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Method of Calculating the Stress-Strain State of Frame Structures of the Autotractor Trailers for Static Loading Conditions

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***Abstract:** In the article on an example of the autotractor trailer, load-carrying capacity of 4 tons considers the technique for calculating the stress-strain state of the trailer frame. The comparative analysis of results of theoretical and experimental researches is given. It is established, that the deviations of the maximum values of stress at driving on road with tar coating of satisfactory quality is in limits of 4 %, on gravel roads with worn areas - 10 %, on the rotary strip with ridges in height of 8-12 cm and step of 90 cm - 11 %, on a deep ditch depth of 40-45 cm and width 100-150 cm - 9 %.*

***Keywords:** trailer, frame, numerical calculation, road conditions, strength, stress-strain state.*

I. INTRODUCTION

Frame is the main transport vehicle-carrying unit, which receives all the stresses resulting from movement of the vehicle on the roads and rough terrain. In addition, the support system is the basis for fixing the components and assemblies of the machine, so it additional requirements and its constructive forms must be subordinated to the general layout plan [1, 2]. Calculation of frame strength is one of the most important tasks in the design of transport machines. In order to emphasize the relevance of the research, we note that the transport machinery, which belongs to the sphere of research object, is significantly different from other branches of engineering. Its peculiarity lies in the fact that the external loads acting on the structure in a temporary variable and applied with a certain frequency, depending on the speed, actual load, road conditions and many other factors. At the same time during the operation possible resonance phenomena, this can result in high relative to nominal, stress and many other adverse events. Variable character external loads lead to a periodic change in stresses, which in turn contributes to fatigue crack growth and development that causes fatigue fracture [3].

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II. SYSTEM DESCRIPTION

The work on the example of the autotractor trailer carrying capacity of 4 tons of the technique of calculation of stress-strain state of the trailer frame.

The proposed method allows calculation of the strength developed at the Joint Stock Company “Tashkent agricultural techniques plant” autotractor trailers carrying capacity 6 and 8 tons. The frame consists of two side members and seven crossbeams, which are rigid rod members open loop and closed ones and have a rather thin-walled profiles cross section is shown in Figure 1. These elements are obtained by stamping from sheet metal 4-6 mm thick. Trailer frame structurally performed according to the following arrangement: the side members are interconnected by cross members by welding, thereby forming a frame structure; in front of the frame is made of fifth wheel couplings; side members connected to the suspension via springs, elastic elements. Topical is to improve the methods of calculations for strength and rigidity of frame structures of trailers. As special tasks in the work are considered: development of computational frame scheme finite element method based on the properties of symmetric structure with respect to the longitudinal axis; study of stress-strain state of the trailer frame by the condition of static loading; frame bending deformation of the external load corresponding to the rated load of the trailer; joint deformation of the frame of the weight of the load and twist relative to the support device at the wheel move (side) through an obstacle; accounting compliance (precipitation) of elastic suspension elements (springs) on the stress-strain state frame; a comparison of the stress-strain state assessment calculations with experimental results for the static loading conditions, carried out at the site of the Uzbek state centre for certification and testing of agricultural machinery and technology, in the test trailer 2PTS-4-793A [4-10].

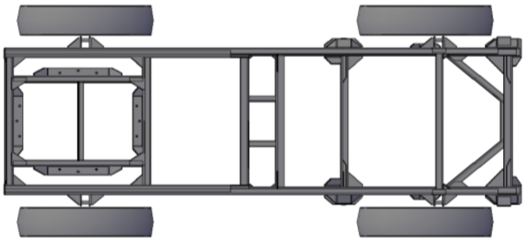


Fig. 1. General view of the autotractor trailer frame

Frame is considered on an elastic foundation under static loading, ensures that the stress distribution in the nature of the structure obtained by calculation, the results of the experimental measurements of strain measurement [11].

The magnitude of the external load, accepted for consideration during the study of the stress-strain state frame corresponds to the rated load of the trailer.

In determining the estimated load on the trailer frame static strength, with sufficient engineering design and practice of error, loading measured by the bending deformation of the weight of the shipment. Effect of twisting the frame caused by movement over uneven surfaces and weight redistribution is taken into account by including in the additional bending equations torsion equations.

