TRANSPORT PROBLEMS 2017 Volume 12 Issue 3
PROBLEMY TRANSPORTU DOI: 10.20858/tp.2017.12.3.6

Keywords: traffic jam; mobile overcrossing; method of finite elements; method of finite differences; orthoplate; mathematical analysis; analytical method of relocation

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THE CONSTRUCTIVE SOLUTION AND CALCULATION OF ELEMENTS OF THE UNIFIED MODULE OF THE MOBILE BRIDGE OVERCROSSING

Summary. In the article the construction of a modular mobile overcrossing is offered. Calculation of its constructive elements is performed and the optimum length of one module is determined.

The purpose is the development of the technique and calculation for the new construction of a mobile bridge overcrossing intended for reduction of traffic jams.

Methods: The methods uses are mathematical analysis, method of finite elements, method of finite differences, and analytical method of relocation.

Dependencies for determination of the optimum length of the module of bridge overcrossing are identified. The calculation of the constructive-orthotropic plate for the carriageway of the bridge overcrossing using numerical methods of finite differences and finite elements is performed; the reliability of results is confirmed with coincidence of deflection values.

The solution matrix of the method of finite differences developed in this work allows calculation of arbitrary plates with a wide variety of geometrical sizes, and also for different values of flexural stiffness properties of the plate and reinforcing elements.

The calculation of the spatial frame of the bridge overcrossing is performed by the precise analytical method of relocation taking into account the bend and torsion of its elements.

1.INTRODUCTION

In the conditions of intensive automobile traffic there are traffic jams on roads, including in twofold and threefold crossroads.

In these cases, for jam elimination, various methods of traffic regulation as well as construction of capital overcrossings of various heights and configurations are applied in the plan.

A distinctive feature of the offered bridge overpass is its mobility is the conveyance on own chassis by means of the automobile trailer or using freight vehicles. Quick assembling and disassembling at the place of its installation is made possible through the use of unified collapsible modules and modes forfixing them between each other and on the ground base. It provides immediate delivery to necessary sites with autojams, repair sites of municipal underground networks or sites with infrastructure damage caused by various emergencies [1].

We offer the construction of the mobile overcrossing, which can be quickly assembled on a crossroad during rush hours, during any public actions or emergency events. The mobile overcrossing consists of horizontal modules equipped with the wheel course and bracing jacks. In necessary cases modules are transported to the crossroad and connected among themselves by means of holders forming one construction. At the same time bracing jacks lean on the base. Mobile overcrossing is different from military bridge layers in having to satisfy traffic rules: passing height under them is more than 4,5 m and transport strip width in one direction not less than 3,5 m.

The mobile overcrossing has two main modules: sloping (Fig. 1a) and horizontal (Fig. 1b).

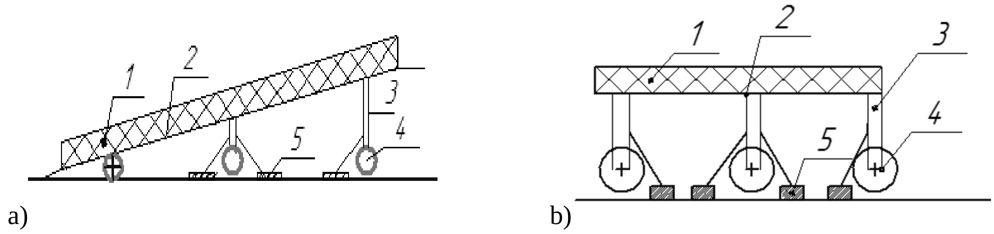


Fig. 1. Modules of the overcrossing: a – sloping module of the overcrossing; b – horizontal module of the overcrossing

The basic constructive elements of the overcrossing are: 1 – barrier; 2 – plate; 3 – support; 4 – wheel engine; 5 – support and the mechanism of its lifting up/down.

A patent is received for the offered construction of the mobile overcrossing.

Maximum travel speed for this design is 20 km / h.

The maximum mass of vehicles corresponds to the movement of passenger cars and medium-freight vehicles (with a total loaded mass of not more than 4 tons).

2. METHODS

The assembled construction allows driving of a part of autotransport over the perpendicular road, and its can be used at various crossroads since its sizes are regulated by the number of modules (Fig. 2).

