

Assessment of Forces Acting on the Gondola Car Body during Transportation of Rolled Wire Bundles

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Abstract: The article gives an assessment of the possible reasons for the fall of a gondola car wall onto the side track, which occurred on the section of the regional branch of the Pridneprovskaya Railway. To determine the possible reasons for the breakage of the car side wall, a comparison of the forces acting from the side of rolled wire bundles on the car body structure with permissible loads on the body elements was made. Vertical and transverse inertial forces and forces from the load thrust were considered as such forces. The total loads obtained as a result of the calculation do not exceed the permissible values for gondola car bodies and confirm that the considered local technical conditions for stowing rolled wire bundles met the current requirements and did not cause a breakage of the side wall of the gondola car body.

Keywords: gondola car; inertial forces; load thrust forces; rolled wire bundle; stowing and securing of cargo; strength

1 INTRODUCTION

Traffic safety on railways depends not only on the maintenance of rolling stock and infrastructure, but also, to a large extent, on the reliability of cargo securing and its stowing in the rolling stock in accordance with the existing standards. The diverse range of cargoes transported by rail requires both a variety of types of freight cars and a significant amount of technical documentation establishing methods for stowing and securing cargo (local technical conditions – LTC, unforeseen technical specifications of UTS and sketches). The need to develop technical conditions is caused by the specifics of a particular cargo and the conditions for its securing, not provided for by the technical conditions for stowing and securing cargo in cars and containers [1, 2]. The development of technical conditions is associated not only with ensuring the reliability of securing, preservation of cargo and rolling stock, but also with the need for rational use of the body volume, carrying capacity of the car and ensuring the minimum cost of the securing method (labor intensity of handling operations, the cost of materials and securing elements). Compliance with these requirements, which may contradict each other, is the main task during the development of cargo stowage and securing schemes. Non-compliance with these requirements results in increase in the cost of transportation or uncoupling of cars along the route due to the displacement/falling of cargo, weakening/breakage of securing means, exceeding the loading gauge, etc., as a result of which both the consignors and the railways bear significant financial costs [3].

In July 2020, on the Voskoboynya – Verkhnedneprovsk section of the regional branch of Pridneprovskaya Railway the side wall of the gondola car body fell onto the track during the train movement, followed by the loss of 14 bundles of rolled wire. Falling of cargo under the rolling stock has led to the derailment of three cars and a locomotive of the train, which was moving along an adjacent track (Fig. 1) [4].

The reason for the fall of the side wall of the car body, which had an extended service life, was its break from the

corner posts with subsequent bending of the intermediate transverse beams and breakage from all transverse beams due to poor-quality welded joints between them.



Figure 1 Consequences of a transport accident on the Voskoboynya – Verkhnedneprovsk section

It was established that the transport accident occurred due to the breakage of the side panel from the fastening points, namely the bolster and intermediate beams and from the end posts and end beam, due to the presence of significant metal corrosion at the points of their connection (Fig. 2).



Figure 2 Breakage of the side panel from the fastening points

Another reason was considered the exceedance of the lateral loads from the transported cargo on the side wall due to the incorrect calculations when developing a method for its stowing in a gondola car.

2 LITERATURE REVIEW AND PROBLEM DEFINITION

When developing technical conditions for stowing and securing of cargoes, as noted in the works [1, 5], the human factor associated with violations of the technological process of stowing and securing of cargoes, which is most often manifested in the supply of faulty cars for loading, excess of the permissible load capacity of the car, uneven cargo stowage should be taken into account. All this can result in serious damage to cargo, rolling stock and railway infrastructure. The human factor can also be associated with the imperfection of the developed securing schemes and errors in them.

In order to increase the reliability of cargo securing when transporting it in the gondola cars, work [6] proposes a modernization option. It provides for the implementation of pull-out bars, which will increase the reliability of cargo securing when loading with a "hat" that is beyond the upper strapping of the side wall.