In the construction of thin-walled bar design scheme considering its "median" surface, which runs through the middle of the elements forming the rod [12]. Next, the median cross-sectional surface forms a plane sectional profile is shown in Figure 2.

According to outline the profile of two types of rods: rods with a closed profile; rods with an open profile. For the open and closed profile geometrical parameters it is defined under the formula

$$J_{\mathrm{k}} = \alpha\sum_{\mathrm{i=1}}^{\mathrm{n}} \frac{s_{\mathrm{i}}\delta_{\mathrm{i}}^{3}}{3}\,;\; W_{\mathrm{k}} = \frac{J_{\mathrm{k}}}{\delta}\,; \tag{1}$$

$$J_{\mathrm{k}} = \frac{4F^{*2}}{\int\limits_{s}\frac{\mathrm{d}\,s}{\delta}}\,;\; W_{\mathrm{k}} = 2F^{*}\delta. \tag{2}$$

where α - factor (for I-Profile beams is taken equal to 1.2, for U-Profile beams - 1.12; for L-Profile beams - 1.0); δ - respectively, the thickness of each part of the profile (the smaller side of the rectangle); s - respectively, the length of the contour of each of the cross-section (large side of the rectangle); F^* - area of "live" cross section.

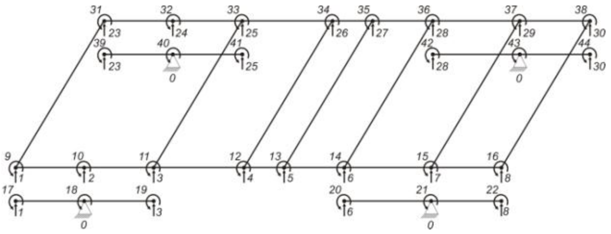


Fig. 2. Design scheme

Work of thin-walled cores of the closed profile essentially does not differ from work of usual rods. At their calculations, it is possible to apply the law of flat sections. Work of thin-walled rods of an open profile cannot be described the law of flat sections. It is replaced with a more difficult law [13].

Cross-sections of thin-walled open profile bars with loads that create twisting do not stay flat. There is a warping of sections related to the movements of the points of the cross-sectional plane along the axis of the rod.

The calculation is carried out in accordance with the known rules of the theory of strength of materials in the following order [13]: the calculated bending moment diagram; bending stress under the formula are defined:

$$\sigma_b = \frac{M_b}{W_x},\; MPa.$$

From the course the strength of materials, we know that bending differential equation has the form

$$\frac{\mathrm{d}\phi_x}{\mathrm{d}x} = \frac{M_x}{EJ}, \tag{3}$$

where ϕ_x – the angle of rotation of the section x, and M_x - bending moment in the section x.

We define the expressions for Q_1, M_1, Q_2, and M_2 (Figure. 3)

Figure 3 shows that the bending moment in the cross-section x is equal to $M_x = Q_1 \cdot x + M_1$, solving the differential equation (3) we will obtain

$$\phi_x = \frac{1}{2}\frac{Q_1x^2}{EJ} + \frac{M_1x}{EJ} + \phi_1$$

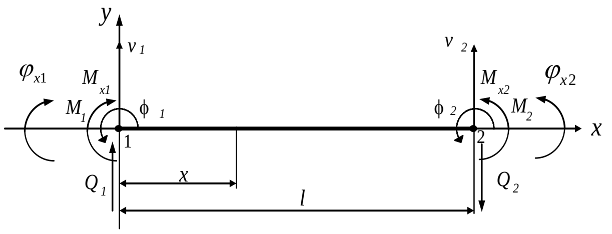


Fig. 3. Scheme of forces and moments acting on the rod element

Deflection v_x in the cross-section x is determined from the equation

$$\frac{\mathrm{d}v_x}{\mathrm{d}x} = \phi_x,$$

$$v_x = \frac{1}{6}\frac{Q_1x^3}{EJ} + \frac{1}{2}\frac{M_1x^2}{EJ} + \phi_1x + C_2, \quad (x=0, C_2 = v_1)$$