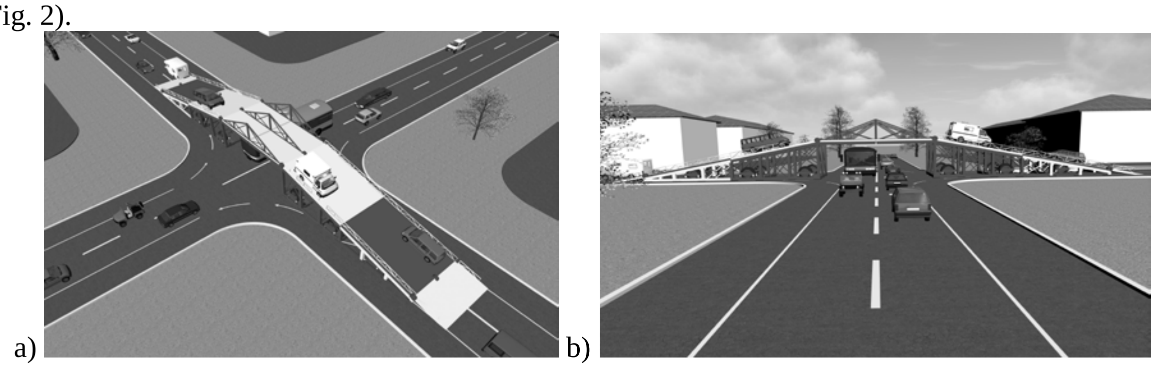


Fig. 2. Mobile overcrossing: a) view from above; b) side view

During projection of the mobile overcrossing, at the first stage, there were two tasks:

- determination of the length of one module and the number of modules in the overcrossing of fixed length with conditions of retaining the size and geometry of the road as well as minimization of the weight of the metal construction;
- calculation of the main (rectilinear) module for construction and loss of equilibrium.

3. RESULTS

For the solution of the first task it is assumed that the weight of the module is proportional to its length x, to the quantity of supports n at one support with wheel engine q; then, the total weight G is determined as follows:

$$G = kx + \frac{L \cdot n}{x} \cdot q, \tag{1}$$

where k is the value of weight of the overcrossing per one meter of length, N/m; L is length of the overcrossing, m; n is number of supports; q is weight of one support, N; $\frac{L}{x}$ is number of modules.

The weight derivatives longwise of the overcrossing are presented as follows:

$$G' = kx - \frac{Lnq}{x^2}, \tag{2}$$

$$G'' = \frac{2Lnq}{x^3}, \tag{3}$$

The critical point (minimax point) at $G' = 0$

$$k = \frac{Lnq}{x}, \tag{4}$$

$$x_{kp} = \sqrt{\frac{Lnq}{k}}, \tag{5}$$

As G'' is greater than zero the point x_{kp} determines the optimum length of one module from the condition of minimization of total load of the overcrossing.

For example, for the overcrossing of 30 m length with 4 supports on each module, each weighing $1{,}5 \cdot 10^4$N, and weight $3 \cdot 10^4$N for one running meter of the construction, the optimum length will be equal to the following:

$$x_{xp} = \sqrt{\frac{30 \cdot 4 \cdot 1{,}5 \cdot 10^4}{3 \cdot 10^4}} = \sqrt{60} = 7{,}74m. \tag{6}$$

When calculating the bearing construction (the second task) the oriented module was chosen orthogonally, which consists of the space frame having four vertical posts at the edges, two longitudinal beams, and seven cross beams, which are completely made of metal.

On the surface of the frame the steel flooring for the carriageway with the supporting longitudinal and cross edges is placed.

In the conditions of space work of load-bearing constructions of the frame when its elements are subjected to multi-axial stress in the form of noncentral compression, bend, and torsion, compound cross sections of posts, and longitudinal and cross beams, consisting of a thin-wall pipe, framed with four equilateral angles, are constructively appointed. Geometrical lengths of frame elements are appointed taking into account the compliance with requirements of traffic organization and norms of the road automotive industry.

Load-bearing constructions of the frame for ensuring space rigidity and stability are untied by longitudinal and transversal binding constructions. The dynamic effect because of transport driving is considered by introduction of the dynamic coefficient of impact appointed by means of experimental expert method. (*Kd=1,3*).

For providing conditions of durability, rigidity, and stability of the bearing elements of the unified module the calculation of carriageway plate and elements of the space frame on the vertical useful load according to Euronorm requirements is made [2]. Let's present the calculation of the module in the following sequence:

The rectangular plate of size $L \times B$ represents a constructively orthotropic plate supported with cross edges with pace $L/6$ and longitudinal edges with pace $B/4$.

For universality of calculated expressions the following geometrical and rigidity characteristics provided to parameters of vertical posts are accepted:

$$\alpha_2 = \frac{l_2}{l_1}; \quad \alpha_3 = \frac{l_3}{l_1}; \quad g_2 = \frac{EJ_2}{EJ_1}; \quad g_{2k} = \frac{EJ_{2k}}{EJ_2}; \quad g_3 = \frac{EJ_3}{EJ_1}; \quad g_{3k} = \frac{EJ_{3k}}{EJ_1}; \tag{7}$$

where l_i is lengths of posts elements $(l = 1,2,3)$; EJ_i is their flexural rigidity; GJ_i is rotating rigidities; α_2, α_3 are the dimensionless relations for length of longitudinal and transversal crossbars of the frame to the post length.

