is the limit of endurance (by amplitude) of the full-scale part in the case of a symmetrical cycle and a stable load mode based on the test $N_0=10^7$ cycles, MPa; $\sigma_{a,e}$ is the calculated value of the amplitude of the dynamic stress of the conventional symmetrical cycle, reduced to the base N_0, equivalent in terms of damaging action to the real regime of operational random stresses during the design life, MPa; $[n]$ is the allowable coefficient of fatigue resistance reserve.

To evaluate the fatigue resistance indicators during the tests, the following were taken into account:

– the forces that arise during dropping from the wedges of the car with the simulation of oscillations of bouncing, twisting of the body, galloping, and side pitching;

– forces of interaction between cars, car and locomotive, braking, collisions.

The calculated value of the endurance limit is determined by the formula:

$$\sigma_{a,N} = \overline{\sigma}_{a,N} \cdot \left(1 - Z_p \cdot J_{\sigma_{a,N}}\right), \tag{2}$$

where $\overline{\sigma}_{a,N}$ is the average (median) value of the endurance limit of the test sample; Z_p is the distribution quantile corresponding to the one-sided probability P, if we consider that $\sigma_{a,N}$ is a random variable with a normal distribution law, then the following values $P=0.95$ and $Z_p=1.645$ are recommended for the main parts of the cars; $J_{\sigma a,N}=0.05$ is the coefficient of variation of the endurance limit;

$$\bar{\sigma}_{a,N}=\frac{\bar{\sigma}_{-1}}{\left(\bar{K}_{\sigma}\right)_{k}}, \tag{3}$$

where $\bar{\sigma}_{-1}$ is the average (median) value of the endurance limit of a smooth standard sample. Numerical values are determined by reference data; $\left(\bar{K}_{\sigma}\right)_{k}$ is the average value of the overall coefficient of reduction of the endurance limit of this full-scale part relative to the endurance limit of a smooth standard sample.

The value of $\left(\bar{K}_{\sigma}\right)_{k}$ can be approximately determined by the formula:

$$\left(\bar{K}_{\sigma}\right)_{k}=\bar{K}_{\sigma}\cdot\frac{K_{H}\cdot K_{IT}}{K_{ID}\cdot K_{S}}, \tag{4}$$

where $\bar{K}_{\sigma}$ – the effective coefficient of stress concentration, which takes into account the decrease in fatigue resistance caused by local changes in the shape and size of the part, determined according to reference and experimental data for some structural elements typical for cars; K_H – coefficient of heterogeneity of the material; K_{IT} – coefficient of influence of surface strengthening treatment of parts; K_{ID} – the coefficient of influence of the dimensions of the parts (scale factor).

The equivalent summed amplitude of dynamic stresses for fatigue calculation is calculated in the general case by the formula:

$$\sigma_{a,e}=\sqrt[m]{\frac{N_{C}}{N_{0}}\cdot\sum_{i=1}^{k}\sigma_{ai}^{m}P_{i}}, \tag{5}$$

where N_0 – the basic number of cycles, the recommended value for steel structures (except wheelsets) is $N_0=10^7$; m – the exponent in the equation of the fatigue curve in the amplitude; N_C – the total number of dynamic stress cycles for the estimated service life; σ_{ai} – the value of the stress level, taking into account its mass share during operation; P_i – the probability of occurrence of an amplitude with a level of σ_{ai};

$$m=\frac{A}{\left(\bar{K}_{\sigma}\right)_{k}}, \tag{6}$$

where A is the coefficient according to DSTU 7598.

For parts in which dynamic stresses arise from oscillations and vibrations during car movement, N_C in cycles, is recommended to be determined by the formula:

$$N_{C}=J_{e}\cdot T_{P}, \tag{7}$$

where T_P is the total time of action of dynamic stresses during movement for the estimated service life of the part (unit), s:

$$T_{P}=B\cdot T_{K}, \tag{8}$$

where B is the coefficient of conversion of the calendar estimated service life in years to the time of continuous movement in seconds; T_K – design (estimated) calendar service life of the part, year. As T_K, the normative (defined by current regulatory documents) service life of the part before the planned replacement or the full service life before the scrapping of the car is taken.

$$J_{e}=\frac{a}{2\pi}g\sqrt{\frac{g}{f_{S}}}, \tag{9}$$

where a is the coefficient for the car body; g – acceleration of free fall, m/s^2; f_S – static suspension deflection;

$$B=365\frac{10^{3}\overline{L_{C}}}{\bar{V}}, \tag{10}$$

where $\overline{L_C}$ – the average daily mileage of the car; $\bar{V}$ – average speed.

Based on the results of tests of the cars and assessment of their technical condition, a decision is made on the possibility of further operation and the value of the new maximum period of operation is established.

The results of tests are formalized in a technical report (act, protocol), in which the data obtained during the examination of the technical condition and tests, the results of the analysis of the obtained information, and the new period of operation are indicated.

The total stress values in the test locations (critical points) of the dump car within the framework of load mode I according to DSTU 7598 and Fig. 1 are given in Table 6 [21]. The permissible stress of the material of load-bearing structures is $0.9\sigma_T$=310.5 MPa.

The object of control tests was a dump car, model 31-638, No. 34004465, built in 1987 (with an expired service life). Control tests were carried out on the territory of KMS-122 Korosten JSC "Ukrzaliznytsia".

Table 6

Total values of stresses at experimental sites (critical points) of the dump car

Channel number	Stress from the forces arising from the release of the car from wedges, MPa	Stress from the forces of interaction between cars, car with locomotive, braking, collisions, emergency collisions (300 t), MPa	Total stress values, MPa	Fatigue resistance reserve factor, n
1	5.4	30.0	35.5	7.50
2	2.9	37.5	40.4	8.57
3	2.2	19.5	21.6	14.47
4	10.1	26.1	36.2	5.41
5	13.5	62.8	76.3	3.26
6	26.5	134.5	161.0	1.60
7	10.6	44.5	55.1	4.34
8	7.8	16.8	24.6	7.38
9	1.0	19.8	20.8	18.09
10	19.8	59.5	79.3	2.63
11	24.1	68.3	92.4	2.21
12	2.6	38.1	40.7	8.74

Channel 6 of the test car has a total stress level of 161.0 MPa.

During the dump car resource test, 782 collisions were made, of which:

– 513 collisions were performed according to the one-impact scheme;

– 269 collisions were performed according to the two-impact scheme.

