STRESS-STRAIN STATE OF CARGO FRAME OF A TRANSPORTER

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ABSTRACT

Standard eight-axle transporters of pit type with typical cargo frame, which are in operation now, are not suitable for transportation of large unique products because of the inability to fix them firmly. A special cargo frame has been created, which is mounted on a standard eight-axle transporter of pit type instead of a standard frame. In laden position it is placed horizontally and has 4 degree bulkiness, and in unladen position it is placed vertically and is located in the clearance of the rolling stock. Stability coefficient of unloaded structure from cross-tipping in curves is 1,96 and it is higher than the maximum permissible value of 1,8. The project was implemented by the department of railway cars and cars facilities of MIIT jointly with Kaluga Turbine Plant.

The objective of the author is to investigate stress-strain state of a cargo frame of a transporter, produced at Kaluga Turbine Plant, using finite element method, comparative and mathematical methods. For that purpose rectangular plates were taken with different geometrical characteristics, perceiving deformations of tension, compression, shear and bending in two planes. Basing on the analysis of the stress strain state of originally designed cargo frame Kaluga Turbine plant-manufacturer got recommendations for more rational distribution of the metal mass in length and cross-section, as well as a decrease in metal intensity of the spaces of the cargo frame where calculations defined very low stresses. In general, studies of stress-strain state of the cargo frame showed that it is workable, strength reliable, easy for fastening of transported products and can be safely used for regular transportation of special products on railways of Russia on the same basis in accordance with the requirements for the mass rolling stock of the car fleet.

Keywords: railway transporter, special cargo frame, stress-strain state, finite element method, stability coefficient.

ENGLISH SUMMARY

Background. _Standard eight-axle transporters of pit type with typical cargo frame, which are in operation now, are not suitable for transportation of large unique products because of the inability to fix them firmly. In order to transport huge goods a special cargo frame had been engineered, which is mounted on a standard eight-axle transporter of pit type instead of a standard frame. The project was implemented by the department of railway cars and cars facilities of MIIT jointly with Kaluga Turbine Plant. Schematic diagram of the frame is shown in Pic. 1._

Cargo frame of pit type weighing 25 tons consists of welded side beams 1 with width 440 mm of sheet metal box cross-section and end portions 2 with center plates 4 and 5. At longitudinal side beams 1 two removable vertical brackets 3 are bolted in order that transported bulky items are fixed to them.

In case of horizontal position of a frame side fourth degree bulkiness occurs (it is 730 mm more than proper size of cargo), which requires appropriate conditions for passage of a transporter through the network (speed decrease, restriction or prohibition of conflicting movement of trains on multiple-track lines, frequent inspection of the transporter with cargo at intermediate stations, increase in the turnover time of the transporter). This reduces the carrying capacity of railways.

To eliminate the bulkiness of the empty transporter a frame after unloading transported cargo rotates by 90 ° around the longitudinal axis and is mounted in a vertical position when center plates 4 rest on the overhand of the structure. In this position the center of mass of the cargo frame is at a height of 3,04 m above the rail heads, and in this case the safety factor against cross-tipping of the transporter in curves is equal to 1,96 and is greater than the maximum permissible value of 1,8.

Development of operating specifications of the transporter required evaluation of the stress-strain state of the frame. It was investigated by using a finite element method (FEM) in the form of displacements [1, 2]. Presentation of the cargo frame as a beam on two supports would be very approximate because of the complexity of its structure. In this case finite elements are rectangular plates perceiving deformations of tension, compression, shear, and bending in two planes.