The calculation for the purpose of identification of power condition of the plate is carried out using numerical methods of finite differences and finite elements as a resilient non-isotropic plate [3, 4]. Boundary conditions are jamming the plate along its outline.

Calculation using the method of finite differences (MFD) was carried out based on thickness of the grid ($n_x \times n_y$) with application of the standard «Matcad» program.

The calculation with the finite element method (FEM) is performed by division of the plate surface into four rectangular elements.

Taking into account the double symmetry (on axes *x,y*) the number of unknown movements is: 12 on MFD and 3 on FEM. At the same time, good concurrence of results on plate deflections with both computational methods is noted, which indicates reliability of the obtained values.

When calculating MFD "grids" were used as follows:

a) for manual calculation (4x3)

b) for machine calculation (4x3)

When calculating MFE the 2x2 grid was used (when carrying out the manual calculation).

On internal efforts M_x, M_y, M_{xy} on the stressed state of the plate is studied, i.e., axial tension $\sigma_x, \sigma_y, \tau_{xy}$ is determined and a check for durability of the plate is performed:

$$\sigma_x = \frac{6M_x}{t^2}; \quad \sigma_y = \frac{6M_y}{t^2}; \quad \tau_{xy} = \frac{6M_{xy}}{t^2}; \quad Kd(\sigma_{\max}) \le R, \tag{8}$$

where t = 20mm flooring thickness; $\sigma_{\max}$ is the largest actual tension; M_{xy} is moment of torque; M_x is moment of deflection on axis *x;* M_y is moment of deflection on axis *y;* Kd = 1,3, dynamic coefficient; R = 300Mpa: the calculated resistance of steel (AUSS 09Г2С) on the bend. Also, the condition of rigidity (on deflections) is as follows:

$$\left(\frac{1}{W_{\max}} = \frac{1}{2150}\right) < \left[\frac{1}{W} = \frac{1}{1000}\right] \tag{9}$$

where $W_{\max}$ is maximal deflection of the plate; $\left[\frac{1}{W}\right]$ is the plate deflection allowed according to norms.

The System of the Simple Algebraic Equations (SSAE), based on MFD, has the representation as follows:

$$A \cdot \vec{w} = \vec{R}_p, \tag{10}$$

where $\vec{w}$ is vector of unknown node movements; $\vec{R}_p$ is vector of the free members considering the loading acting on the plate; A is square matrix of order *n*. This matrix, in general, is given in table 1.

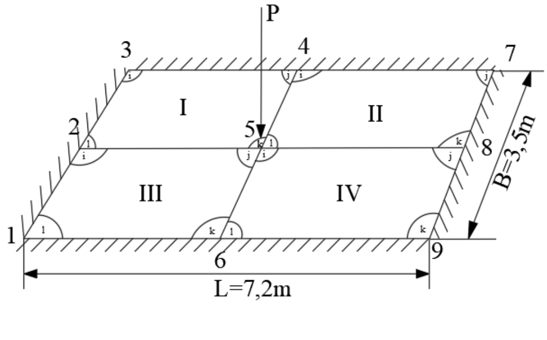


Fig. 3. The calculated scheme of the plate when calculating MFE

Table 1

The solution matrix of the method of finite differences

	1	2	3	4	5	6	7	8	9	10	11	12
1	$a_1+a_5+a_6$	a_2	a_5	0	a_3	0	0	0	0	0	0	0
2	a_2	a_1+a_6	a_2	a_5	0	a_3	a_4	0	0	0	0	0
3	a_5	a_2	0	a_2	0	0	a_3	a_4	0	0	0	0
4	0	$2a_5$	0	0	0	0	0	a_3	0	0	0	0
5	a_3	a_4	0	0	$a_1+a_5+a_6$	a_2	a_5	0	a_3	a_4	0	0
6	a_4	a_3	a_4	0	0	0	a_2	a_5	0	a_3	a_4	0
7	0	a_4	a_3	a_4	a_5	a_2	$a_1+a_5+a_6$	a_2	0	a_4	a_3	a_4
8	0	0	0	a_3	0	0	0	0	0	0	0	a_3
9	$2a_6$	0	0	0	0	0	0	0	0	0	a_5	0
10	0	$2a_6$	0	0	0	0	0	0	a_2	0	a_2	a_5
11	0	0	0	0	0	0	0	0	a_5	a_2	0	a_2
12	0	0	0	0	0	0	0	0	0	0	0	0

As an example of equation realization the plate with size $(L \times B) = (7{,}5 \times 3{,}5)$ m is considered, at thickness of the grid ($n_x \times n_y) = (8 \times 6)$.