5. 3. Development of the calculated strength model of load-bearing structures of the dump car taking into account excessive loads

The lower frame of the dump car is the most stressed element of the load-bearing structures of the car. The model is built according to the characteristics of the dump car of model 31-638 and load modes in the form of a 3D stressed-strained state model.

The spatial model of the lower frame of the dump car is shown in Fig. 2.

Calculations on the strength of the girder beam of the lower frame of the dump car of model 31-638 were performed using the automated design product in the SolidWorks Simulation 2019 software package. A finite element model was built based on the developed 3D model (Fig. 3).

The load diagrams of the girder beam of the lower frame of the dump car, model 31-638, were constructed in accordance with DSTU 7598.

Two main (Mode I, Mode III) and one additional (Mode II) calculation modes were established.

Calculations for Mode I (I compression (I_c) and I elongation (I_e)) and Mode III (III compression (III_c) and III elongation (III_e)) were carried out only for the most disadvantageous possible combination of simultaneously acting normative forces.

Stretching (compression) is a type of deformation of a solid body, in which its size along one axis increases (decreases) under the action of forces whose uniform action is perpendicular to the cross-section of the body and passes through its center of gravity.

Calculations according to mode II were carried out as follows:

– mode II_{odc} – the mode of operation of the dump car, which provides for its unloading;

– mode II_{rm1} – repair mode, which involves lifting the empty body under the ends of pivot beams located diagonally;

– mode II_{rm2} – repair mode, which involves lifting the loaded body with jacks installed at the specified points;

– mode II_{rm3} – repair mode, which involves lifting the loaded body under one end of the pivot beam to change elements of the spring kit.

An example of the calculation scheme of the lower frame of the dump car in accordance with the established mode I_c is shown in Fig. 4.

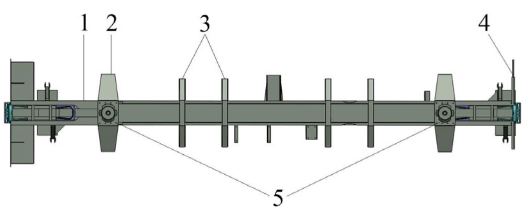

Fig. 2. Spatial model of the lower frame of the dump car (bottom view): 1 — spinal beam; 2 — pivot beam; 3 — cylindrical beam; 4 — end beam; 5 — pivot unit

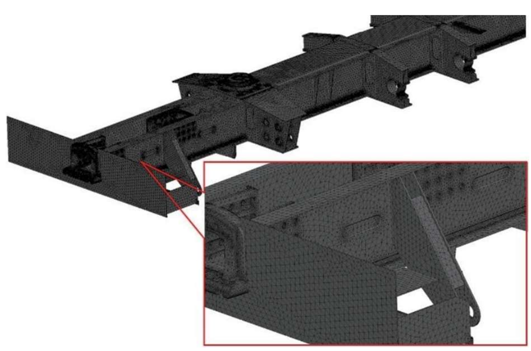

Fig. 3. Finite element model of the girder beam of the lower frame of the dump of car model 31-638

Static and kinematic boundary conditions of design loads according to DSTU 7598 are given in Table 7.

Acceptable stresses adopted in accordance with DSTU 7598 when calculating the strength of load-bearing elements are given in Table 8.

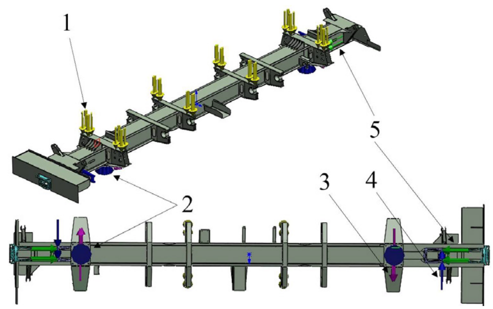

Fig. 4. Calculation scheme of the lower frame of the dump car: 1 — mass of cargo and evenly distributed mass of body elements; 2 — leaning the body on the bogie; 3, 4 — lateral forces; 5 — compression forces from the automatic coupling

On the basis of calculated load modes, a static calculation of the strength of the girder beam of the lower frame of the dump car was carried out. Equivalent stress distribution diagrams were obtained.

Table 7

Static and kinematic boundary conditions of design loads of a 3D model

Calculated forces	Modes		
	Mode I	Mode III	Mode II
Gravity gross	85.7 t	85.7 t	85.7 t
Longitudinal force	–3.0/+2.0 MN	±1.0 MN	–
Lateral force H – horizontal force acting on heels (compression)	196.5 kN	–	–
Lateral force P_F – transverse force of interaction between cars (compression)	160 kN	–	–
Lateral force P_F – transverse force of interaction between cars (stretching)	49.8 kN	–	–
Vertical dynamic force	–	675 kkN	–
The lateral force represented by acceleration	–	0.7 m/s^2	–
The unloading force acting from the unloading cylinders during unloading	–	–	221 kN

Table 8

Permissible stresses when calculating the strength of load-bearing elements

Material	Mode I and II			Mode III		
	σ, MPa	τ_{ss}, MPa	σ_{cs}, MPa	σ, MPa	τ_{ss}, MPa	σ_{cs}, MPa
Girder and pivot beams of the body frame						
09G2S	0.9 σ_τ 310.5	0.55 σ_τ 190	1.2 σ_τ 414	210	130	310

The results of calculating the strength of the girder beam of the lower frame of the dump car, model 31-638, are shown in Fig. 5–12.