Objective. _The objective of the author is to investigate stress-strain state of a cargo frame of a transporter, produced at Kaluga Turbine Plant._

Methods. _The author uses finite element method, analysis, scientific description, comparative method, mathematical methods._

Results. _The process of solving the problems with the finite element method in the form of displacements is as follows:_

- _for items with the same rigidity characteristics stiffness matrices are built in the coordinate system shown in Pic. 2;_
- _on given coordinates of nodes of the cargo frame we build transition matrix from the local coordinate system into the overall system using the relation:_

$$[\overline{R}]=[C]^T\cdot[\overline{R}]\cdot[C]\,, \qquad (1)$$

where $[\overline{R}]$ and [R] are stiffness matrices of finite elements in general and local coordinate systems; [C] is a transition matrix composed of directive cosines of the angles between general and local coordinate systems;

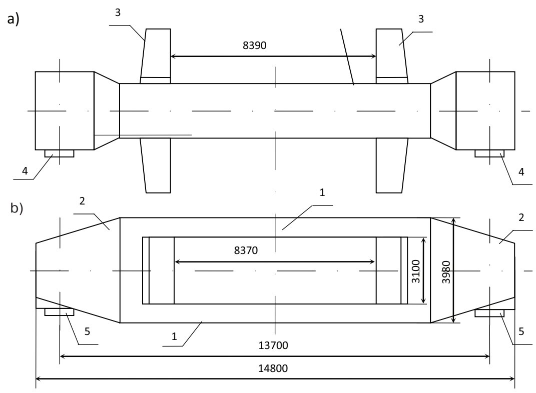
- _the process involves resolving system of algebraic equations of displacement method in the form of:_

$$[A]\cdot[W]-[P]=0, \qquad (2)$$

where [A] is stiffness matrix of the ensemble of finite elements; [W] is a matrix of desired nodal displacements in case of action of nodal loads presented in the matrix [P];

- _using the known nodal displacements for each finite element new stresses and strains in the local coordinate system are found._

Calculations of stresses in the cargo frame were carried out using the software package CAD-3, developed at the department of Structural mechanics of MIIT. Cargo frame is divided into a finite number of elements, which are rectangular plates with an aspect ratio a / b ≤ 2,5 (here a and b are lengths of the sides



Pic. 1. Schematic diagram of a special cargo frame of eight-axle transporter: a – in laden state; b – in unladen state; 1 – longitudinal beams; 2 – end portion of the cargo frame; 3 – removable brackets to fix transported cargo; 4 – center plate for cargo frame to rest on overhand of the transporter in laden state; 5 – center plate for the same purpose, but in unladen state.

of rectangular plates). Node numbers are shown as the figures in Pic. 3. In the future, the name of each finite element of the cargo frame will be determined by the number of nodes.

Support zones of the box cross-section cargo frame are replaced with plates with node numbers 3, 13, 5, 131, 173, 163, 175, 12, 2, 1, 11, 160, 172, 159, 171. The thickness of these plates was determined on the basis of equality of flexural characteristics of a given structure of the support zone and plates, which allowed to more properly assess the impact of the support zone of the cargo frame on its operation as a whole. A half of the cargo frame was calculated (because of its symmetry), it was divided into 196 finite elements in the form of rectangular plates with different geometric characteristics.

In support zones prohibited displacements are shown, and the scheme of stresses in the design scheme corresponds to the first load design mode, specified in the rules for design of cars for railways with 1520 mm gauge [3]. In accordance with the rules, a cargo frame of the transporter was calculated with I and III load modes. In the first mode the static load from the gross weight of the frame with the transported product and the longitudinal design force P_p equal to ± 2,5 MN applied to the thrusts for center - coupler draft gear at its longitudinal axis. In III mode vertical static load of the gross weight of the frame with the transported product, the longitudinal design force P_p of ± 1,0MN, vertical dynamic force at a speed of 33,3 m / s and the lateral load due to centrifugal forces and crosswind forces were taken into account. Additionally option when a transporter moves in low-capacity freight train was calculated. In this case, the longitudinal forces were taken to be ± 1,5 MN, and the values of other types of loads corresponded to analogues of freight trains of increased weight.

The total static load of the weight of transported goods with mounts and mass of cargo frame is 1,6 MN and is applied in areas where transported goods rest on the frame. These zones are final elements with numbers of nodes 48, 60, 50, 62, 120, 132, 122, 134. Vertical force is applied to each node

$$N_z = \frac{P_{vst}}{8}, \qquad (3)$$

where P_{vst} is total vertical static load of the weight of transported goods with fastening and mass of the cargo frame.

