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WORKING OUT OF GENERALIZED DYNAMIC MODEL OF CARGO FIXATION WITH CARGO PADS JOINTLY WITH FLEXIBLE AND THRUST ELEMENTS UNDER THE ACTION SPATIAL FORCE SYSTEM

Summary. The article gives an account of the results of working out a generalized dynamic model of fixation of cargo with pads jointly with flexible and thrust elements. Working out a generalized dynamic model of cargo fixation is rather a complicated problem not in the sense of solving differential equations systems but in the sense of presenting them as a complex mechanical system "cargo – pads – flexible elements – thrust bars". Generalized dynamic model of cargo with pads observed that this model represents technology of joint work of flexible and thrust fastening means of cargo on rolling stock. In particular, on the basis of this model there can be obtained the technology models of joint work of flexible and elastic fastening means of cargo without pads of fastening flexible elements of cargo with pads without thrust bars and also flexible fastening elements of cargo without pads and thrust bars at asymmetrical and/or symmetrical allocation of cargo in the wagon. A specific feature (novelty feature) of the proposed dynamic model is inclusion into the model of both cargo pads and thrust bars which are nailed to the wagon floor close to the butt and lateral sides of cargo.

ФОРМИРОВАНИЕ ОБОБЩЁННОЙ ДИНАМИЧЕСКОЙ МОДЕЛИ КРЕПЛЕНИЙ ГРУЗА С ПОДКЛАДКАМИ СОВМЕСТНО С ГИБКИМИ И УПОРНЫМИ ЭЛЕМЕНТАМИ ПРИ ВОЗДЕЙСТВИИ ПРОСТРАНСТВЕННОЙ СИСТЕМЫ СИЛ

Резюме. В статье изложены результаты разработки по формированию обобщённой динамической модели креплений груза с подкладками совместно с гибкими и упорными элементами. Формирование обобщённой динамической модели креплений груза представляют собой достаточно сложную динамическую систему не в смысле решения систем дифференциальных уравнений, а в смысле представления их как сложной механической системы «груз – подкладки – гибкие элементы – упорные бруски». Обобщённая динамическая модель груза с подкладками представляет собой технологию совместной работы гибких и упорных средств креплений груза на открытом подвижном составе. В частном случае, из этой модели могут быть получены модели технологии совместной работы гибких и упругих средств креплений груза без подкладок, гибких элементов креплений груза с подкладками без упорных брусков, а также гибких элементов креплений груза без подкладок при несимметричном и/или симметричном размещении груза на вагоне. Отличительная особенность (новизна) предложенной динамической модели – это включение в модель одновременно подкладки под груз

и упорных брусков, которых прибивают к полу вагона вплотную к торцевым и боковым сторонам груза.

1. FORMULATION OF A PROBLEM

It is generally known [1] that there exist the following techniques of cargo allocation with flat foundation on the open rolling stock:

symmetrical location of cargo conjoint gravity center (GC) in relation to longitudinal and lateral wagon symmetry axes;

asymmetrical location with GC displacement in relation to lateral wagon symmetry axis which corresponds to GC displacement lengthwise the wagon;

asymmetrical location with GC displacement in relation to longitudinal wagon symmetry axis which corresponds to GC displacement crosswise the wagon;

asymmetrical location with simultaneous GC displacement in relation to longitudinal and lateral wagon symmetry axes which corresponds to GC displacement both lengthwise and crosswise the wagon.

Each of the above mentioned techniques of cargo allocation in the wagon according to the profile of cargo with cargo eyes or without them provides for cargo fixation by flexible thrust elements without cargo pads and thrust bars (as a particular case) in combination with only thrust bars or only with cargo pads (as a particular case) and also in combination with thrust bars and cargo pads (general case).

Solid-state cargo (further cargo) in the open railway rolling stock is kept from displacement by the action of spatial force systems with the help of flexible (stretching, framing), thrust (thrust bars) and supporting (cargo pads) fastening means. Flexible fastening elements are intended mainly for pressing the cargo down to the wagon floor thus increasing the “retaining” forces keeping the cargo from shifting both lengthwise and crosswise the wagon. Thrust fastening means in the form of thrust and spacing wooden bars are designed for keeping the cargo from shifting both lengthwise and crosswise the wagon floor and also for transferring “shifting” forces from the cargo onto the elements of the wagon body. Supporting fastening means (cargo pads) are designed for keeping cargo during loading in the wagon with wood-and-metal floor and for performing handling operations with cargo without lifting lugs. Flexible fastening elements are engaged only when there is a shift of cargo lengthwise and crosswise the wagon separately or simultaneously both lengthwise and crosswise the wagon in case of complete or partial tearing away of supporting fastening means, the impact of fastening elements being experienced only by wagon tying means (rack staple).