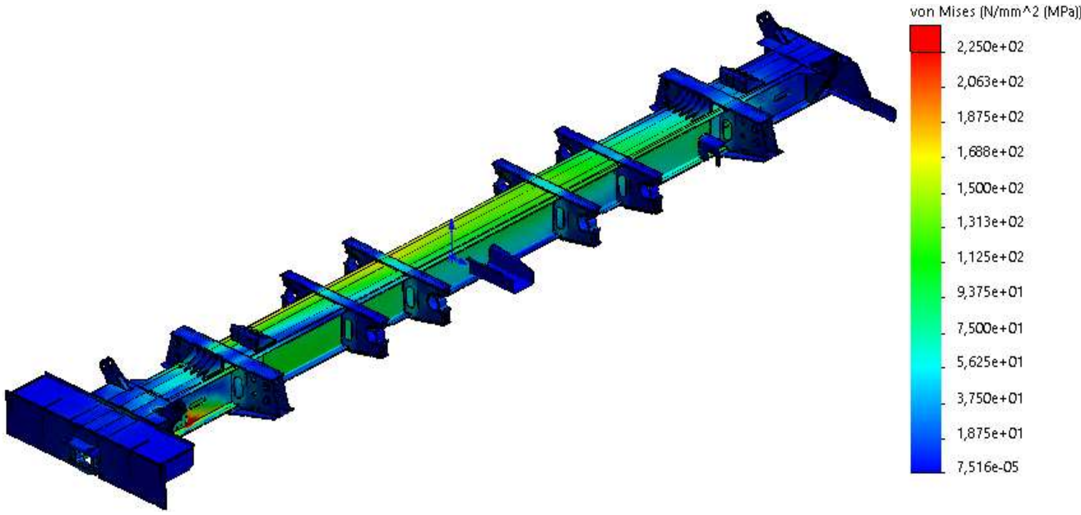

Fig. 5. The diagram of the equivalent stresses of the girder beam of the lower frame of the dump car, model 31-638, according to mode I

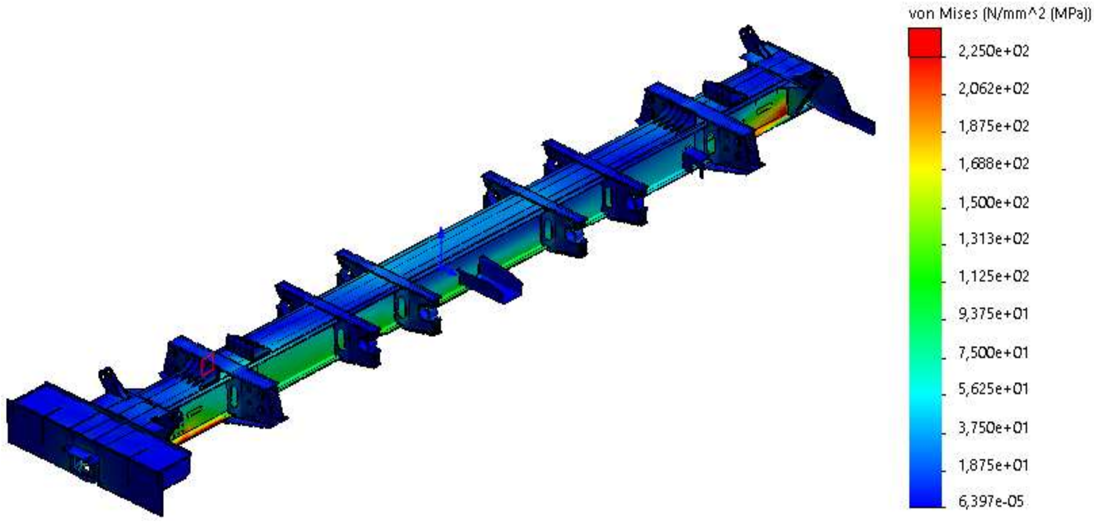

Fig. 6. The diagram of the equivalent stresses of the girder beam of the lower frame of the dump car, model 31-638, according to mode I_e

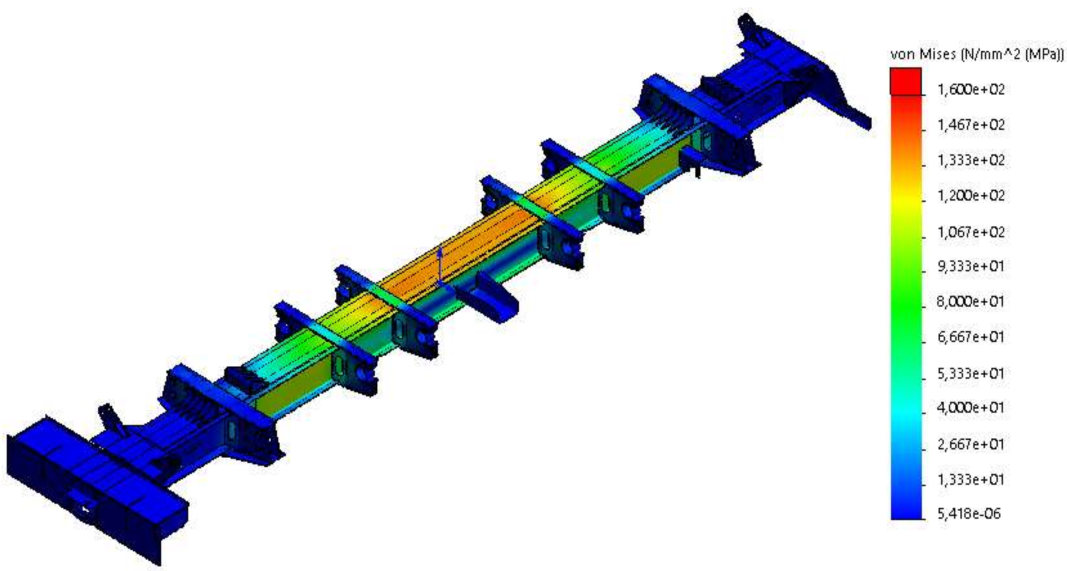

Fig. 7. The diagram of the equivalent stresses of the girder beam of the lower frame of the dump car, model 31-638, according to mode II_{odc}

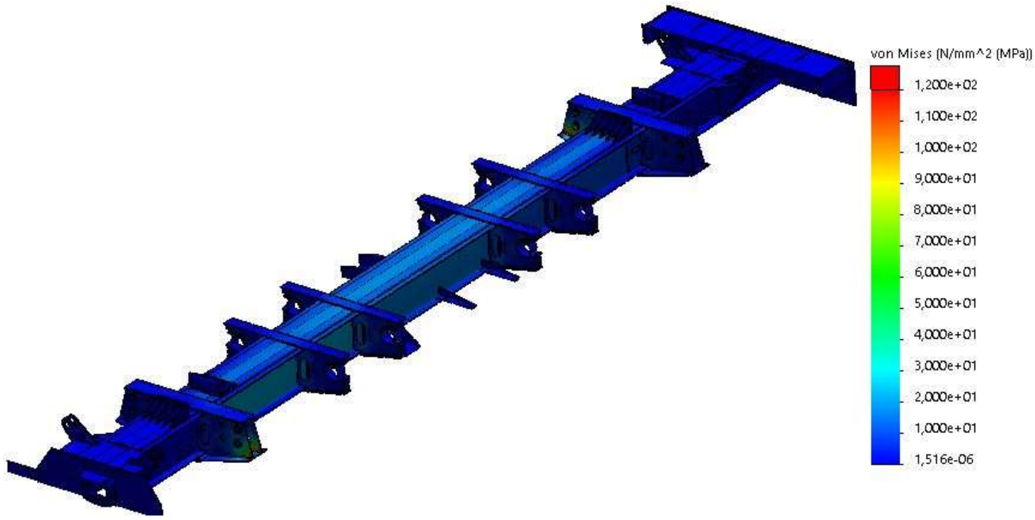

Fig. 8. The diagram of the equivalent stresses of the girder beam of the lower frame of the dump car, model 31-638, according to mode II_{rm1}

