E3S Web of Conferences **460**, 06009 (2023) https://doi.org/10.1051/e3sconf/202346006009
BFT-2023

Development of a mathematical model of the movement of wagons

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Abstract. The article presents the results of modeling displacements and tensions in the flexible elements of cargo fasteners placed with the displacement of the common center of gravity across the car when the rolling stock is moving downhill.

1 Introduction

A technique has not yet been developed for the direct determination of displacements and tensions in the elements of cargo fastenings placed with a displacement of the common center of gravity relative to the longitudinal axis of symmetry of the car, to which longitudinal, lateral and vertical forces are applied simultaneously, as in the static indefinable mechanical system "path wagon – fastening - cargo" [1, 9]. Proceeding from this, it can be noted that securing cargo while moving rolling stock along the critical section of the descent path has still remained a completely unsolved applied problem of scientific and practical interest and is relevant in the railway transport and transportation science industry.

The novelty of the mathematical model considered by us with an asymmetric placement of the overall center of gravity of the oversized cargo of the rear of the car, from the one previously considered in [2, 10], is the determination of displacements and tensions in the flexible elements of the cargo fastenings with the simultaneous action of longitudinal, transverse and vertical forces when moving the rolling stock along a curved section of the track on the descent, taking into account, *firstly*, the moment of inertia forces additionally applied to the load from the lateral pitching of the M_x and galloping of the M_y car with the load and, *secondly*, the moment of forces when the M_{yaw} car is "yawing", arising during full service braking of the rolling stock, for example, when the train is moving downhill.

Problem statement. The improvement of the methodology for calculating the tension in the flexible elements of oversized cargo fasteners with the simultaneous action of longitudinal, transverse and vertical forces on the mechanical system "cargo - fastening - wagon" and when moving rolling stock along a curved section of the track to the descent, first of all, should be aimed at ensuring the safety of train traffic and safe transportation of goods through the path of following. The need to solve the problem of securing non-dimensional cargo when moving rolling stock along a curved section of the track under the action of transverse and vertical forces is justified in [2, 11]. There is still no mathematical

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model that would directly determine the tension in the flexible fastening elements (stretchers, bindings) of an oversized cargo placed with a displacement of the general center of gravity relative to the longitudinal axis of symmetry of the car when the train is moving along a curved section of the track on the descent. The solution of such a problem is of scientific and practical interest and is relevant in the railway transport industry.

Accepted assumptions. Let us assume the same assumptions as those adopted in the work [2, 12]. So, for example, we will take into account the draft of sets of springs on the side frame of the car, located on the side of the inner rail thread due to the elevation of the outer rail thread η, the asymmetric displacement of the load relative to the longitudinal axis of symmetry of the car in one direction or another $\pm yM$, and the associated tilt of the car frame towards both the outer and internal rail thread $\pm\zeta$.

2 Materials and methods

We present a physical model of the placement and fastening of oversized cargo in a wagon placed with the displacement of the general center of gravity of the $\mathbf{CG^o_c}$ relative to the longitudinal axis of the wagon (Fig.1).