Fixation of cargo in the wagon with account taken of thrust bars and without regard for cargo pads is fulfilled according to Technical Specification with the help of trigonometric functions according to formulas (30), (31) and (34), (35) [1]. In Specification the efforts in all cargo fastenings have the same values (i.e. one value) irrespective of fastening geometry which does not square with reality. Furthermore, modulus of elasticity E, diameter d_i, the number of threads n_i and pretension $R0_i$ from wire twists are not taken account of. It should be remembered that modulus of elasticity E is 20 times less ($E = 1{\cdot}10^7$ kN/m^2) than that of a standard steel wire ($E = 2.1{\cdot}10^8$ kN/m^2). Another disadvantage is that it is impossible to take into account the impact of lateral forces of strappings and the usage of trigonometric functions, obtained on the basis of fastening projection l_i onto the corresponding coordinate axes in the form of a_i, b_i and h_i determined according to the data of cargo drawing whereas it would be quite essential to make use of these data. The techniques available in Specification do not take into account thrust and supporting fastening means.

There exists an improved technique of fastening cargo calculation with account of thrust bars and without regard for cargo pads (formulas (1) – (4) Appendix 8 [1]), which has been worked out on the basis of analytical solution of the statistic undefined problem with allowing for the impact of plane force system.

There is a number of papers, for example [2] which contain solutions of problems of cargo fastening by digital modeling without taking into account thrust bars and cargo pads.

In West-European countries and in America cargo is also fastened to the open rolling (wagons and motor transport) together with flexible (straps, cables, forged chains), thrust (thrust bars) and supporting (pads) fastening means (Fig.1) [3-5]. A distinguishing feature of these fastening means as compared to the Russian ones is the fact that fastening elements are the cables fixed to cargo and to a wagon frame by means of screw connection with right-hand and left-hand thread, Modulus of elasticity of these cables just as that of ordinary steel is equal to E = 2,1·10^8 kN/m^2 (whereas modulus of elasticity of annealed fastening wires E is 20 times as little as ordinary steel, i.e. E = 1·10^7 kN/m^2).

Fig. 1. Location and fixation of wheel vehicles on the wagon by flexible, thrust and supporting elements jointly with screw connection with right-hand and left-hand thread

Рис. 1. Размещения и крепления колёсной техники на вагоне гибкими, упорными и опорными элементами в сочетании винтового соединения с правой и левой резьбой

In Fig. 1 one can distinctly see pads for wheel vehicles (cargo) and thrust bars as well as cables fixed to cargo lifting lugs and wagon braces by means of screw connection with right-hand and left-hand thread.

Another distinction of fastening means used in West-European countries and America from those used in Russia is the fact that straps are just ordinary safety belts widely used for keeping cargo from shifting while transporting, for example, by motor vehicle [3-4]. Since the belts are manufactured from composite (rubberized) materials their modulus of elasticity (tension rigidity) is considerably lower than that of ordinary steel.

In [3-4] there are no calculation schemes of cargo fastening except illustrations of cargo transporting by means of motor transport and with the help of straps and thrust bars. They also contain the value and the direction of acceleration, arisen in the process of transportation both lengthwise (during abrupt braking and sudden starting) and crosswise (during movement on a curve) vehicle body as well as while moving along the vertical on a highway.

Unfortunately, in [3-4] there are not any calculation schemes of cargo fastening on motor transport. That is why acceleration values presented here are rather of informative character. It is evident that they don't contain any calculations as far as fastening of cargo transported by motor vehicles is concerned.

In [5], just as in [1] in cargo transportation on the open railway vehicle (wagon) there has been considered as a particular case a calculation scheme of application to the object (cargo) of plane force system (longitudinal land vertical, crosswise and vertical).

The analysis of cargo fastening calculation schemes known in [3-5] makes it possible to point out that the considered schemes of the plane force system are presented in a simplified manner because the calculation technique of cargo fastening with cargo transported in the open rolling stock under the action of plane force system has not been taken into account.