The works [7-11] are devoted to the problem of calculating the strength of the body and the frame of the freight cars. The results of works [6, 12] confirm the sufficient body strength, but they do not take into account the nuances of the transportation of bundles related with the action of a concentrated load, which is applied to the body posts in two places along the body height, which depends on the bundle diameter. In work [8], the structural strength of a universal flat car is estimated when a specialized frame with containers is placed on it. The articles [10, 12] analyze the residual life of gondola cars, depending on the service life and the car body material under conditions of acting operating loads and corrosive wear. Based on the results of the presented studies, it was found that the resource of the supporting body elements is 29-37 years, depending on the level of corrosion damage. However, the work did not take into account the human factor, and the traffic accident on the Voskoboynya – Verkhnedneprovsk section was caused by non-compliance with the requirements of TsV-0142 "Cars of freight railways of Ukraine with 1520 (1524) mm gauge. Depot repair instructions" and the requirements of STP 04-020:2018 "Freight cars and containers. Welding and welding deposition instructions".

To transport rolled wire along the main routes, shippers choose general-purpose gondola cars, it is possible to transport wire in specialized and modernized flat cars for transporting sheet steel. But, in this case, there is a significant underutilization of the carrying capacity of the car due to the impossibility of bundle stowing in two tiers, which significantly increases the transportation cost.

The article [13] describes the capabilities and advantages of an automated system for the development of technical conditions for the stowing and securing of cargoes in cars and containers. The decision-making algorithm makes it possible to automate the process of developing technical conditions, taking into account the possibility of two-axis displacement of the cargo in the car. The article [14] presents a method for the automated calculation of the efforts value in the cargo securing elements. Automated calculation methods make it possible to determine the value of cargo displacement both along and across the car from the action of longitudinal, transverse and vertical forces perceived by the cargo during

transportation. The given method allows optimizing the choice of the mounting location of the support frames, depending on the geometric parameters of the load and the selected method of its securing.

When developing schemes for placing and securing cargo, compliance with the permissible displacement of the cargo gravity center is mandatory. In this case, it is essential to take into account the possible cargo displacement during transportation by rail. The works [15, 16] are devoted specifically to the issue of determining the influence of the longitudinal and transverse displacement of the gravity center of a heavy cargo, taking into account the movement speed, on the main dynamic indicators – maximum coefficients of dynamic increment of sprung and unsprung parts, the maximum ratio of frame force to static axial load, and derailment stability coefficient.

The requirements for stowing and securing of rolled wire bundles on the railways of the member countries of the Organization for Railways Cooperation are established by Appendix 3 to the Agreement on International Goods Transport by Rail. According to it, one of six schemes is selected depending on the carrying capacity of the car, the mass and size of the bundles. The bundles with a diameter of 1150-1400 mm, a length of 450-750 mm and a weight of 500-850 kg are placed in a gondola car in two rows across the width and two tiers along the height of the car. In the lower tier, the bundles are located closely from the ends to the middle of the car. One half of the tier is displaced to one side wall of the car, and the other to the opposite wall. The upper tier of the bundles is placed on the lower tier bundle similarly to it, displaced to the side walls in the opposite direction (Fig. 3a).

The rolled wire bundles in the car in transport accident on the Voskoboynya – Verkhnedneprovsk section, were stowed according to the LTC developed and approved by the consignor (Fig. 3b). The main difference from the previous scheme shown in Fig. 3 is large dimensions and weight of bundles. Bundle diameter D up to 1250 mm, length up to 2400 mm, and weight up to 2500 kg.

The scheme of rolled wire transportation in accordance with the requirements of the European Railways [12], which provides for its securing by wooden profile, lashing straps and cartons laid between the bundles is shown in Fig. 3c.