At the same time, the following values of deflections in grid nodes are obtained:

$$W_1 = \frac{0{,}809}{D_x};\ \ W_2 = \frac{1{,}079}{D_x};\ \ W_3 = \frac{1{,}145}{D_x};\ \ W_4 = \frac{1{,}151}{D_x};\ \ W_5 = \frac{1{,}744}{D_x};\ \ W_6 = \frac{2{,}401}{D_x};$$

$$W_7 = \frac{2{,}578}{D_x};\ \ W_8 = \frac{2{,}604}{D_x};\ \ W_9 = \frac{2{,}122}{D_x};\ \ W_{10} = \frac{2{,}497}{D_x};\ \ W_{11} = \frac{3{,}175}{D_x};\ \ W_{12} = \frac{3{,}212}{D_x};$$

$$W_{\max} = \frac{3{,}212}{D_x}; \tag{11}$$

$$D_x = \frac{Et^3}{12(1-V^2)}; \tag{12}$$

Calculation of the frame consisting of vertical posts, longitudinal and cross beams (crossbars) is performed using analytical method of movements [5-6]. The calculated scheme of the frame taking into account a double symmetry is given in Fig. 4.

$$A \cdot \vec{z} + \vec{R}_p = 0, \tag{13}$$

where A is square matrix of the 11th order (in general, it is given in table 2)

The total number of unknown angular and linear movements of four nodes of the frame (*A*,*B*,*C*,*D*) is equal to eleven ($z_i = 1{,}2,.......11$).

Canonical equations of the method of movements:

$$z_{k1}Z + z_{k2}Z + ...z_{k11}Z + R_{\kappa p} = 0\,, \tag{14}$$

where $k = 1{,}2,.....n)$.

4. DISSCUSION

After calculation of unknown node movements the calculated epure is constructed by the formula:

$$M = \left(\sum_{k=1}^{11} M_k z_k \right) + M_p , \tag{15}$$

The calculated epure of transversal forces (Q) and longitudinal forces (N) are constructed as usual as in the theory of constructions [7-10].