Longitudinal force is perceived by the cargo frame via support nodes with numbers 3, 13, 5, 15, 161, 173, 163, 175. Longitudinal load acts through the automatic coupler eccentrically l = 0,035 m, so in these nodes besides the longitudinal force $N_z = \frac{P_p}{4}$ (P_p is longitudinal design force) the moment $M_y = N_x \cdot l$ will also act.

Within the first load design mode for the transporter, moving in low-capacity train, the scheme of stresses on the frame remains the same as for the transporter moving in a freight train of increased weight. However, values of longitudinal forces and moments from them in the nodes of support zones are respectively 1,6 and 1,68 times less.

On III design mode for the cargo frame total vertical static and dynamic load is:

$$P_v = P_{vst}(1 + K_{av} + K_{sl}), \qquad (4)$$

where P_{vst} is vertical static load; K_{av} is a coefficient of dynamic addition of vertical forces; K_{sl} is a coefficient taking into account the influence of side loads (equal to 0,1 in accordance with the rules for calculating the strength of cars).

The maximum value of the coefficient of dynamic addition of vertical forces is determined by the formula:

$$K_{av} = \frac{\overline{K}_{av}}{\beta}\sqrt{\frac{4}{\pi}\ln\frac{1}{1-P(k_{av})}}, \qquad (5)$$

where $\overline{K}_{av}$ is an average value of the coefficient of dynamic addition of vertical forces;

$$\bar{K}_{av} = a + b\cdot\frac{V-15}{f_{st}}\cdot 3{,}6\cdot 10^{-4}$$

(a and b are coefficients, which are respectively equal to 0,05 and 0,75; V is speed, m/s);

β is a parameter of distribution of random variables K_{av}, which is equal to 1,13;

$P(\kappa_{av})$ is a confidence level, equal to 0,97;

f_{st} is a static deflection of spring group of a bogie, for four-axle model 18–101, equal to 0,05 m.

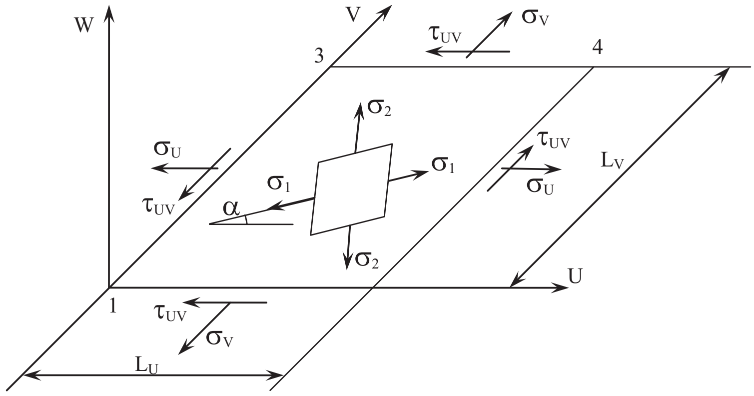
As a result of calculations made with the help of computer in the center of each finite element of the cargo frame, obtained normal σ_u and σ_v and shear stresses τ_u and τ_v were obtained in the upper and lower fibers of plates of finite elements. Principal stresses $\sigma_{1,2}$ are determined by the formula:

$$\sigma_{1,2} = \frac{\sigma_u + \sigma_v}{2} \pm \frac{1}{2}\sqrt{(\sigma_u - \sigma_v)^2 + 4\tau_{u,v}^2}, \qquad (6)$$

where σ_u and σ_v are normal stresses in the direction of the axes of the local coordinate system of U and V,

$\tau_{u,v}$ are shear stresses in the direction of the axes of the local coordinate system.