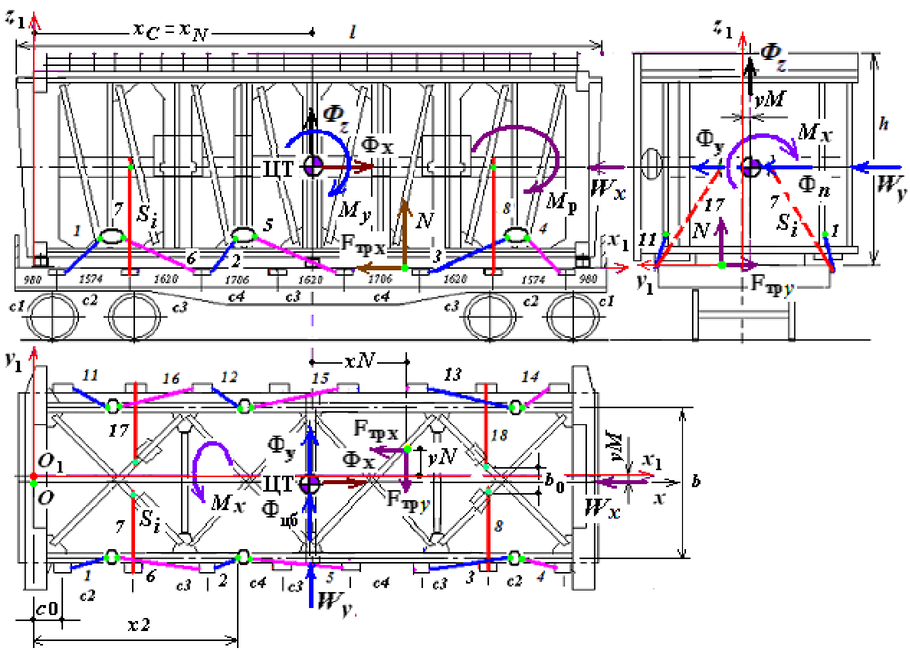

Fig. 1. Physical model of cargo placement and fastening

It should be especially noted that the mounting loops of oversized cargo relative to the transverse axis of symmetry of the car are placed asymmetrically. In accordance with this, among the flexible fastening elements there are fasteners whose lengths are different and which are asymmetrically located relative to the transverse axis of symmetry of the car. For example, the fastening element 2, designed to perceive the longitudinal force in one direction, is shorter in length (0.938 m) than the fastening element 5 (2.146 m), designed to perceive the longitudinal force in the other direction. Moreover, the mounting loops of the load for securing both fasteners 2 and 5 are located to the left of the transverse axis of symmetry of the car (see Fig. 1).

The dynamic model of fastening an oversized cargo placed with a displacement of the common center of gravity relative to the longitudinal axis of the carriage's symmetry when moving the rolling stock along a curved section of the way to the descent, we present in the form shown in fig. 2.

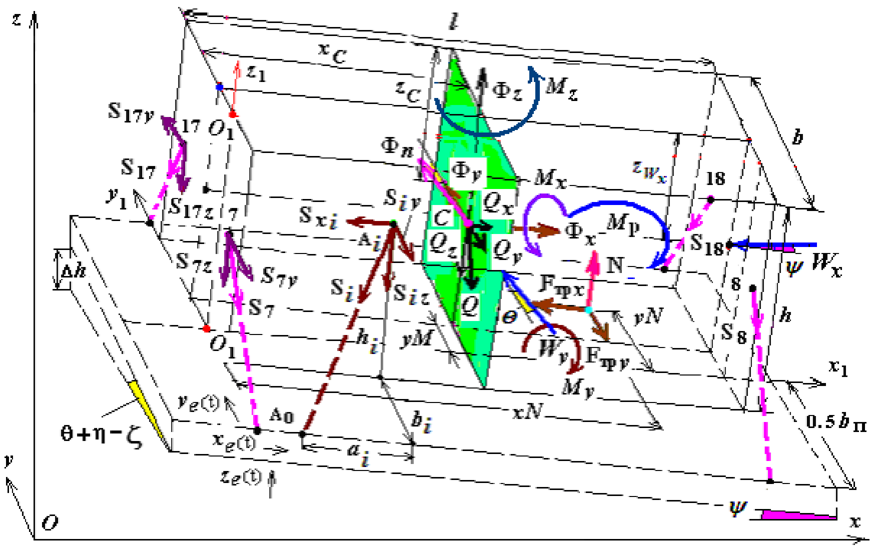

Fig. 2. Dynamic model of cargo placement and fastening

Considering the forced oscillations of the load placed on the oscillating platform, as in [3,4], with kinematic excitation, it was assumed that the cause of the load oscillations are the given fluctuations of the point of attachment of the load with the wagon with the adopted law in the form of xe(t), ye(t) and ze(t). Using the Dalembert principle, the action of these bonds is replaced by longitudinal F_e^x, transverse F_e^y and vertical F_e^z portable inertia forces.