Based on the above-mentioned works, we can conclude that the work related to increasing the reliability of cargo stowing and securing in the cars and containers is undoubtedly relevant and timely. Its solution requires accounting a significant number of factors that affect both traffic safety and the economic aspects of the cargo transportation by rail. The analysis of wire stowing and securing schemes in gondola cars showed the presence of various approaches to the stowing and securing of rolled wire.

The purpose of this case study is to analyze the forces acting on the gondola car body when transporting wire bundles, and to assess the body strength. To achieve this purpose, it is necessary to calculate the forces acting on the gondola car body when transporting wire bundles and to assess the strength of the gondola car body.

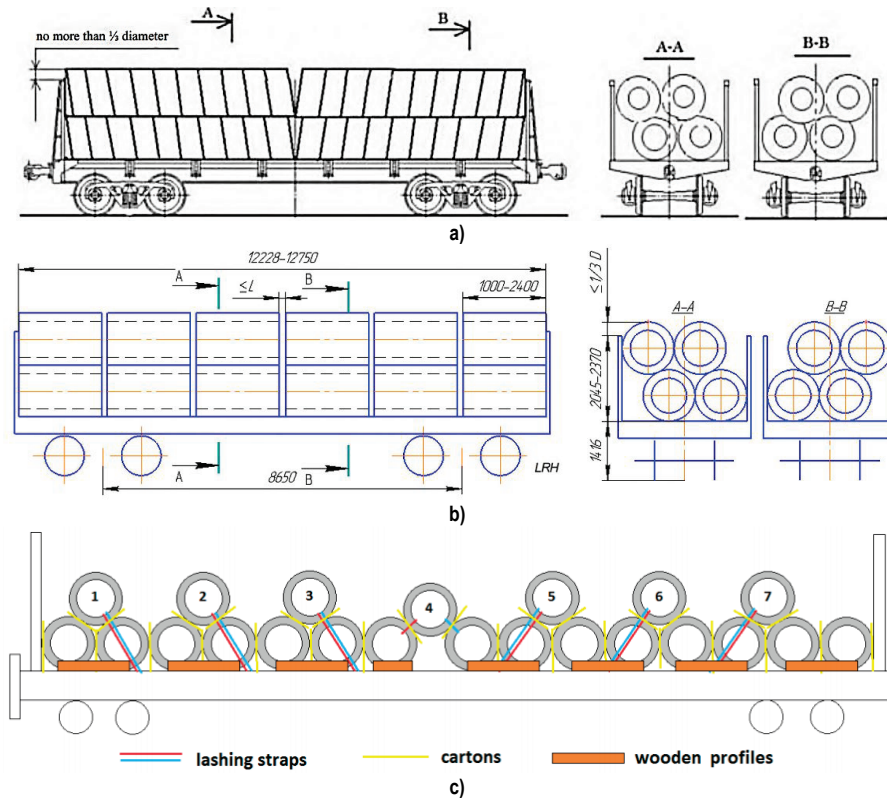


Figure 3 Stowage of rolled wire bundles in a gondola car: a) in accordance with the requirements of Appendix 3 to the Agreement on International Goods Transport by Rail; b) in accordance with the LTC; c) in accordance with the requirements of the European Railways

3 CALCULATION METHODOLOGY

The stowage scheme of the gondola car bundles is shown in Fig. 3 b. Wire in bundles with an outer diameter of 1150-1250 mm and a weight of 1000-2500 kg is stowed in gondola cars with blank end walls in two tiers, two rows in each tier. To load the wire uniformly along the car length, it is loaded alternately from the gondola car ends to the middle. In the lower tier, the bundles are stowed with a displacement of half of the tier close to one side wall of the gondola car, the second half – close to the opposite wall. In the upper tier, the bundles are stowed on the bundle of the lower tier similarly to the lower one, with a displacement to the side walls in the opposite direction (Fig. 4).