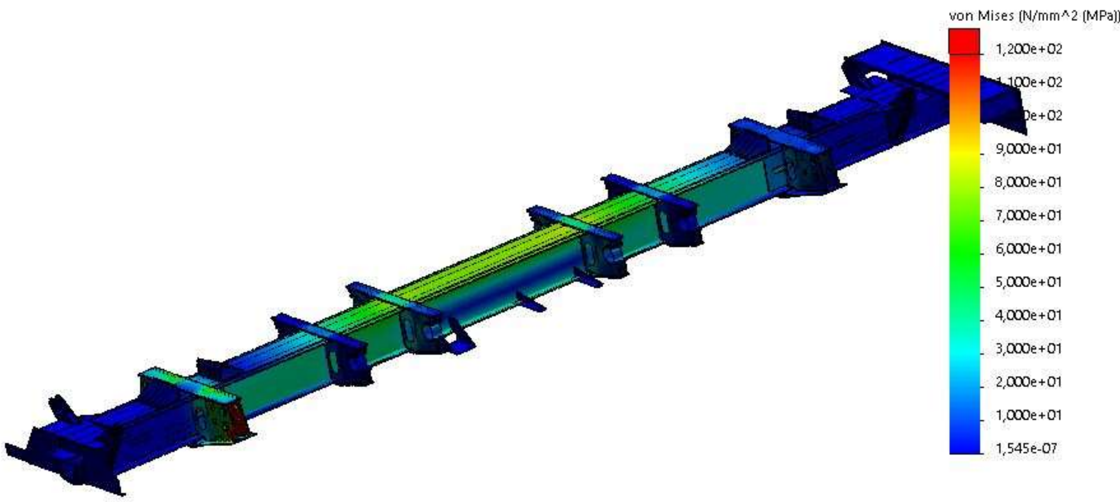

Fig. 9. The diagram of the equivalent stresses of the girder beam of the lower frame of the dump car, model 31-638, according to mode II_{rm2}

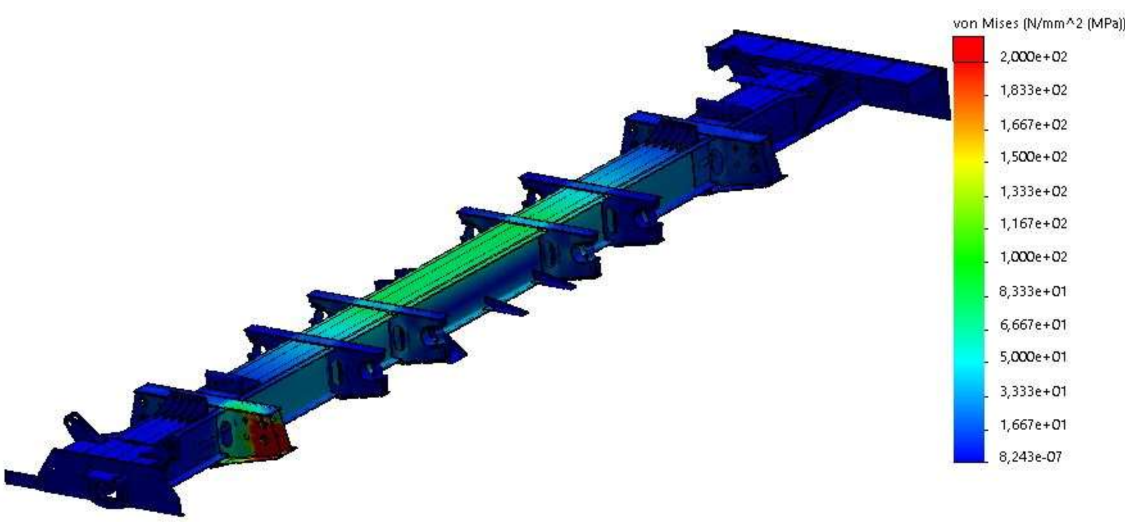

Fig. 10. The diagram of the equivalent stresses of the girder beam of the lower frame of the dump car, model 31-638, according to mode II_{rm3}

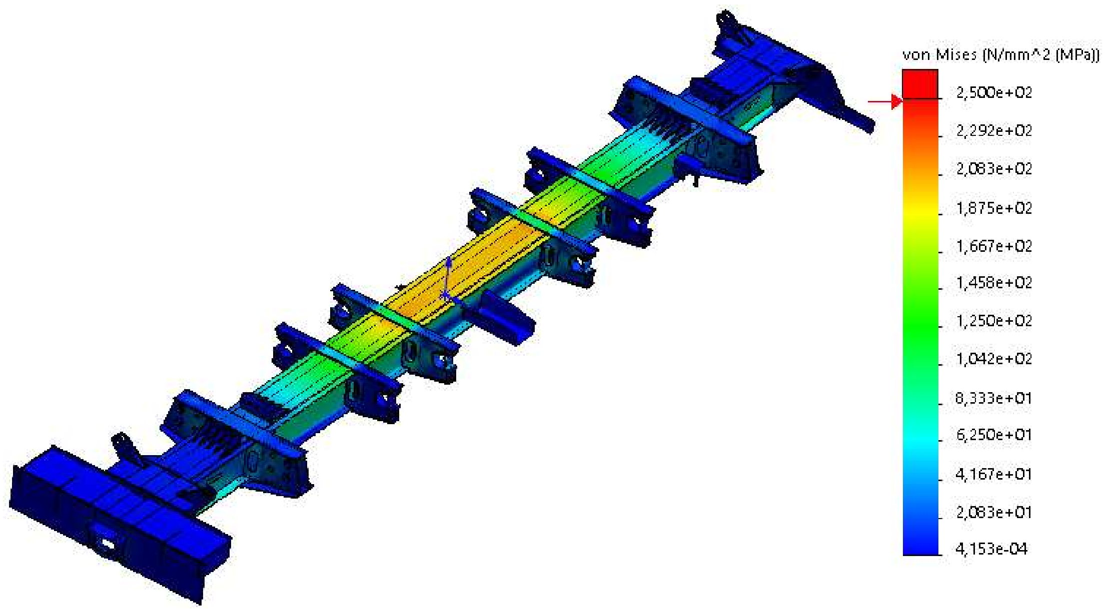

Fig. 11. The diagram of the equivalent stresses of the girder beam of the lower frame of the dump car, model 31-638, according to mode III_c