Due to this fact it is necessary to emphasize that formulation of calculation models of cargo fastening in the open rolling stock under the action of plane force system in west-european and american sources has not been found.

In [6, 7] in order to solve the technical problem of cargo fastening without regard for thrust bars and cargo pads it has also been offered to make use of equilibrium equation during relative motion (at rest) in the direction of the action of the spatial force system.

In [8] the technical problem of cargo fastening under the impact of plane force system (PFS) is solved with regard for thrust bars, in [9] with taking into account of cargo pads. The advantage (a feature of novelty) of the above techniques unlike of all those described earlier lies in the possibility of determining cargo shifts and tensions in the fastening elements in the presence of thrust bars without cargo pads and cargo pads without thrust bars (as a particular case).

The disadvantage of these techniques [8, 9] is the lack of possibility of estimation of stress loading of fastening elements during simultaneous presence of thrust bars and cargo pads (a general case).

Working out a generalized dynamic model of cargo fixation is rather a complicated problem not in the sense of solving differential equations systems but in the sense of presenting them as a complex mechanical system "cargo – pads – flexible elements – thrust bars". Most probably, it is due to this fact that such models have not been the object of investigation yet.

Thus, there has not been so far constructed a generalized dynamic model of cargo fastening in collateral cargo fixation with cargo pads by flexible and thrust elements during rolling stock movement on a descending grade of a curved track section under the impact of SFS.

Due to this fact, it is necessary to note that the technical problem of keeping cargo with pads from shifting in relation to the wagon floor in collateral cargo fixation by flexible and thrust fastening elements under the impact of SFS has not been studied yet and it remains unsolved and quite actual for transport science.

1.1. Man-made assumption

Let us consider a general case when cargo G which is asymmetrically (or symmetrically) located in relation to the longitudinal and lateral symmetry axes of the wagon. One of the examples of practical cargo allocation and fastening techniques during transportation in the form of real model is presented in Fig. 2. In Fig. 6 there can be observed loosening of fastening elements in the direction of the impact, in particular, of lateral forces.

Fig. 2. Real model of cargo location and fastening in the wagon by means of flexible, thrust and supporting elements
Рис. 2. Реальная модель размещения и крепления груза на вагоне гибкими, упорными и опорными элементами

Taking into consideration the fact that stretchings and/or strappings designed for keeping the cargo from shifting are manufactured from annealed wire that was subjected to pretension the value of which ranges from 15 to 25 kN and they can experience considerable deformation under the action of external forces they are modeled by flexible elastic non-retaining constraints. We assume that according to the axiom of geometrical statics solidification these constraints can be looked upon as linear rods experiencing single-axis stretching.

Just as in [2, 6-9] let the rolling stock move down a descending grade at angle ψ_0 both in the regime of release and the regime of service brake application at speed v on a curved track section with curvature radius ρ of the trajectory in the given point of the curve. The wagon moves progressively at speed $\bar{v}_e$ (i.e. transferring movement is progressive ($\bar{\omega}_e = 0$)) with the lengthwise $\bar{a}_x = \bar{a}_{ex}$, the lateral $\bar{a}_y = \bar{a}_{ey}$, and the vertical $\bar{a}_z = \bar{a}_{ez}$, transferring accelerations caused by irregularity of the track due to aberration in maintenance standards, technological clearance between wheel flanges and lengths of rails, design specific features of the wagon and some other factors.

Let us assume that flexible, elastic, thrust and supporting fastening means and wagon frame as external constraints experience the impact of spatial force system (SFS) - $\bar{G}$, $\bar{I}_e$ ($\bar{I}_e \in (\bar{I}_{ex}, \bar{I}_{ey}, \bar{I}_{ez})$ and $\bar{F}_{гв}$ ($\bar{F}_{гв} \in \bar{F}'_{гвx}, \bar{F}'_{гвy}$) gravity force of the wagon with cargo or without cargo), transferring inertia force and aerodynamic resistance force [2, 6-9]. We assume that spatial force systems (longitudinal, lateral and vertical) are perceived by flexible elastic fastening elements and thrust bars, located against the action of these forces, whereas the fastening elements of the opposite direction sag (i.e. lose their constraint features).We assume that the cargo is massive and is not to be broken away from the wagon floor and there does not take place tipping of cargo in relation to its lateral and butt sides either, i.e. the cargo does not lose constraint in the form of wagon floor and does not get the constraint in the form of rotation axis coinciding with its sides. There does not take place a turn of cargo in relation to its vertical axis, i.e. the cargo is pressed down to the floor through the pads by tensions of pretwisted wire of the same value. Such assumptions make it possible to believe that the impact force of cargo is uniformly distributed along the length of thrust bars which in its turn shows that fastening (the nail) on it is loaded with uniformly distributed loads.