The number of bundles in a row depends on their height and the length of the car body and can be from 5 to 12 pieces, and in a car – from 20 to 48 pieces. When stowing the wire bundles without gaps, the maximum weight of the load can be 69 tons. The part of the upper tier bundles going beyond the upper strapping of the gondola car should not exceed 1/3 of the bundle diameter [17].

According to the standard parameters, the mass of the wire bundle will be 1.425 tons, and the total weight of the load will be 68.4 tons. The point of application of longitudinal, transverse, and vertical inertial forces is the center of gravity of the load (CG).

The calculation of the required parameters, permissible displacements of the general center of gravity of the cargo and inertial forces is carried out in accordance with the

methodology described in Chapter 1 of Appendix 3 to the Agreement on International Goods Transport by Rail [2].



Figure 4 Rolled wire bundles after collisions according to the corrected LTC scheme

The height of the general center of gravity of the car with cargo is determined by the dependence:

$$H_{gc}^o = \frac{Q_{w1} \cdot h_{w1} + Q_{w2} \cdot h_{w2} + \dots + Q_{wn} \cdot h_{wn} + Q_{uw} \cdot H_{gc}^{emp}}{Q_w^o + Q_{uw}}, \quad (1)$$

$$H_{gc}^o = 2296 \text{ mm} < 2300 \text{ mm}. \quad (2)$$

where Q_{uw} – wagon tare weight, t; $h_{w1}, h_{w2}, \dots, h_{wn}$ – height of the CG of cargo units from the level of the rail heads

(LRH), mm; H_{gc}^{emp} – CG height of an empty car from the LRH, 1130 mm. Since the obtained value does not exceed the permissible value, the stability of the car is ensured.

The permissible longitudinal displacement of the overall center of gravity of the cargo in a 4-axle car is determined by linear interpolation in accordance with the regulatory document [2]. The values of the displacements of the total center of gravity of the cargo are determined from the corresponding tables depending on the total weight of the cargo and the permissible displacement during the transportation of the cargo along the route.

When loading:

$$\ell_{w-69}^{\ell} = \ell_{w-67}^{\ell} - \frac{\ell_{w-67}^{\ell} - \ell_{w-70}^{\ell}}{70 - 67} \cdot (69 - 67) = 66.67 \text{ mm.} \quad (3)$$

In transit:

$$\ell_{w-69}^t = \ell_{w-67}^t - \frac{\ell_{w-67}^t - \ell_{w-70}^t}{70 - 67} \cdot (69 - 67) = 126.67 \text{ mm.} \quad (4)$$

Further calculation of the forces acting on the body of the gondola car when transporting wire in bundles, as well as assessment of the strength of the body, is carried out at the maximum possible value of the permissible longitudinal displacement of the total center of gravity of the load $\ell_w = 127$ mm.

Longitudinal inertial force is calculated by the equation:

$$F_{long} = a_{long} \cdot Q_w, \quad (5)$$

where Q_w – weight of cargo, including accessories, t; a_{long} – specific longitudinal inertial force, which is calculated by the equation:

$$a_{long} = a_{22} - \frac{Q_w \cdot (a_{22} - a_{94})}{72}, \quad (6)$$

where a_{22} , a_{94} – specific longitudinal inertial forces, $a_{22} = 1.2$ tf/t, $a_{94} = 0.97$ tf/t.

The transverse inertial force is determined by the equation:

$$F_{tr} = a_{tr} \cdot Q_w, \quad (7)$$

where a_{tr} – specific transverse inertial force, which is calculated by the equation:

$$a_{tr} = a_c + \frac{2 \cdot (a_b - a_c)}{L_b} \cdot \ell_w, \quad (8)$$

where a_c , a_b – specific transverse inertial force for cargo located inside the car and above the body bolster, respectively, $a_c = 0.33$ tf/t, $a_b = 0.55$ tf/t; ℓ_w – distance from

the center of gravity (CG) to the transverse axis of the car, mm; L_b – wheel base, 8650 mm.