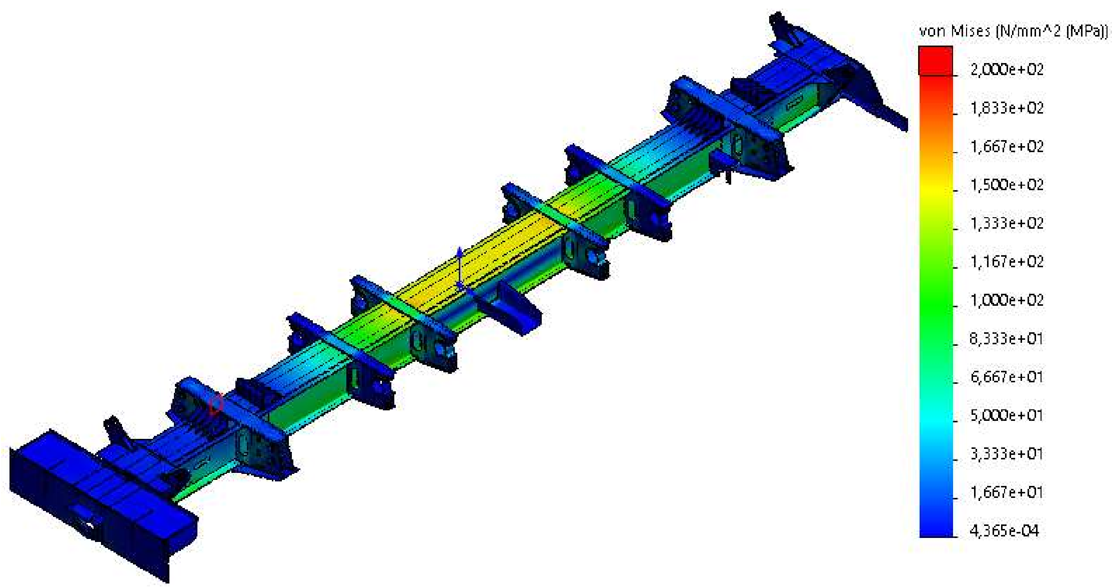

Fig. 12. The diagram of the equivalent stresses of the girder beam of the lower frame of the dump car, model 31-638, according to mode III_e

An additional mode IV – emergency – calculation mode is proposed, which is offered for cars that have unloading devices (pneumatic cylinders), for which a non-standard situation is possible. Examples of such a situation are:

– jamming of one of the two unloading cylinders during unloading of the dump car;

– non-synchronism of unloading devices when unloading a car, etc.

In such a situation, additional moments of twisting of the lower frame occur due to the fact that one of the cylinders works for unloading, and the other prevents it.

The calculation scheme according to mode IV when one of the cylinders is jammed during unloading of the dump car is shown in Fig. 13.

Based on the calculated load scheme, a static calculation of the strength of the girder beam of the lower frame was carried out. Fig. 14 shows the diagram of the equivalent stresses arising in the girder beam of the lower frame of the dump car, model 31-638, due to the action of an over-normative load within the framework of the proposed IV calculation mode.

Fig. 15 shows the direction of the principal stresses (in the form of vectors) in the zone of occurrence of actual defects (cracks) of the girder beams of dump cars. A photograph of such defects is additionally shown in the upper left corner.

The maximum calculated stresses according to mode IV are taken at the level of the values of mode II according to DSTU 7598. In this case, the permissible stress value, taking into account the characteristics of the material given in Table 8, for mode IV according to DSTU 7598 is 190 MPa.

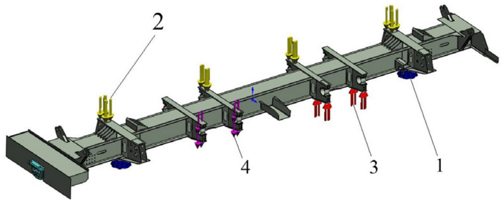

Fig. 13. Calculation diagram of the loading of the girder beam of the lower frame of the dump car, model 31-638, (mode IV): 1 – resting the body on the bogie; 2 – cargo mass and evenly distributed mass of body elements at the beginning of unloading; 3 – unloading forces acting on the elements of the lower frame from the working cylinder; 4 – reactions acting on the elements of the lower frame from the jammed cylinder

5. 4. Ways to eliminate the main malfunctions of the load-bearing structures of dump cars

The experience and practice of repairing the girder beams of rolling stock of various types involve welding the crack and bridging it with overlays. Such repair is provided for by the rules of capital repair of freight cars (STP 04-016:2018) in Ukraine. At the same time, the rules for the overhaul of dump cars (TsV-0033) do not provide for the elimination of such defects. It is appropriate to consider the possibility of such a method of restoring the bearing capacity of the girder beam of the lower frame of the dump car.

Structural strengthening of the girder beam of the lower frame of the dump car is proposed, which implies welding the crack and strengthening the side wall of the girder beam of the lower frame of the dump car by installing a 5 mm thick overlay [22].