The dynamic model shows these forces - longitudinal portable inertia force Fx $=F_e^x$, arising from the presence of elastic elements (springs) in the design of the automatic coupling device and during descent in service braking or release mode; transverse portable inertia force Fy = F_e^y, arising from the presence of elastic elements (sets of springs) in the design of the bogies of the car, as well as from the lateral bearing of the car due to the presence of a lateral gap between the ridges of the wheels and the rails, which ranges from 20 to 45 mm [5, 13]; the vertical portable force of inertia Fz = F_e^z, arising from the presence of elastic elements (spring components) in the construction of the car bogies, as well as from the bouncing of the car with the load during the passage of a wave of unevenness of the track.

Let us explain the physical reason for the appearance of portable inertia forces. In this case, let's consider the relative motion of the load, i.e. the motion with respect to the non-inertial reference frame O1x1y1z1 [6, 14], which moves arbitrarily with respect to the inertial reference frame Oxyz, for example, associated with the train departure station. The appearance of the transfer forces of inertia is due to the effect on the relative movement of the load of the displacement of the movable axes O1x1y1z1. Here it is assumed that the movable axes O1x1y1z1 move relative to the fixed axes Oxyz progressively with accelerations aex, aey and aez. In this case, with respect to the axes O1x1y1z1, any point associated with the reference frame Oxyz will have the accelerations -aex, -aey and -aez. The main reason for the appearance of these accelerations will be the kinematic - motion of the moving reference frame O1x1y1z1 connected to the platform [7, 15], i.e. with the rolling stock moving at the speed of the train v along a curved section of the track with the radius of curvature ρ of the trajectory at this point. Thus, in the non-inertial reference frame O1x1y1z1, the load is accelerated as a result of the accelerated motion of the reference system itself. Otherwise, the cause of the load fluctuations are the specified fluctuations of the attachment point of the flexible elements of the fastenings of this load, which are directly connected with the linking devices of the car.

In this regard, we will essentially consider the forced fluctuations of a device placed on an oscillating platform. Permissible values of accelerations of a car with a load are established experimentally and normalized [8, 16].

The dynamic model also shows the friction force along the longitudinal and transverse axes Ffrx and Ffry; wind loads applied along the frontal and lateral sides of the load Wx and Wy.

In addition, the number of the transverse force when the train is moving along a curved section of the track also includes the normal inertia force Fn. We will also take into account the effect of the moment of inertia forces on the load from the lateral pitching of the Mx and the galloping of My wagon with the load, the moment from the "yaw" of the wagon with the load of the Myaw.

It should be particularly noted that in the dynamic model, the portable inertia forces are applied to the center of gravity of the load, and are perceived by flexible elastic means of fasteners, and not by the load [7, 17].

3 Results and discussion

The occurrence of the moment of Myaw forces is explained by the inclination of the front part of the car with the load, i.e. "yawing" of the car, with service (full or emergency) braking of the rolling stock when the train is moving, both on a curve and on a straight section of the way to the descent. The moment of forces during the "yawing" of the car can be determined by the formula

$$M_{yaw} = (Q_x + F_x)(h_{car} + h_c) \quad (1)$$

where Q_x – is the projection of the weight of the load on the axis *Oh, kN: hcar, hc* – is the height of the floor of the car from the level of the rail heads and the height of the center of gravity of the load from the floor of the car in m.

The projections of the weight of the load on the accepted coordinate axes will be as follows

$$Q_x = Q\sin\psi\,;\; Q_y = Q\sin(\theta + \eta - \zeta)\,;$$
$$Q_z = Q\cos\psi\cos(\theta + \eta - \zeta)\,, \quad (2)$$

where Q is the weight of the load, ψ is the angle characterizing the movement of the train downhill, θ is the angle characterizing the elevation of the outer rail thread relative to the inner one.