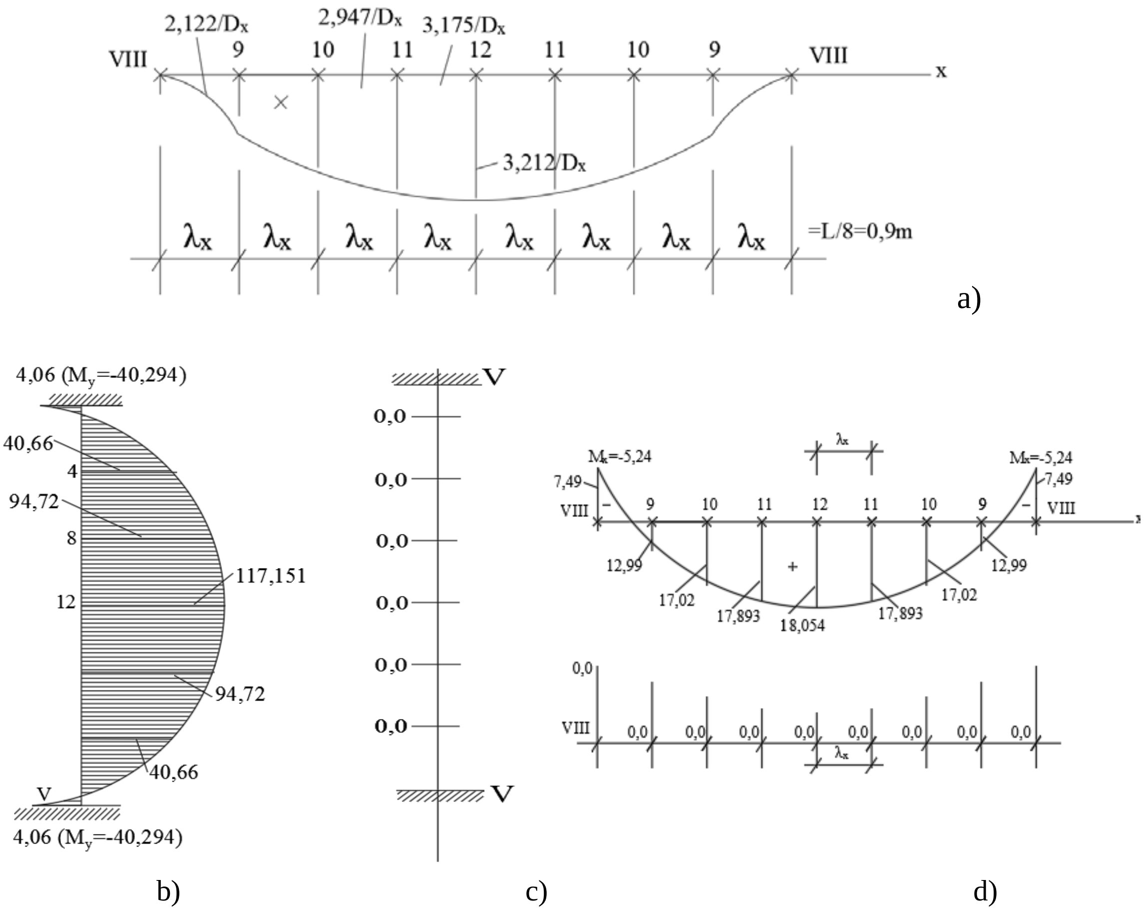


Fig. 4. Epures. a) Deflections by the "x" axis; b) Epure M_y ,kNm; c) Epure M_{xy} , kNm; d) Epure M_x , kNm

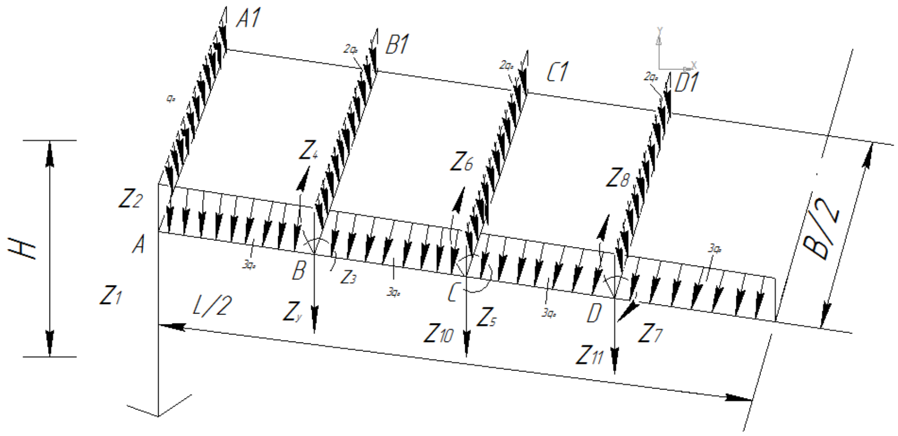


Fig. 5. Calculated scheme of the space frame

As a test task on data of table 2 the calculation of a space frame having the following data is performed:

$$L = 7{,}2m; \quad B = 3{,}5m; \quad l_1 = H = 4{,}7m; \quad l_2 = \frac{L}{6} = 1{,}2m; \quad l_3 = \frac{B}{4} = 0{,}875m;$$

$$\alpha_2 = \frac{1{,}2}{4{,}7} = 0{,}255; \ \alpha_3 = \frac{0{,}875}{4{,}7} = 0{,}186; \ EJ_1 = 16{,}35 \cdot 10^6 (N \cdot m^2); \ G_{1.k} = 0{,}022 \cdot 10^6;$$

$$EJ_2 = 61{,}8 \cdot 10^6 (N \cdot m^2); \ G_{2.k} = 0{,}1367 \cdot 10^6; \ EJ_3 = 19{,}86 \cdot 10^6 (N \cdot m^2); \ G_{3.k} = 0{,}0799 \cdot 10^6;$$

$$g_2 = 3{,}780; \ g_{2.k} = 0{,}00836; \ g_3 = 1{,}2147; \ g_{3.k} = 0{,}0049; \quad (16)$$

According to these data values of nodal movements (fig. 4) are calculated.

$$z_1 = \frac{0{,}527}{i_o}; \ z_2 = \frac{0{,}487}{i_o}; \ z_3 = \frac{-0{,}101}{i_o}; \ z_4 = \frac{0.939}{i_o}; \ z_5 = \frac{-0{,}12}{i_o}; \ z_6 = \frac{0{,}53}{i_o};$$

$$z_7 = \frac{0{,}015}{i_o}; \quad z_8 = \frac{1{,}139}{i_o}; \quad z_9 = \frac{0{,}342}{i_o}; \quad z_{10} = \frac{0{,}024}{i_o}; \quad z_{11} = \frac{0{,}135}{i_o}; \quad (17)$$

On the basis of results of the power condition of the space frame (Fig. 5-8) the stressed state of the frame elements is investigated and the check for durability and stability conditions of load-bearing frames of bridge movement is performed.