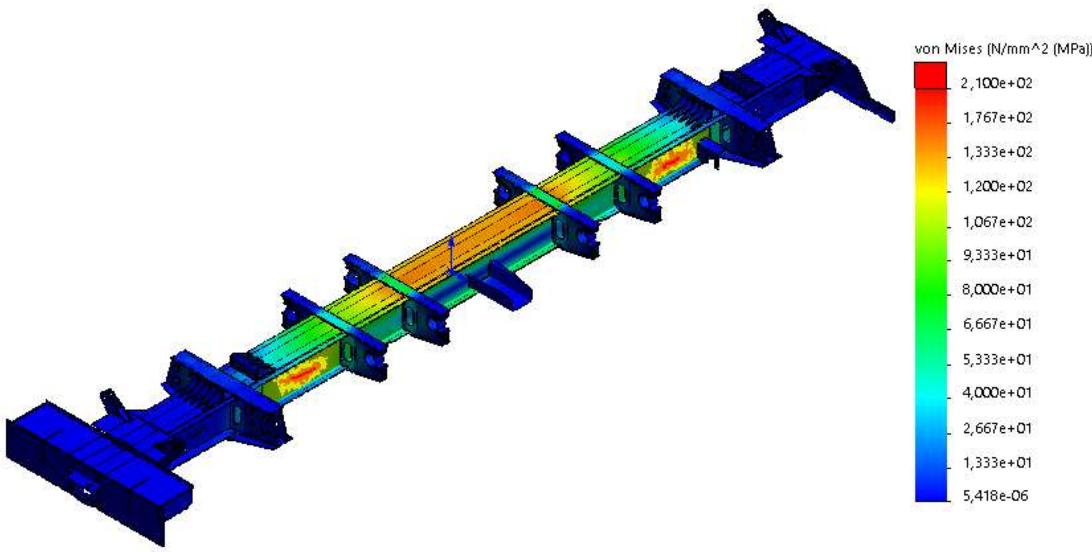

Fig. 14. The diagram of the equivalent stresses of the girder beam of the lower frame of the dump car, model 31-638, according to mode IV

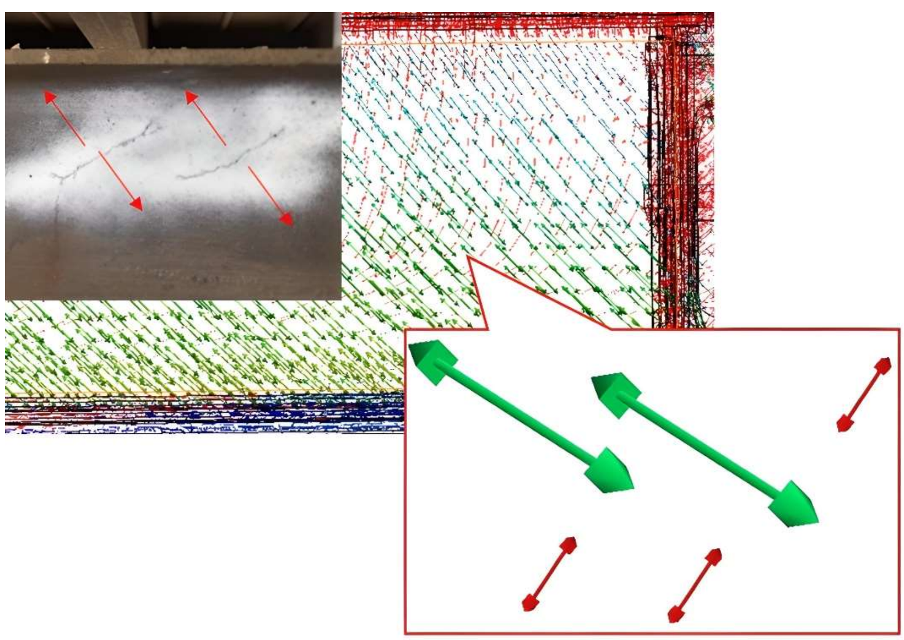

Fig. 15. The direction of the principal stresses under calculation mode IV and the actually detected defects of the girder beam

To this end, the following is required:

1) process the crack, eliminate it by welding and clean the weld of the eliminated crack to the level with the girder beam of the lower frame;

2) install the manufactured pads (4 pieces) on the girder beam of the lower frame and weld them along the contour to the girder beam.

Taking into account the defined calculation regimes, calculations of the equivalent stresses of the restored and reinforced girder beam were carried out.

The maximum tangential stresses when installing the pad are shown in Fig. 16.

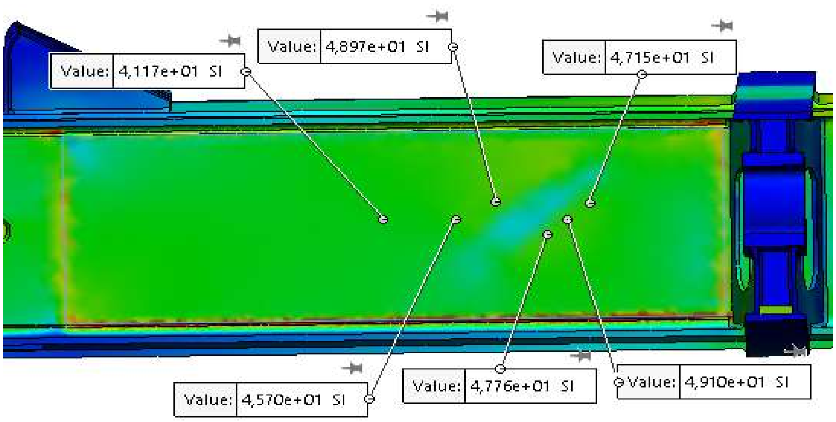

Fig. 16. Diagram of maximum tangential stresses when installing the reinforcing pad

The maximum tangential stresses when installing the pad are 49 MPa. The thickness of the reinforcing pad (Fig. 16) is 5 mm, the size is from the pivot beam to the cylinder bracket, the height is the entire height of the girder beam.

6. Discussion of the results of experimental and theoretical studies of special rolling stock cars

Our research was carried out on the example of dump cars that were in long-term operation.

An in-depth statistical and analytical analysis of the non-replaceable structural elements of the cars – the body and frame – was carried out to determine the malfunctions that occur during the operation of special cars (Tables 4, 5). It has been established that most malfunctions occur in the area of unloading mechanisms due to their failure.

Control tests were conducted to determine the strength of special rolling stock cars. The numerical test results (Table 6) give grounds for asserting that the stresses that occur in the dump cars do not exceed the allowable ones. The coefficient of the margin of resistance to fatigue is within the limits of permissible values. This does not agree with the statistics of detected defects, especially in the girder beams of the lower frame of dump cars in the area of unloading mechanisms.

