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RESOURCE-SAVING RESERVE OF STRENGTH CHARACTERISTICS OF LONGITUDINAL BEAM OF THE METRO WAGON TRUCK

Aleksandr Kuznetzov
Department of theoretical and structural mechanics
National University of Urban Economy in Kharkiv
17 Marshal Bazhanov str., Kharkiv, Ukraine, 61002
alex.kuznetzov2012@yandex.ua

Vladislav Skurikhin
Department of electric transport
National University of Urban Economy in Kharkiv
17 Marshal Bazhanov str., Kharkiv, Ukraine, 61002
VLADSCU@gmail.com

Vyacheslav Shavkun
Department of electric transport
National University of Urban Economy in Kharkiv
17 Marshal Bazhanov str., Kharkiv, Ukraine, 61002
shavkun1977@mail.ru

Abstract

In this paper, an analysis of methods for calculating structures from allowable stresses and from limiting states is made. It is shown that when the transition from the longitudinal beam calculation to the allowable stresses to the calculation of the limiting state, the strength limit increases by 1.5 times.

A mathematical model of the stress-strain state of a longitudinal beam of metro wagon truck without taking into account the transverse force is developed. The mathematical modeling with the given margin of strength of the power calculation of the longitudinal beam metro wagon track, which is a simple beam of a constant hollow rectangular section, pinched at its ends and loaded along the middle of the span by a concentrated stationary force, is carried out.

Thus, the application of the method of calculation for the limiting state makes it possible to identify the resource-saving reserve of the strength characteristics of the longitudinal beam of the metro wagon truck – a 3-fold increase in the maximum permissible load.

Keywords: resource saving reserve, reserve strength characteristics, longitudinal beam, bearing capacity, allowable and limiting voltage, metro wagon.

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1. Introduction

Resource-saving is an element of economic and environmental expediency in advanced developed countries. The contribution of resource saving to the gross domestic product is one of the main indicators of the effectiveness of the economy of each state. Resource-saving is treated as an activity (organizational, scientific, practical, informational), which is aimed at the rational use and economical expenditure of primary and transformed material resources in the national economy, and which is realized using technical, economic and legal methods [1]. The strategic objectives of the state's policy on resource-saving are increasing the efficiency of resource-saving indicators to the level of industrialized countries. Carrying out an active resource-saving policy is an important factor that will guarantee the sustainable and efficient use and provision of material resources to the country's economy [2].

In the urban passenger transport system, the metro takes an important place. This type of electric transport is the most promising in many countries of the world, as it has minimal operating costs, high driving performance and comfort. The development of the metro network allows solving the problems of overloading the city's transport arteries and environmental problems of the city – gas contamination and high noise level.

2. Literature review and problem statement

The problem of resource saving is especially in need of a priority solution in resource-intensive industries, including urban electric transport.

Throughout the world, city electric transport mainly dealt with the rational consumption of energy resources.

Therefore, a comprehensive approach to solving the problem of resource saving is relevant for this type of transport.

In work [3] the method of approach to the rational use of resources in the operation of urban electric transport, in particular, the question of the formation of resource-saving technical operation on the basis of the introduction of diagnostic systems, is displayed.

In [4, 5], the issue of resource-saving and wear resistance of units and parts of ground city electric transport is considered. Dependences of wear of parts and assemblies on different factors are shown. The analysis of the publication shows that the issues of resource-saving reserve strength characteristics of units and aggregates of the metro wagons are not affected.

The authors of [6] carry out research to optimize the selection of wheel-motor blocks with a minimum relative difference in the linear speeds of wheel pairs along the rolling surface. A method is proposed that optimizes the choice of wheel-engine blocks of metro wagons. The analysis of publications shows that the specificity of the operation of underground electric transport does not allow using the proposed method.

In [7, 8], ways to increase resource-saving in the operation of the rolling stock of electric transport are considered. The performed analysis of the work shows that it does not consider metro issues, which has its own peculiarities of operation.