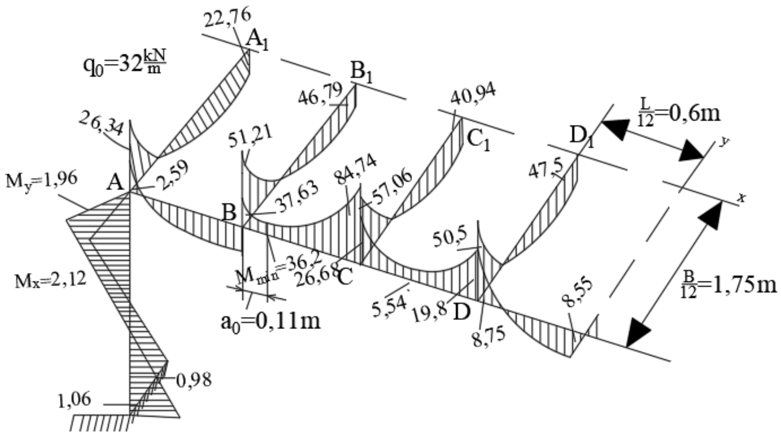


Fig. 6. Calculated epure of deflection moments

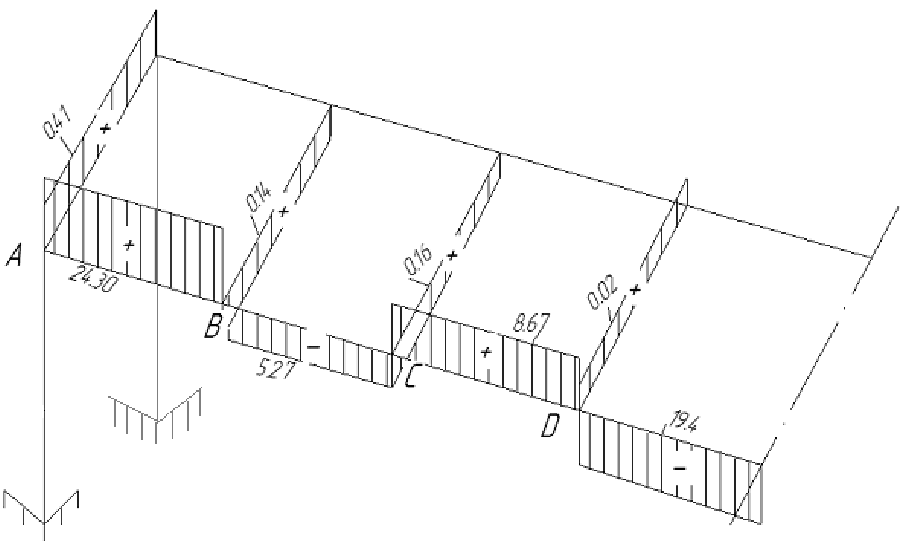


Fig. 7. Calculated epure of torques

Table 2

Matrix «A» and vector $\vec{R}_p$ (for the equation 13)]