From formula (2) it is obvious that when the train is moving downhill with the simultaneous action of the longitudinal inertia force and the wind load acting from the frontal side of the load, the load capacity of the flexible fastening elements will decrease, since in this case Qx will be like a shifting load force. As in [2, 18], it is obvious that the displacement of the total center of gravity of the load of the CGoc towards the inner rail thread (-yM) with the simultaneous action of transverse inertia forces and wind load when the train is moving along a curved section of the track will contribute to an increase in the load capacity of flexible fastening elements, since in this case Qy it will be, as it were, a holding force that has a greater significance than the same force that occurs when the general center of gravity of the load of the CGoc moves towards the outer rail niche (+yM).

The following designations are also adopted in the calculation scheme: xC – the position of the center of mass of the cargo from the accepted origin to the transverse axis of symmetry of the car, m; zC – the location of the center of mass of the cargo relative to the abscissa axis Oh; xM – the location of the center of mass of the cargo relative to the transverse axis of symmetry of the car; zWx – the coordinate of the point of application wind load relative to the abscissa axis Oh; xN – coordinate of the point of application of the coupling reaction N relative to the origin; 01Ai (i=1…n) – distance from the accepted origin to the mounting loops of the load; h, b and l height, width and length of the load; b0 – the width of the base of the load; ayaw, byaw and hyaw – are projections of a flexible element with a length lyaw, respectively, on the longitudinal, transverse and vertical axes of the load.

Determining the Si ($i = \overline{1,n}$) tensions in the flexible fastening elements of a non-barite cargo placed on an open railway rolling stock, with any number of n of these fastening elements, taking into account the pre-tension forces S0i, is a statically indeterminate task, and the mechanical system "path – wagon – fastening - cargo" - is statically indeterminate system [1, 19].

Solution methods. The problem is solved using the basic provisions of theoretical mechanics (the principle of freedom from bonds, the conditions of relative equilibrium, Coulomb's law, the Da Lambert principle), the resistance of materials (the cross-section method, Hooke's law) and computational mathematics using the numerical method, in particular, the method of iterations using the capabilities of the MathCAD tool environment [9, 20].

Based on the application of general formulations and the solution of statically indeterminate problems of finding forces in cargo fastenings [3, 4, 10, 21], the relations necessary for finding forces in flexible elements of cargo fastening, essentially representing a mathematical model of the mechanical system "cargo – fastening – wagon - path":

the shear force along the Ox axis, are compiled:

$$\sum_{i=1}^{n} S_i \frac{\Delta x_i}{l_i} + \Phi_x + Q_x - W_x \cos\psi = T_x; \tag{3}$$

friction force on the Ox axis:

$$F_{\text{fr}x} = if(N > 0, if(T_x < fN, -T_x, -fN), 0) \tag{4}$$

sum of force projections on the Ox axis:

$$T_x + F_{\text{fr}x} = 0 \tag{5}$$

the shear force along the Oy axis:

$$\sum_{i=1}^{n} S_i \frac{\Delta y_i}{l_i} + (F_y + F_n + W_y)\, cos(\theta + \eta - \zeta) - Q_{\text{y}} = T_y \tag{6}$$

the friction force along the Oy axis:

$$F_{\text{fr}y} = if(N > 0, if(T_y < fN, -T_y, -fN), 0) \tag{7}$$

the sum of the projections of forces on the Oy axis:

$$T_{\text{y}} + F_{\text{fr}x} = 0 \tag{8}$$

the sum of the projection of forces on the Oz axis:

$$\sum_{i=1}^{n} S_i \frac{\Delta z_i}{l_i} - (F_y + F_{sb} + W_y)\, sin(\theta + \eta - \zeta) - (Q_z + W_x\, sin\,\psi) + \Phi_z + N = 0 \tag{9}$$

sum of moments of forces around the Ox axis:

$$\sum_{i=1}^{n} S_i \frac{\Delta z_i}{l_i} y_i + \sum_{i=1} S_i \frac{\Delta y_i}{l_i}(-\Delta z_i) - \left[(F_y + F_n)z_C + W_y z_W\right] cos(\theta + \eta - \zeta) + \\ + W_y \, sin(\theta - \zeta) 0.5 b_0 + Q_y z_C - (Q_z - \Phi_z) yM - M_{\text{x}} + N y_N + F_{fry} h = 0 \quad (10)$$