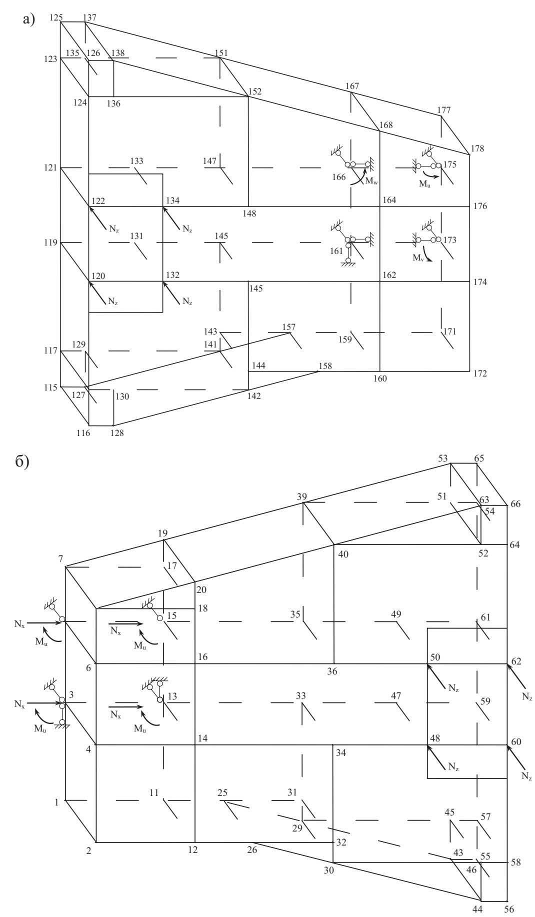
Evaluation of the stress-strain state of the cargo frame was conducted in accordance with the requirements of the rules for calculating the strength of cars [3]



Pic. 2. The local coordinate system in the calculation using finite element method and positive directions of stresses in the finite element: U, W, V – the local coordinate system; L_u, L_v – local sizes of the finite element; Σ_u, σ_v are normal stresses; $\tau_{u,v}$ are shear stresses; σ_1, σ_2 are principal stresses.

a)

b)



Pic. 3. The analytical model of the cargo frame by finite element method: a – the right side, b – the left side.

on the values of equivalent stress, defined on the basis of energy theory of strength. Under biaxial tension or compression and shear equivalent stresses were determined by the formula:

$$\sigma_{eq} = \sqrt{\sigma_u^2 + \sigma_v^2 - \sigma_u \sigma_v + 3\tau_{u,v}^2} \ . \qquad (7)$$

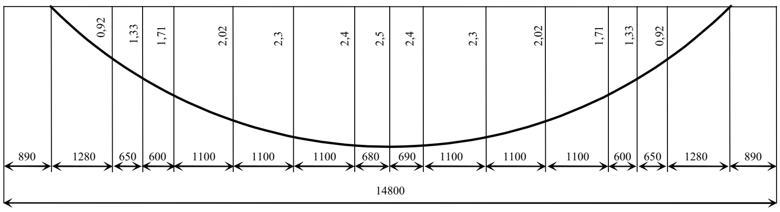
Allowable equivalent stress for low-alloy steel 09G2D, of which the cargo frame is made, are 260 MPa for the first design mode and 210 MPa for III design mode.

Analysis of the results showed that the highest equivalent stresses arise in the first design mode.

The maximum values (207 MPa) are observed in finite elements with numbers of nodes 12, 26, 11, 25 of the vertical longitudinal membrane of the cargo frame and minimum (1 MPa) – in finite elements with numbers of nodes 84, 92, 86, 94 of the top plate of the cargo frame.

The maximum tangential stress values equal to 94 MPa arise in the elements with numbers of nodes 6, 16, 5, 15 of the upper longitudinal aperture of the cargo frame, and the minimum of 7 MPa – in finite elements with numbers of nodes 84, 92, 86, 94 of the top plate of the cargo frame.