	z_1	z_2	z_3	z_4	z_5	z_6	z_7	z_8	z_9	z_{10}	z_{11}	$\vec{R}_p$
1	$4(\frac{g_1}{\alpha_1}+\frac{g_2}{\alpha_2})+\frac{g_{3,k}}{\alpha_3}$	0	$\frac{2g_2}{\alpha_2}$	0	0	0	0	0	$\frac{-6g_2}{l_1\alpha_2^2}$	0	0	
2	0	$4(\frac{g_1}{\alpha_1}+\frac{g_2}{\alpha_2})+\frac{g_{2,k}}{\alpha_2}$	0	$\frac{g_{2,k}}{\alpha_2}$	0	0	0	0	0	0	0	$-\alpha_3^2$
3	$\frac{2g_2}{\alpha_2}$	0	$\frac{8g_2}{\alpha_2}+\frac{g_{3,k}}{\alpha_3}$	0	$\frac{g_2}{\alpha_2}$	0	0	0	0	$\frac{-6g_2}{l_1\alpha_2^2}$	0	0
4	0	$\frac{g_{2,k}}{\alpha_2}$	0	$\frac{4g_3}{\alpha_3}+\frac{2g_{2,k}}{\alpha_2}$	0	$\frac{g_{2,k}}{\alpha_2}$	0	0	$\frac{6g_3}{l_1\alpha_3^2}$	0	0	$-2\alpha_3^2$
5	0	0	$\frac{g_2}{\alpha_2}$	0	$\frac{8g_2}{\alpha_2}+\frac{g_{3,k}}{\alpha_3}$	0	$\frac{2g_2}{\alpha_2}$	0	$\frac{6g_2}{l_1\alpha_2^2}$	0	$\frac{-6g_2}{l_1\alpha_2^2}$	0
6	0	0	0	$\frac{g_2}{\alpha_2}$	0	$\frac{4g_3}{\alpha_3}+\frac{2g_{2,k}}{\alpha_2}$	0	$\frac{g_{2,k}}{\alpha_2}$	0	$\frac{6g_3}{l_1\alpha_3^2}$	0	$-2\alpha_3^2$
7	0	0	0	0	$\frac{2g_2}{\alpha_2}$	0	$\frac{8g_2}{\alpha_2}+\frac{g_{3,k}}{\alpha_3}$	0	0	$\frac{6g_2}{l_1\alpha_2^2}$	0	0
8	0	0	0	0	0	$\frac{g_{2,k}}{\alpha_2}$	0	$\frac{4g_3}{\alpha_3}+\frac{2g_{2,k}}{\alpha_2}$	$\frac{24g_2}{l_1^1l_2^3}+\frac{12g_3}{l_1^2\alpha_3^3}$	0	$\frac{6g_3}{l_1\alpha_3^2}$	$-2\alpha_3^2$
9	$\frac{-6g_2}{l_1\alpha_2^2}$	0	0	$\frac{-6g_3}{l_1\alpha_3^2}$	$\frac{-6g_2}{l_1\alpha_2^2}$	0	0	0	0	$\frac{12g_2}{l_1^2\alpha_2^3}$	0	$-(3\alpha_2^3l_1+\alpha_3^3l_1)$
10	0	0	$\frac{-6g_2}{l_1\alpha_2^2}$	0	0	$\frac{-6g_3}{l_1\alpha_3^2}$	$\frac{-6g_2}{l_1\alpha_2^2}$	0	$\frac{12g_2}{l_1^2\alpha_2^3}$	$\frac{24g_2}{l_1^1l_2^3}+\frac{12g_3}{l_1^2\alpha_3^3}$	0	$-(3\alpha_2^3l_1+\alpha_3^3l_1)$
11	0	0	0	0	$\frac{-6g_2}{l_1\alpha_2^2}$	0	0	$\frac{-6g_1}{l_1\alpha_1^2}$	0	$\frac{-12g_2}{l_1^2\alpha_2^3}$	$\frac{24g_2}{l_1^1l_2^3}+\frac{12g_3}{l_1^2\alpha_3^3}$	$-(3\alpha_2^3l_1+\alpha_3^3l_1)$