We write the expression ϕ_x and v_x when $x=l$

$$\phi_2 = \frac{1}{2}\frac{Q_1l^2}{EJ} + \frac{M_1l}{EJ} + \phi_1$$

$$v_2 = \frac{1}{6}\frac{Q_1l^3}{EJ} + \frac{1}{2}\frac{M_1l^2}{EJ} + \phi_1l + v_1$$

$$\Leftrightarrow \begin{bmatrix} \frac{l^2}{2EJ} & \frac{l}{EJ} \\ \frac{l^3}{6EJ} & \frac{l^2}{2EJ} \end{bmatrix} \begin{bmatrix} Q_1 \\ M_1 \end{bmatrix} = \begin{bmatrix} -\phi_1 + \phi_2 \\ v_2 - \phi_1l - v_1 \end{bmatrix}$$

Solving the system, we get

$$Q_1 = \frac{6EJ(\phi_2l - 2v_2 + \phi_1l + 2v_1)}{l^3},$$

$$M_1 = -\frac{2EJ(\phi_2l - 3v_2 + 2\phi_1l + 3v_1)}{l^2}$$

At the end of the beam $Q_2=Q_1$, $M_2=Q_1 \cdot l+M_1$ expressions for Q_1, M_1, Q_2 and M_2 can be written in matrix form

$$\begin{bmatrix} Q_1 \\ M_1 \\ Q_2 \\ M_2 \end{bmatrix} = \frac{EJ}{l^3} \begin{bmatrix} 12 & 6l & -12 & 6l \\ -6l & -4l^2 & 6l & -2l^2 \\ 12 & 6l & -12 & 6l \\ 6l & 2l^2 & -6l & 4l^2 \end{bmatrix} \begin{bmatrix} v_1 \\ \phi_1 \\ v_2 \\ \phi_2 \end{bmatrix} \qquad (4)$$

The rod element is based on torsion is considered as the union of elements describing: bending in the *xy* plane by the equations (4) and twist with the symmetry axis *x-x* by the following equations

$$\begin{Bmatrix} M_{x1} \\ M_{x2} \end{Bmatrix} = \frac{GJ_{\mathrm{k}}}{l} \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \begin{Bmatrix} \varphi_{x1} \\ \varphi_{x2} \end{Bmatrix}$$

Then the general system of equations takes the form:

$$\begin{bmatrix} Q_1 \\ M_1 \\ Q_2 \\ M_2 \\ M_{x1} \\ M_{x2} \end{bmatrix} = \begin{bmatrix} \frac{12EJ}{l^3} & \frac{6EJ}{l^2} & -\frac{12EJ}{l^3} & \frac{6EJ}{l^2} & 0 & 0 \\ \frac{6EJ}{l^2} & \frac{4EJ}{l} & -\frac{6EJ}{l^2} & \frac{2EJ}{l} & 0 & 0 \\ -\frac{12EJ}{l^3} & -\frac{6EJ}{l^2} & \frac{12EJ}{l^3} & -\frac{6EJ}{l^2} & 0 & 0 \\ \frac{6EJ}{l^2} & \frac{2EJ}{l} & -\frac{6EJ}{l^2} & \frac{4EJ}{l} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{GJ_{\mathrm{k}}}{l} & -\frac{GJ_{\mathrm{k}}}{l} \\ 0 & 0 & 0 & 0 & -\frac{GJ_{\mathrm{k}}}{l} & \frac{GJ_{\mathrm{k}}}{l} \end{bmatrix} \begin{bmatrix} v_1 \\ \phi_1 \\ v_2 \\ \phi_2 \\ \varphi_{x1} \\ \varphi_{x2} \end{bmatrix} = [K][u] \qquad (5)$$

Writing equations (5) in a matrix form is very convenient for programming, as finite element method problem reduces to solving a system of linear equations [14].

When solving static problems by the finite element method, the following analysis procedure was adopted:

- building a model with a partition of the structure into a finite number of elements;
- calculation of stiffness matrices of elements and load vector;
- building a full stiffness matrix and a full load vector;
- the second and third points are performed in parallel;
- solving a system of equations of the first degree with respect to the displacement of nodal points;
- calculation of stresses and strains in an element.

The calculation is in the elastic formulation, taking into account the rigidity of the springs.