The vertical inertial force is found by the equation:

$$F_v = a_v \cdot Q_w, \quad (9)$$

where a_v – specific vertical inertial force (kgf/t);

$$a_v = 250 + k \cdot \ell_w + \frac{2140}{Q_w}, \quad (10)$$

where $k = 5$ – loading factor per car. The specific vertical inertial force is determined for a speed of 100 km/h.

Wind load is determined by the equation:

$$W_w = 50 \cdot S_w / 1000, \quad (11)$$

where S_w – area of the windward surface of the cargo, 5.291 m².

The friction forces were determined in the following direction:

- in longitudinal direction:

$$F_{fr}^{long} = Q_w \cdot \mu, \quad (12)$$

where μ – is the friction coefficient, $\mu = 0.3$ (steel on steel);

The values of the friction coefficient between the supporting surfaces of the cargo, linings, and the floor of the wagon (sprinkled with a thin layer of sand in winter) cleared of dirt, snow, and ice in accordance with [2] are taken to be equal to 0.30 for the pair "steel on steel".

- in transverse direction:

$$F_{fr}^{tr} = Q_w \cdot \mu \cdot (1 - a_v). \quad (13)$$

Longitudinal inertial force to be dampened:

$$\Delta F_{long} = F_{long} - F_{fr}^{long}. \quad (14)$$

Transverse inertial force to be dampened:

$$\Delta F_{tr} = n \cdot (F_{tr} + W_w) - F_{fr}^{tr}, \quad (15)$$

where n – is the coefficient, which is taken as 1.0 for LTC; W_w – wind load.

Longitudinal inertial force – $\Delta F_{long} = 46.649$ tf, perceived by the elements of the end wall and corner posts with permissible values of 40 tf and 2×9.5 tf, respectively [2]: $\Sigma F = [59] > 46.649$ tf.

We will find the transverse forces according to the presented methodology, but taking into account the thrust load on the side walls of the car from the bundles. The scheme of bundle stowing in the car (Fig. 3b) provides for the loading transfer to each side of the car wall on one of its

half from the upper tier, and on the second – from the bottom tier. Fig. 5 shows the action of the thrust loads on the side walls of the car. Fig. 6 presents a design scheme for determining these loads, the corresponding dimensions are as follows: $L = 572$ mm; $\ell = 252$ mm, $r = 625$ mm. Let us determine the reactions in the supports indicated by the points A and B of the upper tier from a bundle with a weight of 1.425 tons.

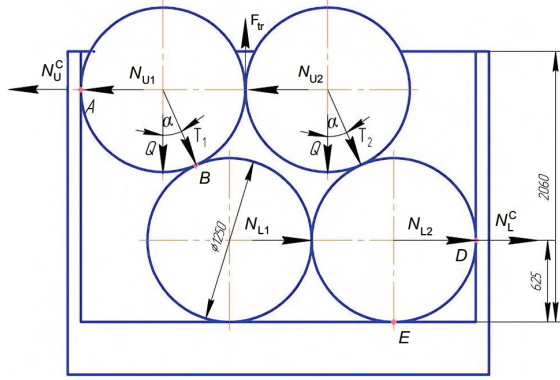


Figure 5 Thrust loads from the bundles

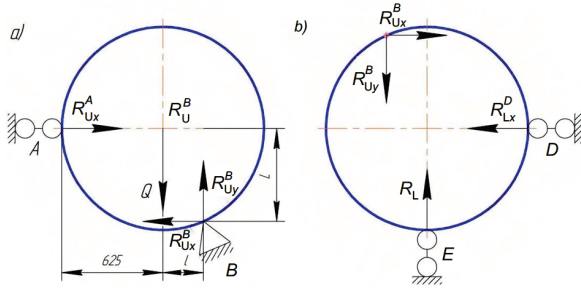


Figure 6 Design scheme for determining the thrust loads

Projection of forces on the Y -axis (Fig. 6a):