2. METHODS OF SOLUTION

In order to work out a generalized dynamic model of cargo fixation let us make use of a classical principle of geometrical statics – the principle of releasing from constraints [10].

3. RESULTS OF SOLUTION

Let us take as the basis of the dynamic model the fact that the cargo fastening elements together with thrust bars experience the impact of SFS which are perceived by the major constraint (wagon) and additional constrains (flexible elastic, thrust and supporting wooden fastening means). In order to construct a cargo dynamic model (object) in presence of thrust and supporting bars during rolling stock movement along a descending grade on a curved track section and according to the principle of releasing from constraints the external constraints - platform frame as a major constraint, and flexible elastic fastening elements and also thrust and supporting bars as additional constraints are mentally discarded from the object.

The impact of discarded external constraints is substituted by reactions $\overline{R} \in (\overline{N}, \overline{F}_\tau)$ (platform frame) and $\overline{R}_i, \overline{R}_{ai}$ (flexible elastic fastening elements of one direction, and of the other direction – $\overline{R}_{pi}, \overline{R}_{api}$); $R_{thr} \in (R_{thr.x}, R_{thr.y})$ by yet unknown reactions of thrust bars, keeping the cargo from shifting both lengthwise and crosswise the wagon ($R_{thr.}$ - being the resultant of two bars 4 and 5, stowed close to the cargo sides: $R_{thr.y} = R_{thr4.y} + R_{thr5.y}$.) and also $\overline{R}_1 \in (\overline{N}_1, \overline{F}_{\tau 1})$ and $\overline{R}_2 \in (\overline{N}_2, \overline{F}_{\tau 2})$ by yet unknown reaction of cargo pads (Fig. 3).

In Fig. 3 the following table of symbols is accepted [6, 7]: A_j, A_{aj}, A_{pj} и A_{apj} and A_{apj} are points. The cargo is fixed by flexible elastic fastening elements to tying wagon devices; M_j, M_{aj}, M_{pj} and M_{apj} are points corresponding to cargo eyes; I_n is the normal constituent inertia force during absolute motion conditionally applied to the cargo mass center (to be more precise to the wheel pairs together with axle bearings and lateral frames of trucks) that will take into account the accelerated motion of the rolling stock on a curved track section; j and i are indexes showing the number of rack staples and elastic fastening elements (i = 1, n_p the number of flexible elastic fastening elements); $2L$, $2B$ and $2H$ are the cargo length, width and height correspondingly; l_{wi} and l_{wai} are projections of the lengths of flexible elastic elements of fastening of one direction onto the lateral axis y (l_{wpi} and l_{wapi} the same of the other direction); Δh is super elevation; $2S$ is the distance between wheel rolling circles of gauge 1 520 mm ($2S$ = 1 520 mm); θ is the angle characterizing super elevation; ζ is the angle allowing for tilting of the wagon frame with cargo during its displacement onto the lateral axis at the value ± yM.

Reaction of external constrain $\overline{R}$ is factorized into normal $\overline{N}$ and tangent $\overline{F}_\tau$ constituents i.e. $\overline{R} = \overline{N} + \overline{F}_\tau$ (Fig. 4). Tangent constituent $\overline{F}_\tau$ directed along the floor surface is called friction force $\overline{F}_{fr.}$ and is defined according to the Coulomb law. Coordinates x_R, y_R (or x_N, y_N) are application points of external constraint reaction $\overline{R} \in (\overline{N}, \overline{F}_\tau)$ are unknown and have to be defined

The table of symbols in Fig. 4 is the same as in Fig. 3.