III. SIMULATION RESULTS

The calculations should take into account the specific road conditions of cotton producing countries, which have been taken in four categories of road sections: road tars satisfactory coating having a little worn out areas with the average statistical irregularities in height $\sqrt{R_{(0)}} = 1{,}5\ cm$; gravel road with worn areas with the average statistical irregularities in height $\sqrt{R_{(0)}} = 1{,}5 \div 3{,}0\ cm$; rotary strip with ridges in height of 8-12 cm and step of 90 cm; the deep ditch 40-45 cm depth and width of 100-150 cm.

As the criterion defining an intense condition of the frame of the autotractor trailer stress from action on the frame of the vertical dynamic loadings causing a bend of elements of the frame of the trailer in the vertical plane of normal stress leading to occurrence is accepted

$$\sigma = \frac{M_x}{J_x} \cdot y \cdot$$

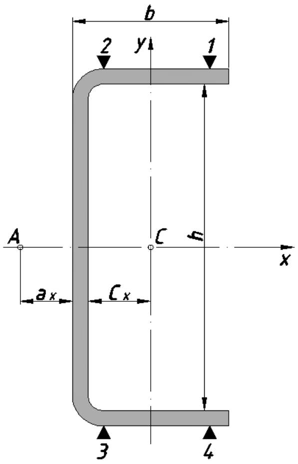


Fig. 4. Cross-section of the longeron

The velocity of the tractor train, on the basis of several studies [15, 16] and constructive features of the cotton tractor, the three types of road was selected respectively 23.12 km/h and 13.2 km/h and 9.25 km/h, and at moving of the deep ditch 6.1 km/h.

In strain measurement of the trailer frame, obtained the normal stresses in the individual points of the section longeron.

Using the method of calculating the normal stresses and using the following formula, we obtain the normal stresses in the frame of the trailer from the action of the vertical dynamic loads.

$$\sigma_{\mathrm{N}} = \frac{C_x}{b}\left(\frac{\sigma_1 + \sigma_4}{2}\right) + \frac{b - C_x}{b}\left(\frac{\sigma_2 + \sigma_3}{2}\right),$$

where $y=h/2$, $x=C_x$, $x=a_x$ – the coordinates of the spar section (Figure 4.), *b* - flange width, *h* - height of the longeron, *C* - center of gravity, *A* - bending center.

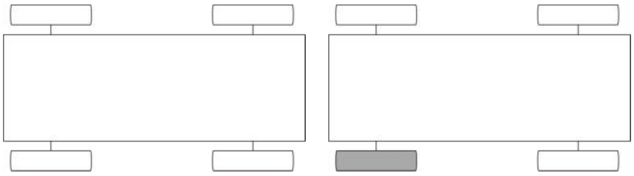
The geometrical characteristics of sections of the units are shown in figure 4 and Table-I.

Table-I: Geometrical characteristics of cross sections

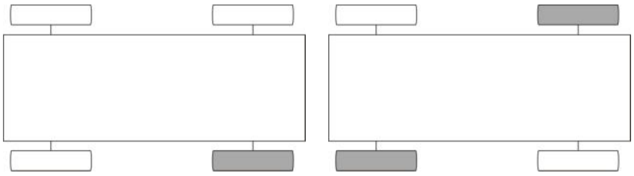
The unit name		a_x	C_x	F	J_x
		cm	cm	cm^2	cm^4
Unit №1	Longeron	1,56	1,61	12,10	347
	Cross-beam	1,42	1,20	6,82	140
Unit №2	Longeron	1,6	1,58	13,15	352
	Cross-beam	1,48	1,18	7,12	146
Unit №3	Longeron	1,56	1,61	12,10	347
	Cross-beam	1,42	1,20	6,82	140
Unit №4	Longeron	2,65	1,61	24,2	2620
	Cross-beam	1,56	1,61	12,10	347
Unit №5	Longeron	2,65 (1,56)	1,61	24,2 (12,10)	2620 (347)
	Cross-beam	1,56	1,61	12,10	347
Unit №6	Longeron	0,6	3,0	19,43	412
	Cross-beam	1,42	1,20	6,82	140
Unit №7	Longeron	0,6	3,0	19,43	412
	Cross-beam	1,56	1,61	12,10	347

Moving through irregularities in the assessment procedure, it was taken into account by changing the reference wheel surface characteristics.