$$R_{Uy}^B - Q = 0, \quad (16)$$

$$R_{Uy}^B = Q = 1.425 \text{ tf}. \quad (17)$$

Moment of forces relative to the point B (Fig. 6a):

$$\sum M^B = Q \cdot \ell - R_{Ux}^A \cdot L = 0. \quad (18)$$

From which it follows:

$$R_{Ux}^A = \frac{Q\ell}{L}. \quad (19)$$

After substitution, we obtain $R_{Uy}^B = 1.425$ tf, $R_{Bx}^A = 0.628$ tf. Projection of forces on the X -axis (Fig. 6a):

$$R_{Ux}^B - R_{Ux}^A = 0. \quad (20)$$

From which:

$$R_{Ux}^B = R_{Ux}^A = 0.628 \text{ tf}. \quad (21)$$

Thus, the force N_{U1} (Fig. 5) is equal to the support reaction R_{Ux}^A and is 0.628 tf. The total thrust load N_U^C from two adjacent bundles will be equal to the sum of the forces N_{U1} and N_{U2} and will be 1.256 tf.

We will define the reaction R_{Lx}^E at point E by making a projection of forces on the X -axis (Fig. 6, b).

$$R_{Ux}^B - R_{Lx}^E = 0. \quad (22)$$

It follows that

$$R_{Lx}^E = R_{Ux}^B. \quad (23)$$

Having substituted the value, we obtain $R_{Lx}^E = 0.628$ tf.

Thus, the force N_{L2} (Fig. 5) is equal to the support reaction R_{Lx}^E and is 0.628 tf. The total thrust load N_L^C from two adjacent bundles will be equal to the sum of the forces N_{L1} and N_{L2} and will be 1.256 tf.

Thus, the total thrust load on the elements of the car side wall, in accordance with the bundle stowing scheme (Fig. 5), is 7.536 tf for the upper and lower tiers.

According to the bundle stowing scheme in the car (Fig. 3, b), the thrust loads from the upper tier act on one corner post and 3 side ones at the level of 1875 mm at a height of the upper strapping of 2050 ... 2360 mm, and from the lower tier at a height of 625 mm from the floor level. Permissible load on the side wall elements at the above load application heights is as follows [2]:

- side post at a height of 625 mm – (4.47) tf;
- side post at a height of body end plate – (1.2) tf;
- corner post at a height of 625 mm – (17.57) tf;
- corner post at a height of body end plate – (4.6) tf.

The total thrust load N_{UL}^C from the upper N_U^C and lower N_L^C tiers is 15.072 tf (Fig. 4).

The undampened transverse inertial force acting from the upper and lower tiers, according to the Eq. (15), is:

- upper tier $\Delta F_{Utr} = 8.514$ tf;
- lower tier $\Delta F_{Ltr} = 8.249$ tf.

The total overload from the thrust and inertial forces is determined by the equation:

$$N = N_{UL}^C + \Delta F_{Utr} + \Delta F_{Ltr}. \quad (24)$$

After substitution of values, we obtain $N = 31.835$ tf. Total permissible load on side wall elements:

$$[R] = 3 \cdot [R_{post}^U] + 3 \cdot [R_{post}^L] + 1 \cdot [R_{cor}^U] + 1 \cdot [R_{cor}^L], \quad (25)$$

where R_{post}^U , R_{post}^L – permissible loads on the side post, respectively, at the contact point with the upper and lower

bundle row; R_{cor}^U , R_{cor}^L – permissible loads on the corner post, respectively, at the contact point with the upper and lower bundle row.

The total permissible load on the side wall elements is $[R] = 39.18$ tf. The total loads acting on the elements of the car side wall are less than permissible, that is, 31.835 tf < 39.18 tf.