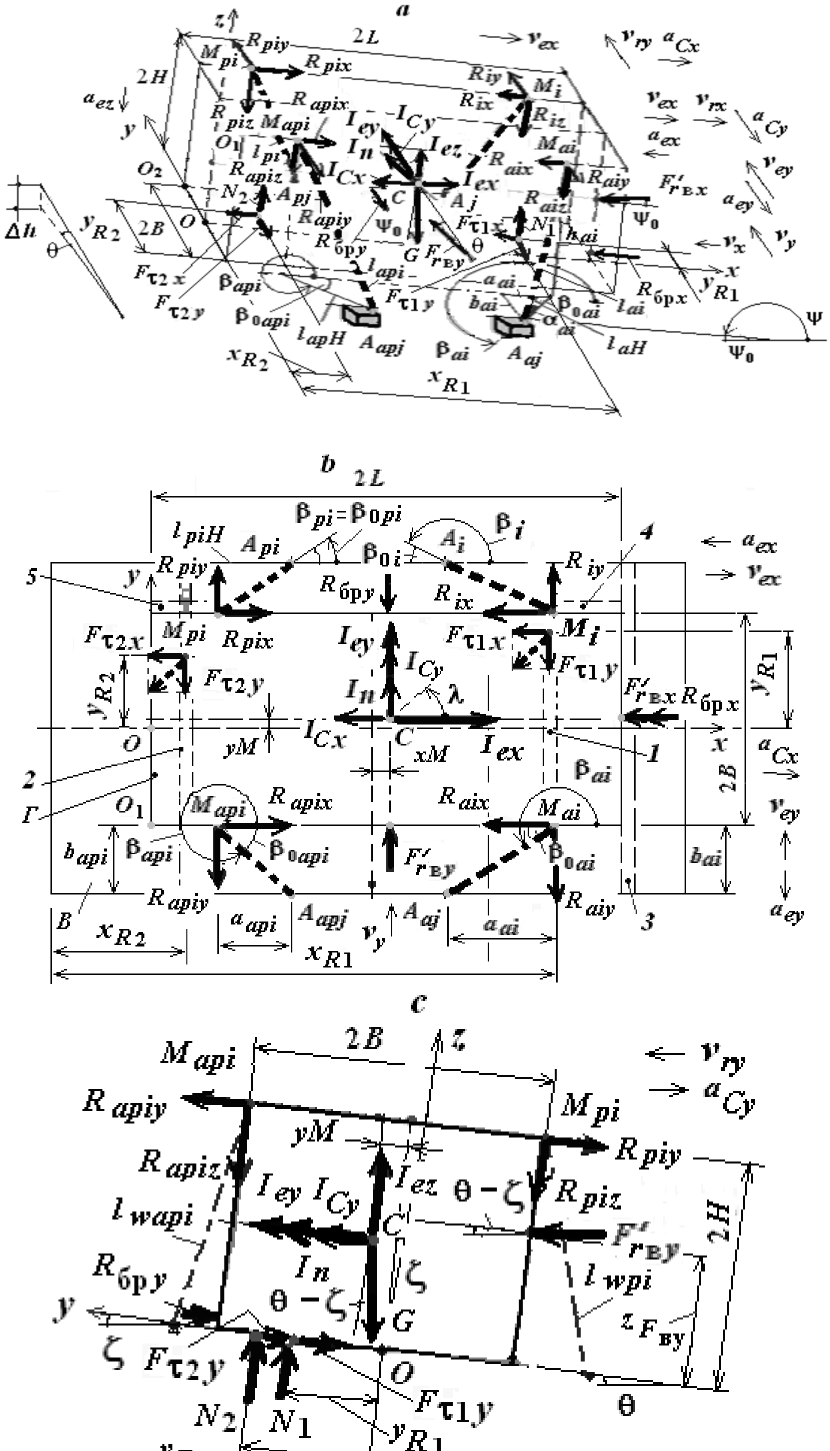

Fig. 3. Variation of generalized dynamic model of cargo with flexible, thrust and supporting fastening means: a) axonometry; б) top view; в) butt view; *B* wagon; *Г* weight; 1 and 2 pads; 3 thrust bar, located close to the end surface of cargo; 4 and 5 thrust bars located close to the side surface of cargo.