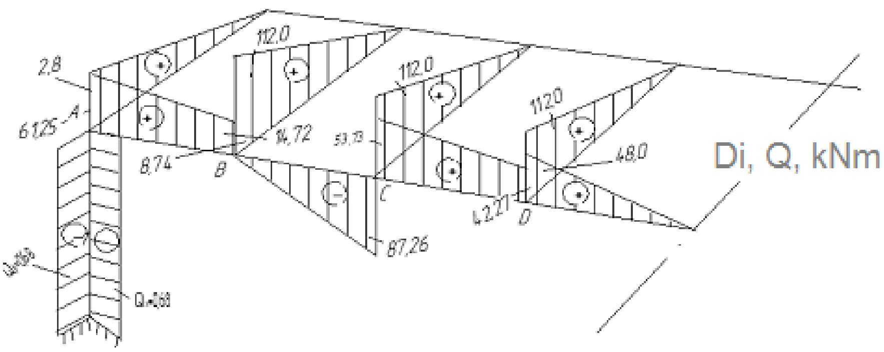


Fig. 8. Calculated epure of transversal forces

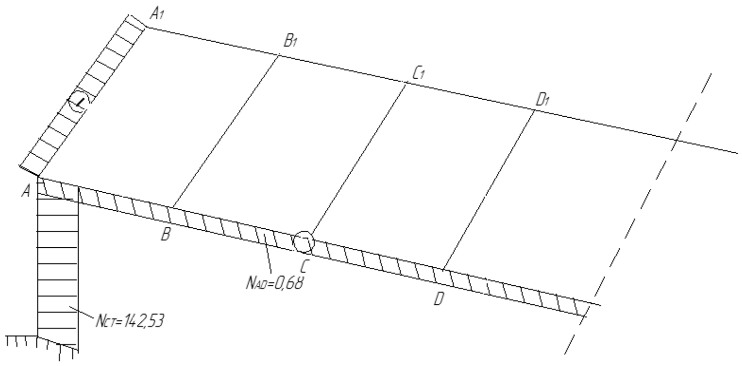
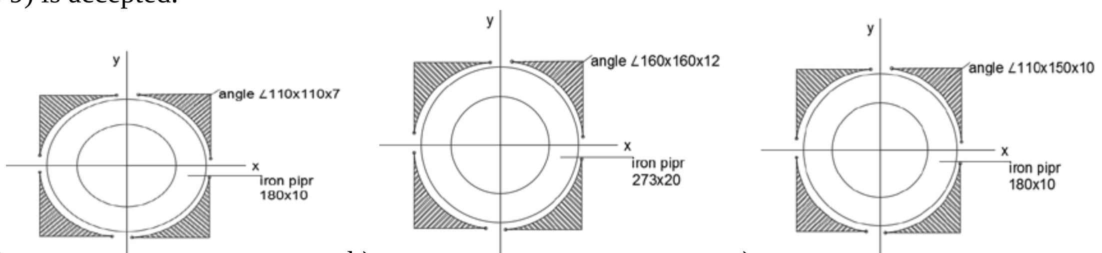


Fig. 9. Calculated epure of longitudinal forces

As a transverse section the compound section cosisting of pipes and the framing angles and corners (Fig. 9) is accepted.



a) b) c)

Fig. 10. Transverse sections of elements of the space frame: a - vertical posts; b - longitudinal posts; c - cross posts

Realization of durability and stability conditions of the space frame elements was made according to the theory of strength of materials [11-15] as the constructions working for the composite resistance (noncentral compression, bend, and torsion).

a) Check of durability conditions of vertical posts (taking into account flexible work of steel):

$$Kd[\left(\frac{N}{AR}\right)^{\frac{3}{2}}+\frac{M_x}{W_x \cdot R}+\frac{M_y}{W_y \cdot R}] \le 1, \tag{18}$$

where (Kd = 1,3) is dynamic coefficient; (*R=300MPa)* is calculated resistance of steel (AUSS 09Г2С); A, W_x, W_y is area and the resistance moments of transverse sections; b) check for stability of the whole post in the plane of action of the moment $M = M_x$:

$$Kd(\left(\frac{N}{\varphi_x^{ex} \cdot A} \right) \le R_b, \tag{19}$$

where $\varphi_x^{ex} = f(\lambda_x, m_{1x})$ is coefficient of the longitudinal bending; c) check of stability of the whole post from the plane of action of the moment of $M= M_x$:

$$Kd\left(\frac{N}{c\varphi_y A} \right) \le R, \tag{20}$$

where $c\varphi_y$ is coefficient of space stability, d) check of durability conditions of longitudinal and cross beams (using the III-rd failure theory)

$$Kd(\sigma_{cr} = \frac{N}{A} + \frac{M_{eq}}{W_x}) = R, \tag{21}$$

$$M_{rd} = \sqrt{M_u^2 + M_k^2}, \tag{22}$$

$$\begin{cases} M_u - \text{bending moment;} \\ M_k - \text{torque moment;} \end{cases}$$

e) Check of durability of longitudinal and cross beams for cross-section:

$$(\tau = \frac{Q \cdot S_1}{J_x \cdot \delta_{st}})Kd \le R_{av}, \tag{23}$$

where Q is transversal force, R_{av} is 130MPa: calculated resistance for cross-section.

The solutions for equations (7,9) were obtained by means of PC with use of the standard Matcad program.

5. CONCLUSION

1. The construction of the mobile overcrossing is proposed, which allows solving the problem of automobile jams on roads.
2. In this work the effectiveness of calculation for the constructive-orthotropic plate of the carriageway of bridge movement is shown using numerical methods of finite differences and finite elements; reliability of results is confirmed with concurrence of deflection values.
3. The accepted concrete geometrical and physical–mechanical characteristics of load-bearing constructions and the supporting edges of steel flooring (plate) with large drift provide their durability.
4. The accepted thickness of sheet flooring, equal to 20 mm, or the corresponding load-bearing frames of the plate provide a high rigidity to the carriageway of bridge movement as per requirements of autobridge building norms.
5. The obtained matrix based on the method of finite differences in a general view (with thickness of grid $n_x \times n_y) = (8 \times 6).$ in Table 1 allows calculation of the arbitrary plates with a wide variety of geometrical sizes in the plan using thickness as well as various values of flexural rigidities of the plate and the elements supporting it.
6. The calculation of the space frame of bridge movement is performed on the main vertical loadings (useful load) by means of analytical method of movements taking into account bending

and torsion of its elements «A» and vector $\vec{R}_p$ for calculation of the frame with arbitrary geometrical and rigidity characteristics.

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Received 14.11.2015; accepted in revised form 07.09.2017