sum of moments of forces around the Oy axis:

$$-(\sum_{i=1}^{n} S_i \frac{\Delta z_i}{l_i} \text{x}_i) + \sum_{i=1} S_i \frac{\Delta x_i}{l_i} \Delta z_i + \left[(F_y + F_{sb})x_C + W_y x_W\right] sin(\theta + \eta - \zeta) + (Q_z - F_z)x_{\text{C}} \\ + (Q_x + F_x) z_C - W_x \cos\psi \, z_{Wx} + W_x \sin\psi \, x_{Wx_y} + \\ + (M_y + M_{\text{p}}) N x_N + F_{fr\text{x}} h = 0 \quad (11)$$

sum of moments of forces around the Oz axis:

$$\sum_{i=1}^{n} S_i (\frac{\Delta y_i}{l_i} x_i - \frac{\Delta x_i}{l_i} y_i) + \left[(\Phi_y + \Phi_{sb}) x_C + W_y x_W\right] cos(\theta + \eta - \zeta) - Q_y x_C + \\ F_{fry} x_N - F_{fr\text{x}} y_N = 0 \quad (12)$$

deformation relations:

$$[(\Delta x - \sum_{i=1}^{n} y_i \Delta\varphi) \sum_{i=1}^{n} \frac{\Delta x_i}{l_i} + (\Delta y + \sum_{i=1}^{n} x_i \Delta\varphi) \sum_{i=1}^{n} \frac{\Delta y_i}{l_i}] = -\sum_{i=1}^{n} (S_i - S_{0i}) \frac{l_i}{EA} \quad (13)$$

where x i, yi, zi are the x, y, z coordinates of the upper mounting loops of flexible elements; Si (i = 1…i is the number of such fastening elements); li – the lengths of flexible fastening elements (i.e. stretch marks or strapping); Δxi , Δyi , Δzi are the projections of flexible elements on the axis Ox, Oy, Oz.

Expressions (3) and (13) use the following notation (see Fig.1): Δx, Δy, Δφ – the sought values of small movements of the load along the axis Ox, Oy in m and its rotation around the axis Oz in rad.; EA – physical and geometric characteristics (tensile stiffness) of the flexible element in kN. Here E is the elastic modulus of a flexible element twisted from annealed steel wire, kNpm2 (E = 1·104 MPa) [11], Ai – the cross–sectional area of the flexible element in m2: $A_i = n_i \cdot \frac{\pi \cdot d_i^2}{4}$ taking into account that ni is the number of threads in the i-th flexible element in pcs.; di is the wire diameter of the flexible element in m; 0.5l, yC, xW, zC, zWx are the coordinates of the points of application of the longitudinal, transverse and vertical forces of inertia and wind load, respectively, along the axes Ox, Oy and Oz; N and xN are as yet unknown values of the normal coupling reaction in kN and the coordinates of the point of its application; S0i are the initial tensions of the flexible fastening elements.

Thus, it can be noted that the compiled system of algebraic equations in the form (3)... (13) taking into account the nature of the change in the friction force, it is essentially a mathematical model of an oversized cargo fixed with a displacement across the carriage, which allows you to directly determine the tension in the flexible elements of the fasteners, the normal coupling reaction and the coordinate of the point of its application, the values of cargo movements along the longitudinal and transverse axes of the carriage, as well as its rotation around the vertical axis.

For example, we present the results of computational experiments to assess the combined effect of longitudinal, transverse, vertical portable accelerations on the movement of cargo and tension in flexible elements of fasteners, conducted using the MathCAD computing environment.

By the method of sequential selection, the following maximum values of longitudinal, transverse and vertical portable accelerations of an oversized cargo symmetrically placed in the car were established in the absence of lateral pitching (εx = 0) and galloping of the car with a load (εy = 0): aex = 0.21g, aey = 0.28g and aez = 0.66g, at which the tension values in the most loaded flexible fastening elements 2 (as the shortest fastening element in length) and 7 (as a fastening element placed perpendicular to the side of the load) do not exceed the permissible (38.7 kN).