At the same time, dealing with the following four cases, the relevant categories of road conditions (see: figure 5): 1- all four wheels in contact with the surface, uniformly distributed load; 2- all four wheels in contact with the surface, the load is distributed unevenly; 3- the front left wheel or rear left wheel is not in contact with the supporting surface; 4- front left and rear right wheels not in contact with the supporting surface.



a) 1 and 2 cases b) 3-case



c) 3-case d) 3-case

Fig. 5. Schemes of road influence

On figure 6 values of normal stress in longeron knots are resulted at loading of 4 ton and the maximum values of compression and a stretching of fibres.

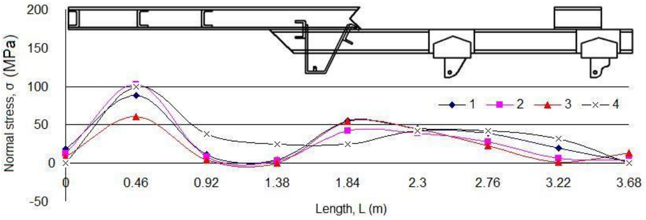
The calculation was performed for static loading, and in order to compare the obtained results with the experimental results, factor of safety (FOS) (f = 1.5) and dynamic coefficient (k) were included in the calculation process.

Experimental values are received at speeds of movement of 23,12 km/h, 13,2 km/h, 9,25 km/h.

Initial conditions: the initial displacement values of the frame are zero: $U_0=0$.

Boundary conditions: for case 1, $u_{18}=u_{21}=u_{40}=u_{43}=0$; for case 2, $u_{21}=u_{40}=u_{43}=0$; for case 3, $u_{18}=u_{40}=u_{43}=0$; for case 4, $u_{21}=u_{40}=0$.

The calculations made: for position 1 (see Figure 6, a and b) $P_2=P_{24}=P_7=P_{29}=8800$ N, $P_4=P_5=P_{26}=P_{27}=2200$ N, stiffness of the springs $EJ=12056$ N·m^2; for position 2 (see Figure 6, c and d) $P_2=P_{29}=10800$ N, $P_7=P_{24}=6800$ N, $P_4=P_5=P_{26}=P_{27}=2200$ N; for position 3 (see Figure 6, e and f) $P_2=P_{24}=14080$ N, $P_7=P_{29}=8000$ N, $P_4=P_5=P_{26}=P_{27}=3520$ N or $P_2=P_{24}=8000$ N, $P_7=P_{29}=14080$ N, $P_4=P_5=P_{26}=P_{27}=3520$ N; for position 4 (see Figure 6, g and h) $P_2=P_{29}=12800$ N, $P_7=P_{24}=4800$ N, $P_4=P_5=P_{26}=P_{27}=2200$ N.



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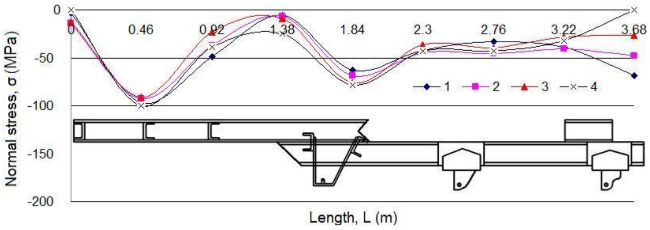

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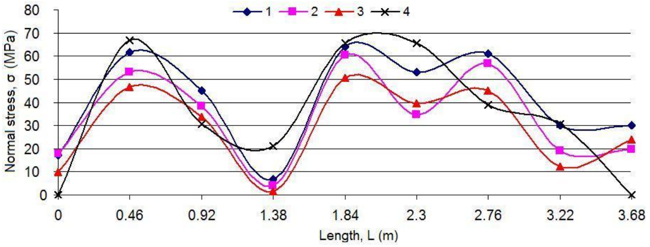

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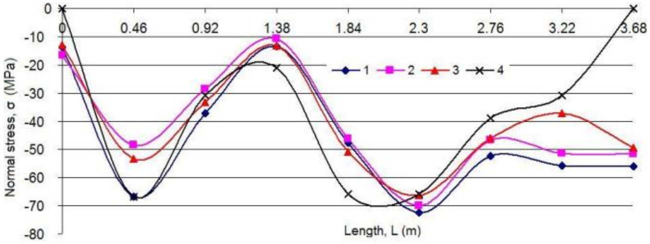