4 MODELLING RESULTS

Based on the mathematical model presented in [18, 19], a package of application programs was developed. Analytical modeling to determine specific inertial forces was carried out using a model of spatial vibrations of the car when moving along a curve with a radius of 200 m and an elevation of the outer rail of 150 mm. The maximum permissible speed for freight trains is 55 km/h. In accordance with [2], specific inertial forces are determined up to a speed of 100 km/h inclusive.

Specific vertical and transverse inertial forces at $H_{gc}^o = 2.296$ m are presented in Fig. 7 and Fig. 8.

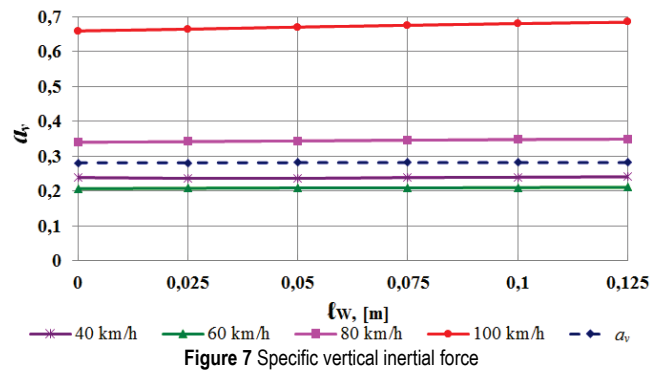


Figure 7 Specific vertical inertial force

From Fig. 7, it can be seen that with permissible longitudinal displacements of the general center of gravity of the cargo in the car, the values of the specific vertical inertial force practically do not change and depend to a much greater extent on the speed of movement. Value a_v , determined by Eq. (10), is, on average, 58.15% less than the calculated values for a speed of 100 km/h.

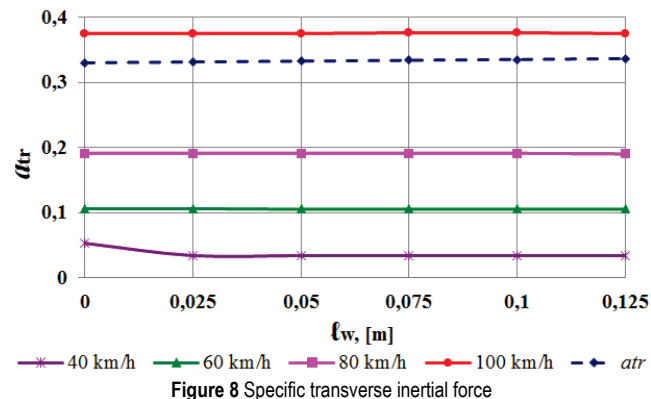


Figure 8 Specific transverse inertial force

The values of the specific transverse inertial force (Fig. 8) also depend to a much greater extent on the speed of movement. Value a_{tr} , determined by Eq. (8), is, on average, 11.23% less than the calculated values for a speed of 100 km/h.

To study the influence of the height of the general center of gravity of a loaded car on the values of specific inertial forces, calculations were performed at $H_{gc}^o = 1.8$ m. The specific vertical inertial force is presented in Fig. 9.

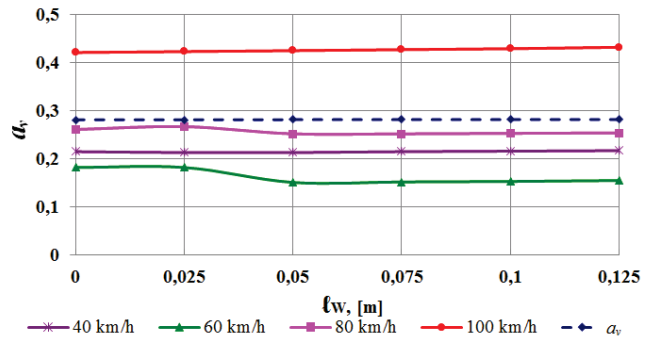


Figure 9 Specific vertical inertial force

Value a_v , determined by Eq. (10), is, on average, 33.92% less than the calculated values for a speed of 100 km/h.