Having conducted a literary analysis on the sources of industrially developed countries [9–12], it can be concluded that in the field of urban electric transport, the directions of resource saving in the operation of transport are also a priority. These works do not touch upon issues that are aimed at improving the design of technical equipment, the introduction of new technological processes for maintenance and repair.

Therefore, the most important task in this regard is increasing the efficiency of operating the metro rolling stock, to increase its service life and reliability.

3. The aim and objectives of research

The aim of research is increasing the resource-saving reserve strength characteristics of the longitudinal beam of the metro wagon truck, by developing new scientific solutions in the approach to the modernization of resource saving in urban electric transport. That will make it possible to rationally use material and labor resources, to increase the service life of the rolling stock as a whole.

To achieve the aim, the following tasks are set:

– to formulate the main advantages of methods for calculating structures for permissible stresses and for limiting states;

– to analyze the degree of increase in the safety factor of the longitudinal beam of the truck when going over to the limit state calculation;

– to develop a mathematical model of the stress-strain state of the longitudinal beam of the metro wagon truck without taking into account the transverse force;

– to carry out mathematical modeling with a given margin of strength of the force calculation of the longitudinal beam metro wagon truck, which is a simple beam of a constant hollow rectangular section clamped at its ends and loaded in the middle of the span by a concentrated stationary force;

– to analyze the simulation results to obtain data on the maximum permissible load when calculating the longitudinal beam for the allowed voltages and for the maximum permissible load when calculating the limit state;

– to determine the influence of each calculation method on the value of the maximum permissible load and to give a quantitative estimate of the strength of the longitudinal beam of the truck.

4. Determination of the resource–saving reserve of the strength characteristics of the longitudinal beam of the metro wagon truck

The frame of the metro wagon truck is a universal construction consisting of beams of rectangular cross-section, which is used on all wagons of the type: Eg, Eg3, 81–714 and 81–717, which are operated on the territory of Ukraine.

Let's draw strength analysis of the longitudinal beam from the soft low-carbon steel of the front truck (**Fig. 1**) of the metro wagon, which has a creep pad *cd* on the stress diagram (**Fig. 2**).

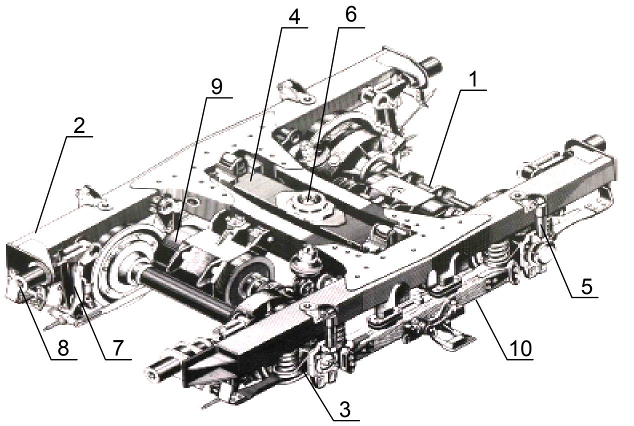

Fig. 1. Metro wagon truck: 1– wheel pair with axle boxes and reducer; 2– longitudinal beam; 3 – axle suspension; 4 – central beam; 5 – hydraulic vibration damper; 6 – spherical center plate; 7 – brake lever transmission; 8 – brake cylinder; 9 – traction motor; 10 – current collector

4. 1. Determination of the dangerous value of the bending moment when calculating the longitudinal beam of the metro wagon truck with a specified margin of safety for the permissible stresses and for the limiting state

When calculating the strength of rods, beams and structures, the largest normal, tangential or equivalent stresses, depending on the type of stress state and the accepted strength theory in the dangerous section and at the dangerous point, are compared with the allowable stresses. If the maximum design stresses do not exceed the permissible values, then it is considered that the proper safety factor of the structure is ensured by this. Such method of calculating the strength is called calculating the allowable stresses. It provides structural strength, but in many cases it does not allow to rationally use all its capabilities and often leads to overestimation of weight. When calculating the permissible stresses, the dangerous state of the structure is one in which the greatest stress at least at one point in the material of the structure reaches a dangerous value, the yield point for a plastic material or a temporary resistance for a brittle material. The state of the rest of the mass of material is not taken into account.