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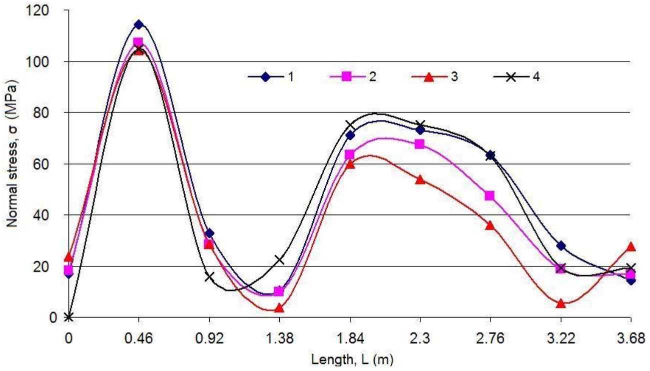
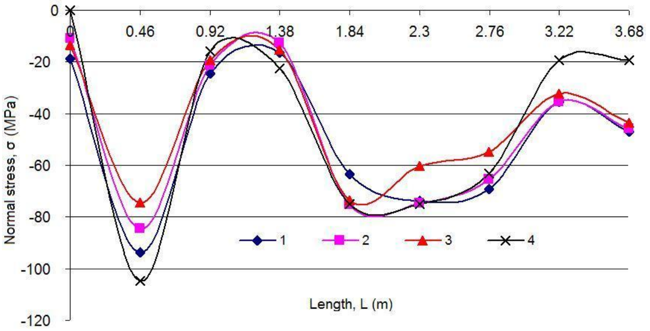
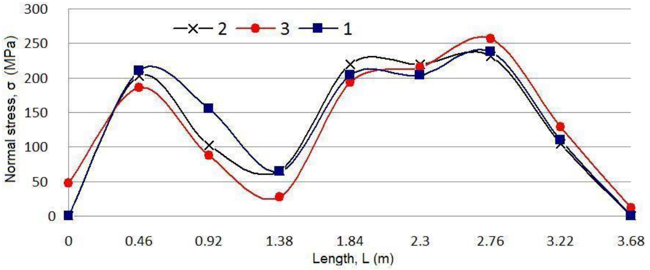


e)



f)



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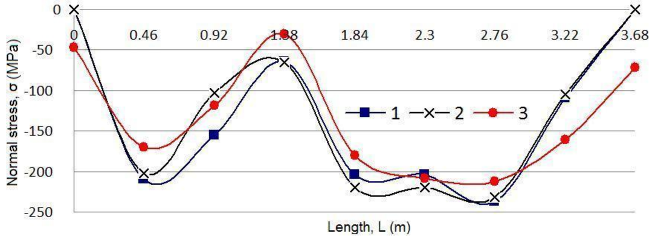

h)

Fig. 6. Normal stresses in the longeron nodes at the load of 4 tons: a), c), d), g) -with maximum values of tensile fibers; b), d), e), h) - with maximum values of fiber compression; for a), b), c), d), e), f) 1, 2, 3 - experimental values, 4 - calculated values; for g), h) 3 - experimental values, 1, 2 - calculated values

IV. CONCLUSION

Comparative analysis of the results of theoretical and experimental studies have shown that the maximum stress values for roads with tar coating of satisfactory quality are respectively (dynamic coefficient k=1) 3% (see Figure 6a) and 3.2% (see Figure 6b), for the gravel roads with worn patches (dynamic coefficient k=2) - respectively 2.6% (see Figure 6c) and 9.3% (see Figure 6d), for the headland ridges with 8-12 cm high and 90 cm increments (dynamic coefficient k=2) - respectively 8.2% (see Figure 6e) and 10.6% (see Figure 6f), for the deep ditch depth of 40-45 cm and a width of 100-150 cm (dynamic coefficient k=2.5) - respectively 7.4% (see Figure 6g) and 8.5% (see Figure 6h).

Thus, the proposed method of calculation of stress-strain state of the frame gives a good agreement with the experimental data (maximum values of stress in the range 11%) and can be used in justifying the strength parameters of autotractor trailers.

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