The results of strength calculations showed that the maximum equivalent stresses of the girder beam of the lower frame of the dump car, model 31-638:

– under calculation mode I, they occur between the end and pivot beams. The numerical values of the stresses were about 200 MPa (Fig. 5, 6);

– under calculation mode II, they occur in the middle part between the pivot beams. The numerical values of the stresses were about 133 MPa (Fig. 7–10);

– under calculation mode III, they occur in the middle part between the pivot beams. The numerical values of the stresses were about 208 MPa (Fig. 11, 12).

This proves that the equivalent stresses do not exceed the permissible ones.

The results of our control tests and normative calculations meet the requirements of regulatory documents. But the actually detected cracks on the girder beams of the lower frame of dump cars (they have a characteristic direction of their development at an angle of 45° to the horizontal) do not agree with the results of normative calculations. The result of the study of the probable causes of loads affecting the development of cracks is the assumption of the feasibility of taking into account the additional calculation mode IV.

The maximum calculated stresses for the proposed mode IV are 205 MPa (Fig. 14). Thus, the maximum calculated stresses will exceed the accepted permissible values. For this, there is a need to make structural reinforcements in the dangerous sections of the girder beam of the lower frame of the dump car.

To confirm the calculation model according to load mode IV, it is advisable to conduct control tests, which are planned in further studies.

The accepted endurance limit for the tangential stresses of a symmetrical load is 70 MPa. Therefore, the margin of strength beyond the limit of endurance is 1.42 (Fig. 16). The results of strength calculations after improving the design contribute to the reduction of tangential stresses by 31 % compared to the typical one. The limitation of the calculation of the maximum tangential stresses is that they apply only to the girder beam of the cars and do not take into account the possibility of restoring other load-bearing elements.

When conducting a set of studies, the impact of pneumatic cylinders of unloading mechanisms on the strength of the girder beam of the dump car was revealed, which leads to the appearance of defects. The direction of the main stresses in the form of vectors is determined (Fig. 15), which has not yet been presented. It was established that the mechanism of this process involves the jamming or non-synchronous operation of the unloading cylinders and leads to twisting of the girder beam. The proposed comprehensive approach will make it possible to calculate emergency modes separately from normative ones and, if necessary, determine overtime loads individually for each type of rolling stock. This approach will allow one to take into account the design features of a certain type of rolling stock.

As a drawback of this study, it can be noted that the change in the configuration of the reinforcing pad and the change in the welding technology were not considered. In future studies of the strength characteristics of load-bearing structures, it is advisable to consider the possibility of more technologically modernizing and improving the structure as a whole.

In contrast to works [3–5, 8, 12], control tests were carried out, during which real loads acting on the rolling stock during operation were determined.

The advantage of our research in comparison with those highlighted in works [6, 7, 9, 10] is that we proposed to introduce a reinforcing overlay on the girder beam. This will make it possible to ensure the necessary strength of the structure and restore its bearing capacity.

In comparison with work [11], it is proposed to carry out strength calculations according to calculation mode IV, which was not used before. The set of normative and proposed strength calculations made it possible to determine zones with an excess of allowable stresses. These zones correspond to the places of defects in the girder beam of the lower frame of the dump car in operation.

The proposed calculation mode IV will make it possible to more accurately determine the strength indicators of the rolling stock at the stage of design and testing.

The presented version of restoration and strengthening of the girder beam of the lower frame of the dump car corresponds to the normative and proposed calculation regimes.

The practical significance of the study is:

– in specifying the calculated load modes for cars that have unloading devices (pneumatic cylinders);

– the possibility of restoring the bearing capacity of the girder beam of the lower frame of dump cars with cracks that appear between the cylinder and pivot beams.

The scope of application is railroad rolling stock, namely cars with unloading mechanisms.

Our research will contribute to the improvement of the strength characteristics of special rolling stock cars, the development of theoretical and practical methods of restoring the load-bearing capacity of rolling stock.

In further research in this area, it is important to conduct control tests with the proposed option of restoring the supporting structure. This can be done after the production of a control sample of the car.

Also, it is advisable to consider the issue of replacing the steel grade 09G2S, from which load-bearing structures are made, with another, more plastic one, when designing and manufacturing new models of cars.

This approach to determining the strength characteristics of load-bearing structures can be used during research of other types of railroad and rail rolling stock.

7. Conclusions

1. An analysis of malfunctions of dump cars in operation was carried out, and similar places of occurrence of car frame defects, which are not subject to restoration, were identified. It was established that defects occur between the cylinder and pivot beams of the vertical wall of the girder beam of the lower frame of the dump car.

2. According to the results of the control tests of the experimental car, model 31-638, the zones with the lowest coefficient of fatigue resistance margin were established, which coincide with the places of cracks detected during the inspection: the smallest value of the coefficient of fatigue resistance margin corresponds to the point on the girder beam in the zone of the pivot beam and is equal to 1,6, with an admissible value of $[n]\geq 1.5$. At the same time, the normative methods of tests and calculations did not make it possible to determine the overloaded zone of the girder beam in which defects occur.

3. The estimated strength model of the load-bearing structures of the dump car was developed in the SolidWorks Simulation 2019 software package. In addition to the known three standard load modes, the load scheme with one working pneumatic cylinder was additionally considered. The model differs from the existing ones in that it takes into account the malfunction of the unloading cylinders, their asynchrony of action during unloading of the dump car. The (additional) design load mode IV is proposed. According to the results of the assessment of the stress state, it was determined that the girder beam is twisting while the maximum calculated stresses are 205 MPa. The excess of allowable stresses and the perpendicularity of the direction of the principal stress vectors to the direction of the actually detected cracks have been established.

4. A method of troubleshooting and increasing the strength of the girder beam of the lower frame of the dump car is proposed. Its feature is that the defect is eliminated by welding the crack and strengthening the side wall of the girder beam of the lower frame of the dump car by installing an overlay. A similar method of restoration is used for various types of cars but without installing a reinforcing overlay, which did not provide the necessary strength characteristics. Based on the results of our research, it is proposed to implement this method of repair (restoration and strengthening) for all types of freight cars.

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.

Funding

The study was conducted without financial support.