Рис. 3. Разновидность обобщённой динамической модели груза с гибкими, упорными и опорными средствами креплений: а) – аксонометрия; б) – вид сверху; в) – вид с торца; *В* – вагон; *Г* – груз; *1* и *2* – подкладки; *3* – упорный брусок, расположенный вплотную к торцевой поверхности груза; *4* и *5* – упорные бруски, расположенные вплотную к боковой поверхности груза

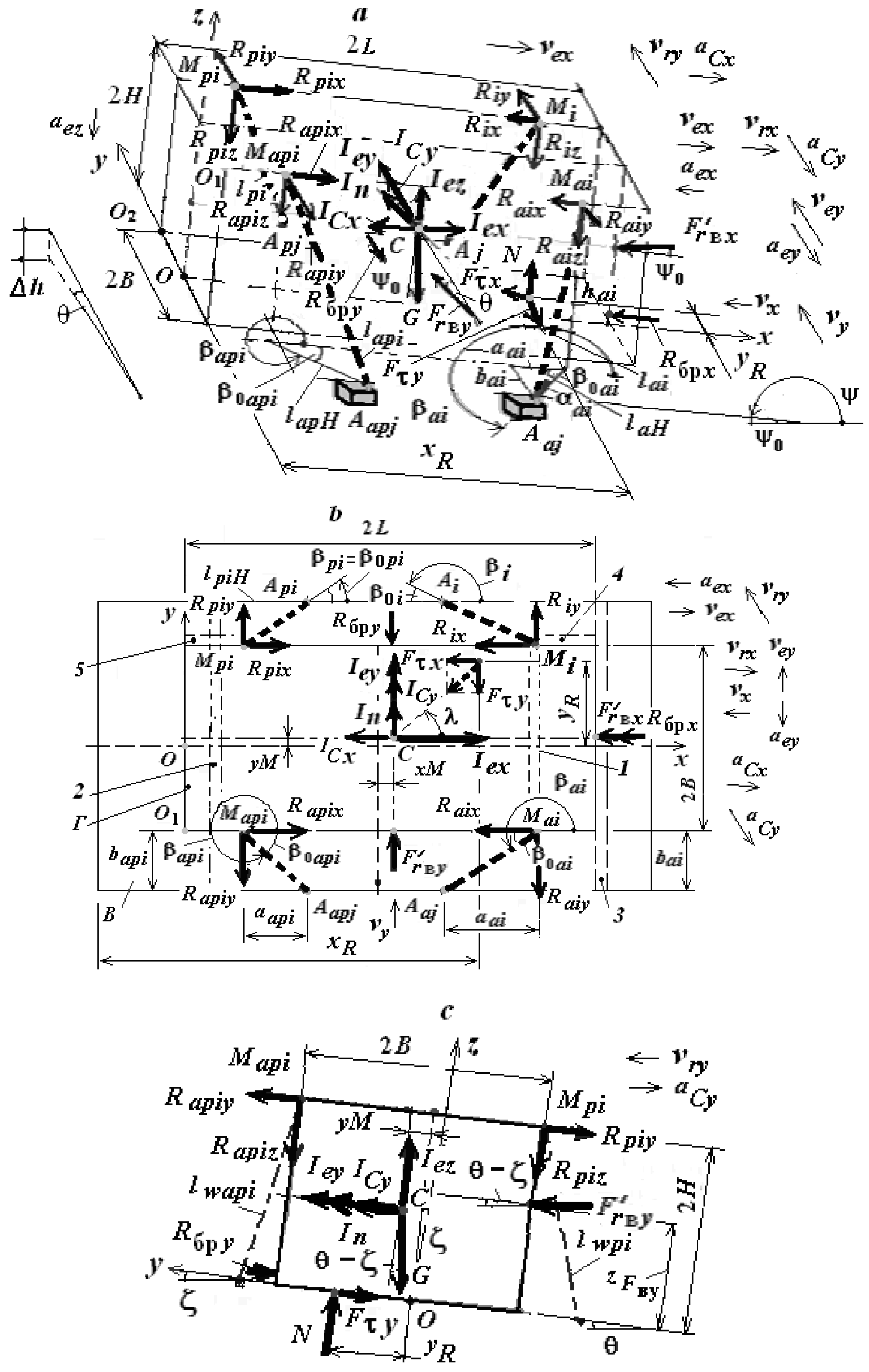

Fig. 4. Dynamic model of cargo with flexible, thrust and supporting fastening means: a) axonometry; b) top view; c) butt view

Рис. 4. Динамическая модель груза с гибкими, упорными и опорными средствами креплений: a) аксонометрия; b) вид сверху; c) вид с торца

The object is subjected to the application of active (G, I_e, $F_{гв}$) and reactive (R, R_i, $R_{бр}$) forces. Active forces are conditionally (formally) applied to the material system mass center (cargo) C but in reality they are experienced by external constraints and they are directed from the object, whereas reactive forces $\overline{R} \in (\overline{N}, \overline{F}_\tau)$ to the object while reactive forces of flexible elastic fastening elements of one direction $\overline{R}_i, \overline{R}_{ai}$ as well as of the other direction $\overline{R}_{pi}, \overline{R}_{api}$ - from the object. Besides, reactive forces $\overline{R} \in (\overline{R}_1, \overline{R}_2)$ with coordinates $x_R \in (x_{R1}, x_{R2})$ and $y_R \in (y_{R1}, y_{R2})$ (normally chosen according to cargo weight and length) are applied to the object (Fig. 4).