The specific transverse inertial force is presented in Fig. 10. Value a_{tr} , determined by Eq. (8), is, on average, 4.17% less than the calculated values for a speed of 100 km/h.

Analyzing the results obtained, it is possible to conclude that the values of specific vertical and transverse inertial forces depend to a much greater extent on the speed of movement. Height H_{gc}^o and longitudinal displacement l_w , when freight trains move at maximum permissible speeds in curved sections of track with an undamped acceleration of 0.3 m/s², do not have a noticeable effect.

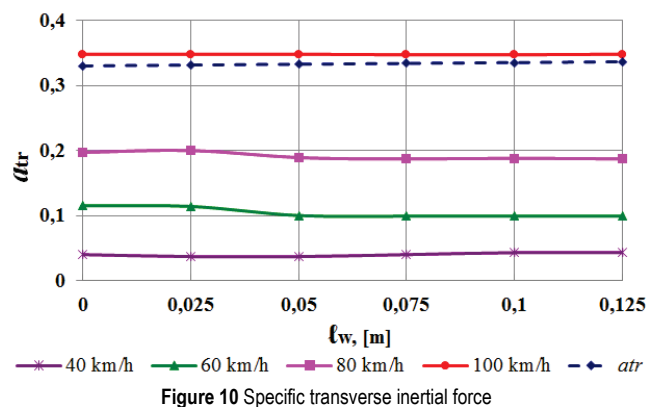


Figure 10 Specific transverse inertial force

On Figs. 7-10 present the simulation results in the presence of longitudinal displacements of the overall center of gravity of the load in the direction of the front bogie. When the CG is shifted towards the rear bogie, the values of the specific inertial forces are less than 1% of those presented. The direction of the longitudinal displacement along the

direction of travel of the car does not have a significant effect on the values of the specific inertial forces.

Thus, when the car moves in a curve with a radius of 200 m at the maximum permissible speed, the strength of the body elements will be ensured.

During theoretical studies, it was established that when a loaded car is moving at speeds of up to 100 km/h, the minimum values of the stability coefficient against wheel derailment are not lower than 1.2. The results obtained indicate that traffic safety is ensured on curved sections of the railway track.

In accordance with [2], for the cargo under study, a lateral displacement of the overall center of gravity of the cargo in a 4-axle car b_w is allowed when loading 70 mm and along the route (in transit) 100 mm.

In [16, 20], it was found that longitudinal displacements of the load's center of gravity have a much smaller effect on the dynamic forces arising during the movement of freight cars than transverse displacement or the presence of simultaneous displacement in both directions from the axis of symmetry of the rolling stock. The lateral displacement, defined by the regulatory documentation, should be taken into account since it leads to a significant change in the safety factor against wheel derailment.

The results obtained show the feasibility of further research in this direction.

5 CONCLUSION

The work determines the loads acting on the elements of the side wall of the gondola car body during the transportation of rolled wire bundles. In the calculations, the total weight of the cargo in the car was assumed to be 69 tons, while the transportation experience of these products shows that the bundle weight in the car usually does not exceed 66 tons. Total load from the thrust and inertial forces acting on the car side wall elements during the bundle transportation according to the scheme presented in the article is 31.835 tf, which does not exceed the permissible load on the side wall elements of the gondola car (three side posts of the body and the corner post), taking into account the height of the forces application – 39.18 tf.

The presented results confirm that the transport accident on the Voskoboynya – Verkhnedneprovsk section occurred precisely because of the unsatisfactory technical condition of the car, but it is not the reason for the disadvantages in the LTC for the transportation of rolled wire bundles.

The correspondence of the results obtained to the real object is ensured by the fact that the inertial forces are calculated in accordance with the approved methodology. To determine the thrust forces from the action of bundles of the upper and lower tiers, in accordance with the calculation schemes presented in the work, the force balance equations were written and solved.

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