Data availability

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

References

1. Cole, C., Spiryagin, M., Wu, Q., Sun, Y. Q. (2017). Modelling, simulation and applications of longitudinal train dynamics. Vehicle System Dynamics, 55 (10), 1498–1571. doi: https://doi.org/10.1080/00423114.2017.1330484
2. Hecht, M. (2014). Innovative rail freight wagons – a precondition to increase the market-share of rail freight. Archives of Transport, 29 (1), 17–26. doi: https://doi.org/10.5604/08669546.1146959
3. Horobets, V. L., Miamlin, S. V., Yanhulova, O. L. (2015). Perspektyvy rozvytku metodiv otsinky sroku sluzhby rukhomoho skladu zaliznyts. Visnyk sertyfikatsii zaliznychnoho transportu, 8, 44–47.
4. Leonets, V. A. (2017). Vplyv tryvaloi ekspluatatsiyi zaliznychnoho rukhomoho skladu na pratsezdatnist yoho nesuchykh konstruktsiy. Zaliznychnyi transport Ukrainy, 1, 24–31. Available at: http://nbuv.gov.ua/UJRN/ZTU_2017_1_6

5. Li, X., Fang, J., Zhang, Q., Zhao, S., Guan, X. (2020). Study on Key Technology of Railway Freight Car Body Fatigue Test. Journal of Failure Analysis and Prevention, 20 (1), 261–269. doi: https://doi.org/10.1007/s11668-020-00828-7
6. Barbas, I. H., Kostritsa, S. O., Datsenko, V. N., Sultan, A. V., Dzychkovskyi, Ye. M., Krivchykov, A. Ye. (2009). The study of dynamics and strength of hoppers (review article). Science and Transport Progress, 30, 27–32. doi: https://doi.org/10.15802/stp2009/14600
7. Sulym, A., Khozia, P., Strynzha, A., Rechkalov, V., Fedorov, V. (2022). Approaches and prospects of improvement of dump cars for operation on 1520-mm mainline railways. Collection of Scientific Works of the State University of Infrastructure and Technologies Series "Transport Systems and Technologies," 39, 51–65. doi: https://doi.org/10.32703/2617-9040-2022-39-6
8. Zhang, Q., Li, X., Ma, Y., Li, W. (2023). Fatigue test loading method for wagon body based on measured load. Railway Sciences, 2 (1), 68–83. doi: https://doi.org/10.1108/rs-01-2023-0001
9. Gawlak, K. (2022). Safety critical components (SCC) in the maintenance management system for railway vehicle. Diagnostyka, 23 (4), 1–9. doi: https://doi.org/10.29354/diag/156166
10. Płaczek, M., Wróbel, A., Buchacz, A. (2016). A concept of technology for freight wagons modernization. IOP Conference Series: Materials Science and Engineering, 161, 012107. doi: https://doi.org/10.1088/1757-899x/161/1/012107
11. Assemkhanuly, A., Niyazova, Z., Ustemirova, R., Karpov, A., Muratov, A., Kaspakbayev, K. (2019). Mathematical and computer models in estimation of dynamic processes of vehicles. Journal of Theoretical and Applied Information Technology, 97 (10), 2803–2820. Available at: http://www.jatit.org/volumes/Vol97No10/14Vol97No10.pdf
12. Poveda-Reyes, S., Rizzetto, L., Triti, C., Shi, D., García-Jiménez, E., Molero, G. D., Santarremigia, F. E. (2021). Risk evaluation of failures of the running gear with effects on rail infrastructure. Engineering Failure Analysis, 128, 105613. doi: https://doi.org/10.1016/j.engfailanal.2021.105613
13. Jagadish, H. V. (2015). Big Data and Science: Myths and Reality. Big Data Research, 2 (2), 49–52. doi: https://doi.org/10.1016/j.bdr.2015.01.005
14. Tang, L., Li, J., Du, H., Li, L., Wu, J., Wang, S. (2022). Big Data in Forecasting Research: A Literature Review. Big Data Research, 27, 100289. doi: https://doi.org/10.1016/j.bdr.2021.100289
15. Fomin, O. V., Prokopenko, P. M., Burlutsky, O. V., Fomina, A. M. (2019). Control testing of freight wagon with the aim of assessing the residual resource of non-construction structures. Scientific Notes of Taurida National V.I. Vernadsky University. Series: Technical Sciences, 3 (2), 177–182. doi: https://doi.org/10.32838/2663-5941/2019.3-2/31
16. Marinkovic, D., Zehn, M. (2019). Survey of Finite Element Method-Based Real-Time Simulations. Applied Sciences, 9 (14), 2775. doi: https://doi.org/10.3390/app9142775
17. Cremonesi, M., Franci, A., Idelsohn, S., O ate, E. (2020). A State of the Art Review of the Particle Finite Element Method (PFEM). Archives of Computational Methods in Engineering, 27 (5), 1709–1735. doi: https://doi.org/10.1007/s11831-020-09468-4
18. Koshel, O. O., Kara, S. V., Hryndei, O. O. (2022). Mitsnisnyi analiz nyzhnoi ramy dumpkara (vahona-samoskyda) z metoiu vyznachennia mozhlyvosti prodovzhennia terminu ekspluatatsiyi. Scientific Collection «InterConf», 111, 439–444. Available at: https://archive.interconf.center/index.php/conference-proceeding/article/view/637
19. Gil, D., Song, I.-Y. (2016). Modeling and Management of Big Data: Challenges and opportunities. Future Generation Computer Systems, 63, 96–99. doi: https://doi.org/10.1016/j.future.2015.07.019
20. Koshel, O., Sapronova, S., Tkachenko, V., Buromenska, M., Radkevich, M. (2021). Research of Freight Cars Malfunctions in Operation. Proceedings of 25th International Scientific Conference. Transport Means 2021, 589–592. Available at: https://transportmeans.ktu.edu/wp-content/uploads/sites/307/2018/02/Transport-Means-2021-Part-II.pdf
21. Koshel, O., Sapronova, S., Bulich, D., Tkachenko, V. (2020). Determination of the Load-Bearing Metal Structures Residual Operation Time of the Ukraine Railway. Proceedings of 24th International Scientific Conference. Transport Means 2020, 228–232. Available at: https://transportmeans.ktu.edu/wp-content/uploads/sites/307/2018/02/Transport-means-A4-I-dalis.pdf
22. Koshel, O. (2022). Varianty vidnovlennia nyzhnoi ramy dumpkara (vahona-samoskyda) z metoiu podalshoi mozhlyvosti prodovzhennia terminu ekspluatatsiyi. Scientific Collection «InterConf+», 22 (113), 431–436. doi: https://doi.org/10.51582/interconf.19-20.06.2022.044