Initial data with symmetrical placement of cargo in the car and the presence of an elevation of the outer rail thread:

f = 0,4, Δh = 0,104 m, yM = 0, ρ = 1200 m, v = 100 kmph, Q = 294.3 kN (30 ts), Qx = 0, Qu = 20.98 kN, Qz = 293.551 kN, Fn = 19.29, Wy = 3.998, Wx = 0.222 kN, Fx = 61.8 (aex = 0.21g); Fu = 82.4 (aey = 0.28g); Fz =135.378 kN (aez = 0.66g), θ = 3.75 deg., η = 0.338 deg., ζ = 0 deg., δz0 = 0.006 m, δz = 0, n = 6 pcs ∅6 mm.

Results of computational experiments. As a result of the conducted research, the following results were obtained:

the load-shifting forces Tx and Ty, the friction force Ffr, the normal coupling reaction Nv kN and the coordinates of the point of its application xN and yN in m –

Tx = -69,5, Ty = 31,69, Ffrx = 69,5, Ffry = -31,69, N = 201,858, N/Q = 0,686, Ffr = 80,743, xC = 6,21, xN = 6,98, yN = -0,0035;

the movement of the load along the longitudinal Δx and transverse Δy at the axis of symmetry in m, as well as rotation around the vertical axis Δφ in degrees. – Δx = 9,58, Δx = 19, Δφ = -0,023;

tension in the flexible elements of Si fasteners operating on the longitudinal axis in kN –

S2 = 38,68, S1 = 34,73 , S3 = 28,64, S12 = 34,78 (l2 = l12 = 0,938 m), S11 = 32,33 (l1 = l11 = 1,18 m), S13 = 28,64 (l3 = l13 = 1,918 m);

tension in flexible elements of Si fasteners working on tension along the transverse axis in kN –

S2 = 38,68, S1 = 34,73, S4 = 8,9, S7 = 38,48, S8 = 35,23, S3 = 28,64, S6 = 12,87, S5 = 13,5, S12 = 34,78 (l2 = l12 = 0,938 m), S11 = 32,33 (l1 = l11 = 1,18 мм), S14 = 4,4 (l4 = l14 = 1,18 m), S17 = 1,7, S18 = 5,0 (l7 = l8 = l17 = l18 = 1,304 m), S13 = 28,36 (l3 = l13 = 1,918 m), S16 = 10,54 (l6 = l16 = 1,918 m), S15 = 11,67 (l5 =l15=2,146 m).

Analysis of research results. The results of the research showed that when the oversized cargo was symmetrically placed relative to the longitudinal axis of symmetry of the car, the combined actions of longitudinal, transverse and vertical forces caused the load to shift, respectively, along and across the car by Δx = 9.6 and Δy = 19 mm. At the same time, there was a shift of the load around the vertical axis opposite to the direction of counting angles by Δφ = -0.023 degrees. The coordinates of the application of the normal feedback N are equal to xN = 6.98 and yN = -3.46 mm.

The tension in the most loaded flexible elements of fasteners 2 (having the smallest length) and 7 (located perpendicular to the side surface of the load), respectively, are 38.68 and 38.5 kN, which is less than the permissible value (38.7 kN).

From the simultaneous actions of longitudinal, transverse and vertical tension forces in the flexible elements of fasteners 2, 1 and 3, designed to keep the load from shifting only along the car, are distributed proportionally to their lengths. Moreover, the smaller the length of the flexible element, the greater the force it is able to perceive, i.e. S2 = 38.68, S1 = 34.73, S3 = 28.64 kN in accordance with their length l2 < l1 < l3 (0.938 < 1.18 < 1.918). The tension in the flexible elements of fasteners 12, 11 and 13 is less (i.e. S12 = 34.783, S11 = 32.33, S13 = 28.36 kN), than the fastening elements 2, 1 and 3, since they are located on the opposite side of the oversized cargo to the action of transverse forces.