Meanwhile, in the case of uneven distribution of stresses (for example, in bending or torsion) in constructions made of ductile materials, the appearance of local stresses equal to the yield strength is in some cases not dangerous for the entire structure. Practice shows that with the appearance of local plastic deformations, the design can still satisfy the requirements imposed on it and for its transition to the limiting state (which means a state of construction in which it loses its ability to resist external influences or ceases to meet the performance requirements), a further increase is required load. Thus, in reality the design has a safety margin greater than that calculated for the allowed voltages. In connection with this drawback of the method for calculating the strength of permissible stresses, a new approach to assessing the strength of the structure has emerged. Therefore, along with the calculation of the allowed stresses, the method of calculating structures by the limiting state is applied [13].

There are three types of limiting states:

– by bearing capacity (strength, stability and endurance at variable voltages);

– by development of excessive deformations (deflections, distortions, etc.);

– by formation or crack opening.

The creep flow area *cd* has stress diagrams for low-carbon steels and some other materials (**Fig. 2**).

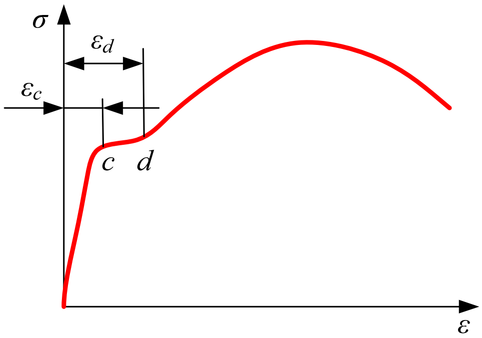

Fig. 2. Stress diagram of low-carbon steels

For example, the curve on the stress-strain diagram of aluminum (**Fig. 3**), outside the action of Hooke's law, has a very weak slope, and in calculations it can be taken as a horizontal line.

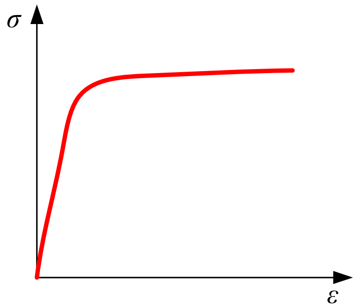

Fig. 3. Stress diagram of aluminum

To simplify the calculations, the tension, compression, and shear diagrams for plastic materials are schematized so that the straight line of the Hooke's law directly mates with the horizontal straight line without a smooth transition (**Fig. 4**), thereby accepting the equality between the limits of proportionality and yield.

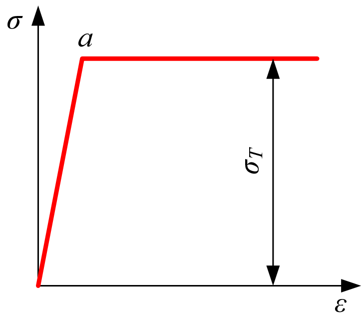

Fig. 4. Prandtl diagram

The length of the horizontal section of the diagram is not limited; the material is considered to be perfectly plastic – not hardening. Such diagram is called the Prandtl diagram.

For a complex stress state, various theories of the transition of a material to a plastic state are proposed. The simplest calculations are carried out using Saint Venant's theory of plasticity

[13], according to which the plastic state of a material under a complex stress state occurs when the greatest tangential stresses reach the limiting value – the shear yield strength.

In the cross sections of the beam during bending, the normal stresses in the elastic state of the material are distributed unevenly, linearly varying along the height of the beam (**Fig. 5**).