The maximum values of the principal stresses equal to 102 MPa, are recorded in the elements with



Pic. 4. Diagram of deflections (in mm) of the cargo frame in its various sections.

numbers of nodes 12,2, 11, 25 of the vertical longitudinal aperture, and the minimum of 16 MPa – in finite elements with numbers of nodes 82, 90, 81, 89 of the vertical aperture of the cargo frame.

In the lower plate of the cargo frame maximum values of equivalent stresses reach 120 MPa in the element with numbers of nodes 13, 33, 15, 35, and shear stresses 60,1 MPa are obtained in the finite element with numbers of nodes 5, 15, 7, 17. Maximum values of the principal stresses are equal to 137 MPa in the finite element with numbers of nodes 13, 33, 15, 35.

In the top plate of the cargo frame maximum values of equivalent stresses are 58,7 MPa in the finite element with numbers of nodes 4,14,6,16, and maximum values of shear and principal stresses respectively equal to 29,3 and 59,4 MPa, occur in the element with numbers of nodes 14, 34, 16, 36.

Calculation results also showed that in different places of the cargo frame stress values differ from each other. Thus, in a vertical transverse aperture equivalent stresses vary from 7,74 to 157 MPa, shear stresses- from 3,36 to 58 MPa, and principal stresses – from 0,84 to 71,4 MPa. In the vertical longitudinal aperture of the frame equivalent stresses are spread from 4,8 to 208 MPa, shear – from 2,7 to 94 MPa. In the low plate equivalent stresses vary from 2,4 to 121 MPa, shear stresses – from 1,2 to 60,1 MPa, principal stresses – from 0,067 to 137 MPa. In the top plate similar stresses vary accordingly from 0,3 to 59, from 0,16 to 29,3, from 0,05 to 59,4 MPa.

Within III design mode values of stresses in its various finite elements are much less: equivalent – by 2,1–3,6 times, shear – by 1,7–2,9 times, principal – by 1,6–3,7 times. Moreover, the load is mainly perceived by finite elements of transverse and longitudinal apertures in support zones and the top plate of the cargo frame: stresses in these finite elements do not exceed 98 MPa. In remaining elements their level is of only 17–25 MPa.

For the cargo frame of the transporter moving in low-capacity trains within the first design mode maximum equivalent, shear and principal stresses do not exceed 71 MPa in the vertical apertures of support zones.

Therefore, the analysis of stress values in the cargo frame shows that it has a large margin of safety, because design equivalent stresses in it are much less than permissible. However, and it is seen, the structure was originally designed irrationally from the viewpoint of metal intensity and metal mass distribution over the cross section and length of the cargo frame. This is indicated by a significant difference in the values of stresses in finite elements. For example, in support zones equivalent stresses reach 163 MPa, and in finite elements of the cargo frame, the most distant from them, and in places of a load application to the frame the same stresses do not exceed 17–25 MPa. In addition, top plates of the middle part of the cargo frame are not almost involved in the perception of loads, stresses in them are almost two times less than in low plates. Loads are perceived mainly by support zones and the surrounding finite elements. Here, the values of equivalent stresses vary within 67–163 MPa.

The study of stress-strain state of the cargo frame also identified its deflections in various sections along the length (Pic. 4). Diagram of deflections shows that the maximum of them does not exceed 2,5 mm in the middle section (at a distance of 7,4 m from the place where the frame rests on the center pad of the overhand of the transporter). This indicates that the structure has a very high stiffness.

Conclusion. *Basing on the analysis of the stress-strain state of originally designed cargo frame Kaluga Turbine plant-manufacturer got recommendations for more rational distribution of the metal mass in length and cross-section, as well as a decrease in metal intensity of the spaces of the cargo frame where calculations defined very low stresses. These recommendations were taken into account at the plant and were used for the subsequent adjustment of the structure, and then a variant of the cargo frame was produced, which is now used to carry bulky unique items.*

In general, studies of stress-strain state of the cargo frame showed that it is workable, strength reliable, easy for fastening of transported products and can be safely used for regular transportation of heavy bulky goods on railways of Russia in accordance with the same requirements that exist for ordinary rolling stock of the car fleet.

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