The simultaneous actions of longitudinal, transverse and vertical tension forces in the flexible elements of fasteners 7 and 8 having the same length (l7 = l8 = 1.304m), located perpendicular to the side of the load and designed to keep the load from shifting only across the car, have different values, i.e. $S7 = 38.48$ and $S8 = 35.23$ kN. Moreover, the flexible element 7, located on the side of the short-length element 2, which is designed to perceive longitudinal forces, is more loaded than the element 8, located on the side of the long-length element 3, which is also designed to perceive longitudinal forces. The physics of this fact is explained by the rotation of the load in relation to the direction of the angles (clockwise), which is why the flexible element 8, placed on the right side of the load relative to the transverse axis of symmetry of the car, has a reduced projection on the transverse axis. In the flexible element 7, placed on the left side of the load relative to the transverse axis of symmetry of the car, on the contrary, the projection on this axis increases.

It is also established that the flexible elements of fasteners 4 and 14, 5 and 15, 6 and 16, designed to keep the load from shifting along the carriage in the opposite direction, do not perceive the applied forces at all. The proof of this is the lower value of the tensioning in these elements of the fasteners than the tensioning of the preliminary twists $S0i = 20.1$ kN.

Thus, it is established that in the absence of side pitching fluctuations ($\varepsilon x = 0$) and galloping of a car with a load ($\varepsilon y = 0$), any deviation in the direction of an increase (or decrease) in the values of aex (for example, $0.21g < aex < 0.20g$) and aey (for example, $0.28g < aey < 0.27g$) at $aez = 0.66g$ leads to an increase (or decrease) in the tension values in the most loaded flexible elements of fasteners 2 and 7 more (less) than permissible.

4 Conclusion

1. The proposed approach to the preparation of initial data when placing an oversized cargo with a displacement of its common center of gravity relative to the longitudinal axis of symmetry of the car, taking into account the lateral attitude and galloping of the car with the load, as well as the moment from the "yaw" of the car with the load, subsequently simplifies the compilation of a mathematical model, allowing you to automate the calculation of determining the tension in flexible fastening elements cargo.
2. The compiled mathematical model of the fasteners of the system "path – wagon – fastening - cargo" with the simultaneous action of longitudinal, transverse and vertical forces in the form of systems of algebraic equations allows you to directly determine unknown movements of cargo (along and across the wagon, the rotation of cargo relative to the vertical axis) and the tension of flexible elastic means of fasteners when placing oversized cargo with the displacement of the general center of gravity relative to the longitudinal axis of symmetry of the car when the rolling stock moves along a curved section of the way to the descent.
3. From the simultaneous actions of longitudinal, transverse and vertical forces in the absence of lateral pitching fluctuations ($\varepsilon x = 0$) and galloping of the wagon with the load ($\varepsilon y = 0$), the tension in the flexible fastening elements intended to keep the load from shifting only along the wagon is distributed proportionally to their lengths. Moreover, the smaller the length of the flexible element, the greater the force it is able to perceive, i.e. $S2 = 38.68$, $S1 = 34.73$, $S3 = 28.64$ kN in accordance with their length $l2 < l1 < l3$ ($0.998 < 1.18 < 1.918$ m).
4. From simultaneous actions of longitudinal, transverse and vertical forces in the absence of lateral pitching fluctuations ($\varepsilon x = 0$) and galloping of the wagon with the load ($\varepsilon y = 0$) tension in flexible fastening elements having the same length, located perpendicular to the side of the load and designed to keep the load from shifting only across wagons have different meanings. Moreover, the flexible element located on the side of a short-length element designed to absorb longitudinal forces is more loaded than the one designed to perceive longitudinal forces of the opposite direction, i.e. $S7 = 38.48$ and $S8 = 35.23$ kN ($l7 = l8 = 1.304$ m). The physics of this fact is explained by the rotation

of the load opposite to the direction of the angles (clockwise), which is why the flexible element 8, placed on the right side of the load relative to the transverse axis of symmetry of the car, has a reduced projection on the transverse axis. In the flexible element 7, placed on the left side of the load relative to the transverse axis of symmetry of the car, on the contrary, the projection on the transverse axis increases.

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