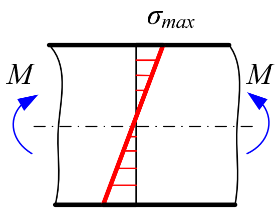

Fig. 5. Diagram of normal stresses in bending

The greatest normal stresses at the points of the cross-section far from the neutral line are determined by the formula:

$$\sigma_{max} = \frac{M}{W}, \tag{1}$$

where M – bending moment; W – axial moment of resistance.

When calculating strength for permissible stresses, the margin of safety is defined as the ratio of the yield strength of the material to the maximum stress, thus for the dangerous one the beam state corresponding to the achievement by the greatest normal stresses in the dangerous sections of the yield strength is assumed. Such condition can only be considered conditionally dangerous. The beam still retains the ability to perceive an increasing bending moment.

Let's determine the value of the limiting bending moment in the case of pure bending of the longitudinal beam of the front carriage of the metro wagon, the cross section of which has two axes of symmetry. The yield stresses under tension and compression will be assumed to be the same.

After the appearance of yield at the points of section most distant from the neutral axis, the plastic state of the material propagates in the direction towards the neutral axis. Before the full exhaustion of the bearing capacity of the beam in the cross sections there will be two zones – plastic and elastic (**Fig. 6**).

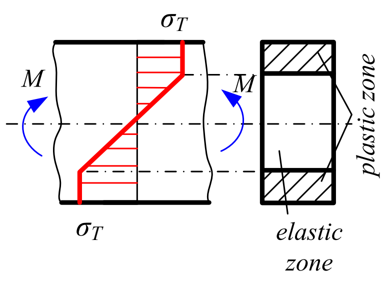

Fig. 6. Plastic and elastic zones in cross sections of the beam

The diagram of normal stresses in the cross section for the limiting state is shown in **Fig. 7**. In the considered cross-section, a so-called plastic hinge is formed, which transmits a constant moment equal to the limiting bending moment.

The limiting moment can be calculated as the sum of the moments with respect to the neutral axis of forces $\sigma_T dF$ in the cross section (**Fig. 7**)

$$M_{lim} = \int_F \sigma_T y dF = \sigma_T 2 \int_{F/2} y dF = \sigma_T 2S_{max}, \tag{2}$$

where S_{max} – the static moment of the area of half the cross section with respect to the neutral axis.

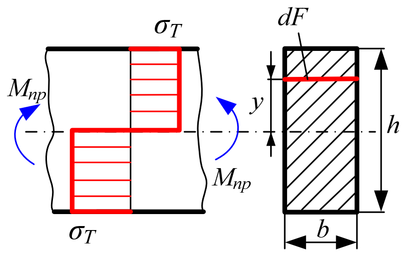

Fig. 7. Diagram of normal stresses in the cross section for the limiting state

$2S_{max}$ is called the plastic moment of resistance and is denoted W_{pl}. Then

$$M_{lim}=\sigma_T W_{pl}. \tag{3}$$

For a closed hollow rectangular cross-section, using the engineering methods of calculating the longitudinal beam (**Fig. 8**) of the metro wagon truck:

$$W_{pl}=\frac{\left(b_1h_1^2-b_2h_2^2\right)}{4}, \tag{4}$$

where b_1, b_2 – outer and inner section width.

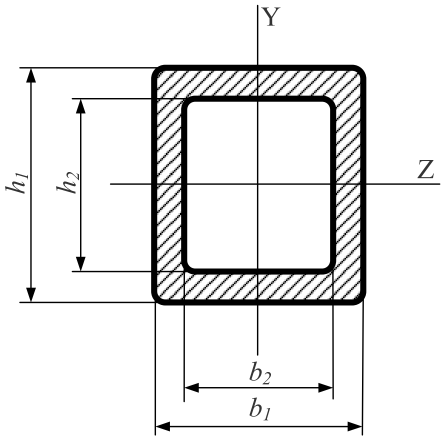

Fig. 8. Cross-section of the longitudinal beam of the truck

Dangerous value of bending moment when calculating for permissible stresses

$$M_T=\sigma_T W_{pl}. \tag{5}$$

Relation

$$\frac{M_{pl}}{M_T}=\frac{W_{pl}}{W} \tag{6}$$

characterizes the degree of increase in the safety factor of the beam in the transition to the calculation of the limiting state. In the case of a beam of a hollow rectangular cross section

$$\frac{W_{pl}}{W}=\frac{\left(b_1h_1^2-b_2h_2^2\right)/4}{\left(b_1h_1^2-b_2h_2^2\right)/6}=1{,}5. \tag{7}$$

The above reasoning concerning the definition of the limiting state equivalent to the formation of a plastic hinge in the beam cross-section, strictly speaking, is valid only for pure bending, when there are no tangential stresses.