Thus, it should be noted that because the impact of SFS as active forces is experienced by the external constraints – wagon,(the main constraint), flexible elastic fastening elements, thrust and supporting wooden bars (additional constraints) in reality it is impossible to identify points of application of these forces. However, in a dynamic model of the object (cargo) these forces are applied conditionally (mentally) to the mass center of the material system (cargo).

According to the condition of equilibrium of arbitrary force system of geometrical statics it is known [10] that in a particular case the resultant of two parallel forces pointed in one direction, for example, $\overline{N} \in (\overline{N}_1, \overline{N}_2)$, $\overline{F}_{\tau x} \in (\overline{F}_{\tau 1x}, \overline{F}_{\tau 2x})$, and $\overline{F}_{\tau y} \in (\overline{F}_{\tau 1y}, \overline{F}_{\tau 2y})$ irrespective of its application point is equal as fast as its module is concerned the sum of modules of these forces and is directed in the same way: $N = N_1 + N_2$, $F_{\tau 1x} = F_{\tau 1x} + F_{\tau 2x}$ and $F_{\tau 1y} = F_{\tau 1y} + F_{\tau 2y}$ (Fig. 4).

The line of action of the resultant of the two parallel forces $\overline{N}_1$ and $\overline{N}_2$ divides internally the distance between the lines of action of the above forces into the parts in inverse proportion to these forces:

$$N_1 / N_2 = (x_R - x_{R2})/(x_{R1} - x_R) \tag{1}$$

where: x_R is a still to be found coordinate of application point of resultant $\overline{N} \in (\overline{N}_1, \overline{N}_2)$ along the wagon, m. It should be noted that $x_R \in (x_{R1}, x_{R2})$ and $y_R \in (y_{R1}, y_{R2})$ can be found only after determining N.

Summing up the results of working out of generalized dynamic model of cargo with pads (availability of $\overline{N} \in (\overline{N}_1, \overline{N}_2)$), it can be observed that this model represents technology of joint work of flexible and thrust (availability $R_{thr} \in (R_{thr.x}, R_{thr.y})$) fastening means of cargo on rolling stock. In particular, on the basis of this model there can be obtained the technology models of joint work of flexible and elastic (availability $R_{thr} \in (R_{thr.x}, R_{thr.y})$) or only $R_{thr.x}$) fastening means of cargo without pads (absence of N_1 and N_2) of fastening flexible elements of cargo with pads (availability $\overline{N} \in (\overline{N}_1, \overline{N}_2)$) without thrust bars (absence of $R_{thr} \in (R_{thr.x}, R_{thr.y})$) or availability only $R_{thr.x}$) and also flexible fastening elements of cargo without pads (absence of N_1 and N_2) and thrust bars (absence $R_{thr} \in (R_{thr.x}, R_{thr.y})$) at asymmetrical and /or symmetrical allocation of cargo in the wagon.

4. SUMMARY

Developed for the first time the generalized dynamic model of collateral fixation of cargo with padding by flexible and thrust elements made it possible to indentify the conditions providing workability of thrust bars together with pretwisted fastening wires and cargo pads. It should be emphased that it is only when these conditions are not fulfilled that elastic forces of flexible fastening elements are engaged in work on retaining cargo from shifting. In a particular case, on the basis of the constructed generalized mathematical model there can be obtained analytical formulas for calculating collateral cargo fixation by flexible and thrust [8], flexible and supporting (pads) [9] fastening means separately and also by flexible fastening elements without thrust bars and pads in accordance of worked out technique of allocation and fixation of cargo in the wagon.

A specific feature (novelty feature) of the proposed dynamic model is inclusion into the model of both cargo pads and thrust bars which are nailed to the wagon floor close to the butt and lateral sides of cargo.

In perspective the results obtained can be used for working out normative documents on fixation of cargo under the action of PFS unprovided for by technical conditions.

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