4. 2. Calculation of the longitudinal beam of the metro wagon truck for bending according to the permissible stresses and the limiting state without taking into account the effect of lateral force

Let's perform a force calculation of the longitudinal beam of the metro wagon truck (**Fig. 1**) for bending according to the permissible stresses and the limiting state, without taking into account the effect of lateral force.

The longitudinal beam of the wagon truck is a simple beam of a constant hollow rectangular section, pinched at its ends and loaded along the middle of the span by a concentrated force P (**Fig. 9**)

$$P=mg, \tag{8}$$

where m – half the wagon mass; g – acceleration of terrestrial attraction; l – beam length; A and B – points of elastic suspension of the longitudinal beam.

Let's determine the maximum intensity of this load, which is permissible according to the calculation for the allowed stresses and for the limiting state with the same margin of strength.

4. 2. 1. Calculation of the allowed stresses

The beam is statically indeterminate. Its calculation is greatly simplified due to symmetry. Applying the displacement method for statically indeterminate systems [13], let's find extra unknowns and build the bending moment diagram (**Fig. 9**).

The bending moment has the greatest value in the support clamped sections:

$$M_{max} = M_A = M_B = \frac{P_{lim1} l}{8} \tag{9}$$

and in the middle of the beam under the force P

$$M_C = \frac{P_{lim1} l}{8}. \tag{10}$$

With increasing load P, the stresses in these sections first of all reach the yield point.

Taking the margin of safety for the yield strength equal to n, let's find the maximum permissible load from the condition of strength:

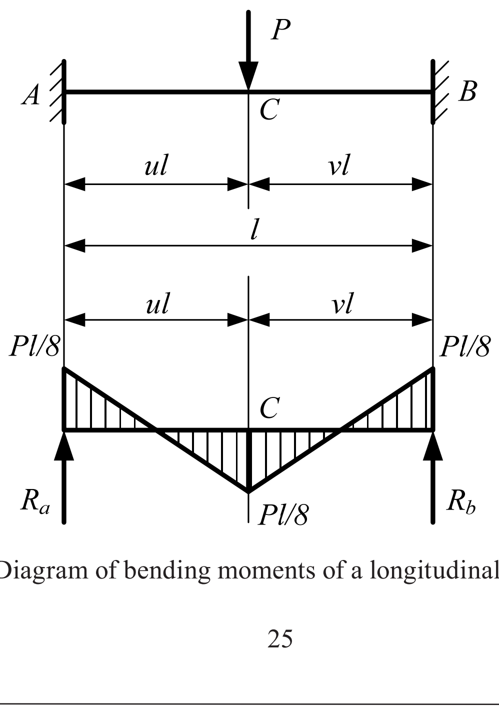

Fig. 9. Diagram of bending moments of a longitudinal beam

$$\frac{M_{max}}{W}=\frac{\sigma}{n}. \qquad (11)$$

Taking into account that

$$W=\left(b_1h_1^2-b_2h_2^2\right)/6$$

and

$$M_{max}=\frac{P_{lim\,1}l}{8},$$

let's obtain the expression for the maximum permissible concentrated load when calculating the longitudinal beam for bending according to the allowed stresses

$$P_{lim\,1}=\frac{4\sigma_T\left(b_1h_1^2-b_2h_2^2\right)}{3ln}. \qquad (12)$$

4. 2. 2. Calculation of the limiting state

With further growth of the load P_{lim2} in the reference sections and along the middle of the span, the values of the bending moments will increase. After the appearance of plastic deformations at the points of the reference sections farthest from the neutral axis and along the middle of the beam, further growth of the load will lead to the formation of plastic hinges in these sections, and the bending moment will reach the limiting value M_{lim}.

Now the beam works as hingedly supported, to which constant moments are attached on the supports (**Fig. 9**)

$$M_{lim}=\sigma_T W_{pl}=\frac{\sigma_T\left(b_1h_1^2-b_2h_2^2\right)}{4}. \qquad (13)$$

With further load growth, these moments retain their importance, and the problem becomes statically determinate. At the same time, along the middle of the span, the bending moment becomes equal to the same value M_{lim} and a plastic hinge is formed there. Further load growth becomes impossible and the bearing capacity of the beam is depleted.

The condition for the equality of the bending moments in the reference sections and along the middle of the span is:

$$\frac{P_{lim\,2}}{8}-M_{lim}=M_{lim}, \qquad (14)$$

from which let's find that

$$M_{lim}=\frac{P_{lim\,2}l}{16}. \qquad (15)$$

Equating the right-hand sides of formulas (13) and (14), let's find

$$\frac{\sigma_T\left(b_1h_1^2-b_2h_2^2\right)}{4}=\frac{P_{lim\,2}l}{16}. \qquad (16)$$

Assuming a margin of safety equal to n, let's obtain from (16) the maximum permissible intensity of the concentrated load when calculating the longitudinal beam for bending according to the limiting state:

$$P_{lim\,2}=\frac{16\sigma_T\left(b_1h_1^2-b_2h_2^2\right)}{4ln}=\frac{4\sigma_T\left(b_1h_1^2-b_2h_2^2\right)}{ln}. \qquad (17)$$

The ratio of the maximum permissible loads in the calculations for the limiting state (17) and the allowable stresses (12)

$$\frac{P_{\lim 2}}{P_{\lim 1}} = \frac{(3\ln 4\sigma_T)(b_1 h_1^2 - b_2 h_2^2)}{(\ln 4\sigma_T)(b_1 h_1^2 - b_2 h_2^2)} \cong 3. \qquad (18)$$

Thus, the power calculation of the longitudinal beam of the metro wagon with the given margin of strength in the calculations for the limit state and the allowable stresses makes it possible to determine the maximum permissible concentrated load in each case, and their ratio gives a quantitative estimate with an error of up to 8 % of the strength reserve – an increase in the bearing capacity of the beam three times.

5. Conclusions

1. The main advantages and disadvantages of methods for calculating structures for permissible stresses and for limiting states are formulated.

2. The analysis of the degree of increase in the safety factor of the longitudinal beam of the truck during the transition to the calculation of the limiting state is conducted. A 50 % increase in the safety factor is shown in the transition from the longitudinal beam calculation to the allowable stresses to the limit state calculation.

3. A mathematical model is developed with a given margin of strength of the force calculation of the longitudinal beam of the metro wagon truck.

4. Mathematical modeling with a given margin of strength of the force calculation of the longitudinal beam of the metro wagon truck is carried out.

5. According to the results of force calculation of the longitudinal beam with a certain margin of safety in terms of the limiting state and the allowable stresses, the greatest permissible load in each case is determined and the quantitative estimation of the increase in the strength reserve of the longitudinal beam of the metro wagon truck is given.

6. It is shown that the application of the method of calculation for the limiting state under the action of a stationary concentrated load makes it possible to increase the load-carrying capacity of the longitudinal beam of the truck 3 times, which will significantly increase the resource-saving indicators and the efficiency of operating metro wagons as a whole, as well as the service life.

The obtained research results are universal and can be used in the calculation and design of load-bearing parts of trucks (frames, longitudinal and transverse beams) of vehicles.

The advantage of this method of calculations for limiting stresses is a 3-fold increase in the maximum permissible load.

However, this method does not imply the complete elimination of the calculation method for allowable stresses.

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