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Research and Calculation of the Deformed State of the Roadway Mobile Overpass

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Abstract. The article proposes a new type of transport equipment that is a mobile overpass. The proposed design is used during underground repairs of urban utility networks and is a prefabricated modular bridge structure equipped with its own chassis. The overpass structure is installed through open repair trenches on highways, which will ensure continuous traffic through repair sections. The overpass is equipped with its own chassis and is mobile. The use of the overpass improves the city transport logistics during repair work: eliminates traffic jams due to the lack of need to detour repair sections, reduces the accident rate, distributes traffic flows, improves the environment, etc. It can also be used during emergency situations where it is necessary to overcome various landslides, ditches, trenches, etc. After the end of operation, the overpass structure is dismantled and can be used multiple times. The aim of the study is to calculate the deformed state of the structurally orthotropic slab of the roadway of a mobile overpass with a check for standard rigidity. Calculations of the roadway for rigidity from moving motor vehicles are performed by means of the Bubnov-Galerkin variational method. The final results include calculations of deflections in the center of the slab clamped along the contour, as well as the conditions for implementing the deflection limitation according to the standards of automobile bridge construction. Based on the results obtained, the design parameters of the slab satisfying the rigidity and strength condition are determined. The studies and calculations conducted allow for the practical design of the roadway structure of the overpass.

Keywords: mobile overpass, transport equipment, traffic jam elimination, mobile bridge structures, orthotropic slab, variational methods, rigidity calculations.

Introduction

Various municipal utility networks (heating, water supply, cable, etc.) according to the planning of cities in the CIS countries are usually located under the roadways of the city's highways and lie at a certain depth. Scheduled repairs or renovation of such municipal utility infrastructure are associated with the development of repair trenches along city roads, which causes the closure of city transport arteries for a long time and the need to organize detours of repair sections. This contributes to the formation of traffic jams due to the increased concentration of cars due to detours of repair sections, increases the accident rate, worsens the city's transport logistics, its ecology, etc. [1, 2, 3]

In such conditions, instead of detours around repair areas, we propose organizing direct bridge crossings over utility network trenches, without blocking vehicle traffic on adjacent city highways.

A new type of transport equipment is proposed as such direct crossings – a mobile municipal overpass (Figure 1). The overpass is installed through the repair trenches of municipal networks and allows not to stop traffic flows for the entire period of repair of underground utility networks. The use of such overpasses improves transport logistics in the city during repair work on municipal networks: reduces the formation of traffic jams, there are no forced detours of repair sections, inconveniences for car drivers and residents of city districts are reduced, due to forced detours of transport, etc. [4, 5].

The mobile municipal overpass is assembled from standardized prefabricated modules: one orthogonally oriented module (Figure 2,a, position I) and two inclined modules (Figure 2,a, position II). The orthogonally oriented module is a spatial steel frame, the base of which is attached to the bottom of the repair trench using special methods. The upper part of the frame is a roadway in the form of an orthotropic slab with reinforcing ribs (Figure 2,a, position III). The inclined module is steel trusses equipped with a chassis and supporting the roadway also in the form of an orthotropic slab. The cantilever part of the trusses rests on the ground base, the suspended part of the trusses rests on the supporting frame of the orthogonal module. The bridge crossing is delivered to the installation site under its own power on a trailer and assembled into a single structure using special assembly methods. After using the overpass, it is disassembled into individual modules at the coupling units, placed on wheels and delivered to storage sites [6, 7, 8].

The overall dimensions of the "single-lane" modules are as follows: length of the orthogonally oriented module - 8 m; width - 3.5 m; height (taking into account their installation on the bottom of the trenches) - 3.85 m. Length of the inclined module - 4 m; width - 3.5 m; height - 0.85 m. Such dimensions provide passage of light vehicles weighing up to 3.5 tons.

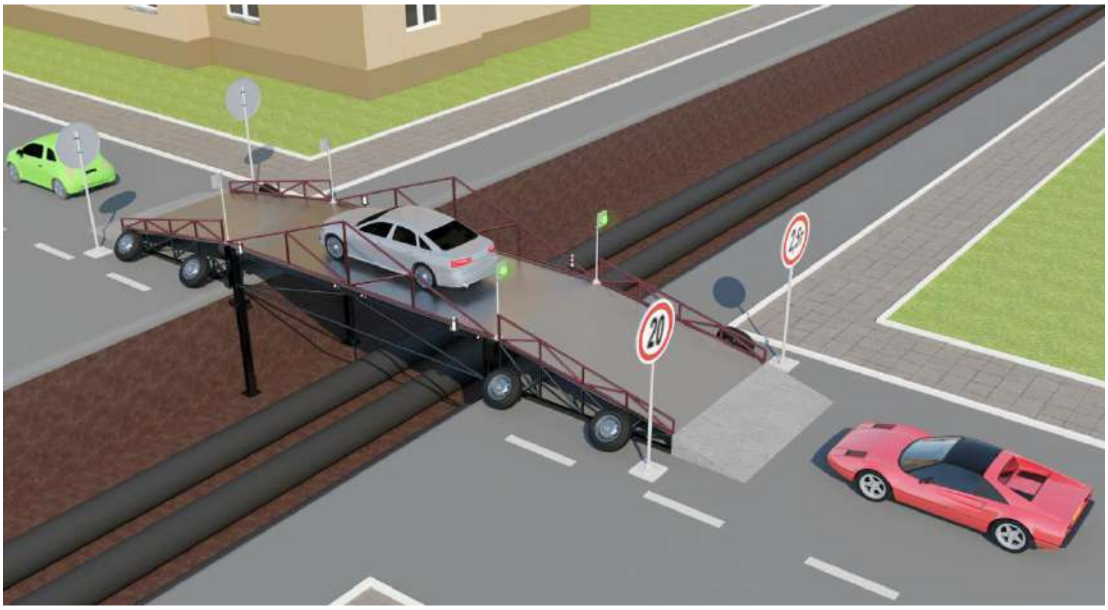
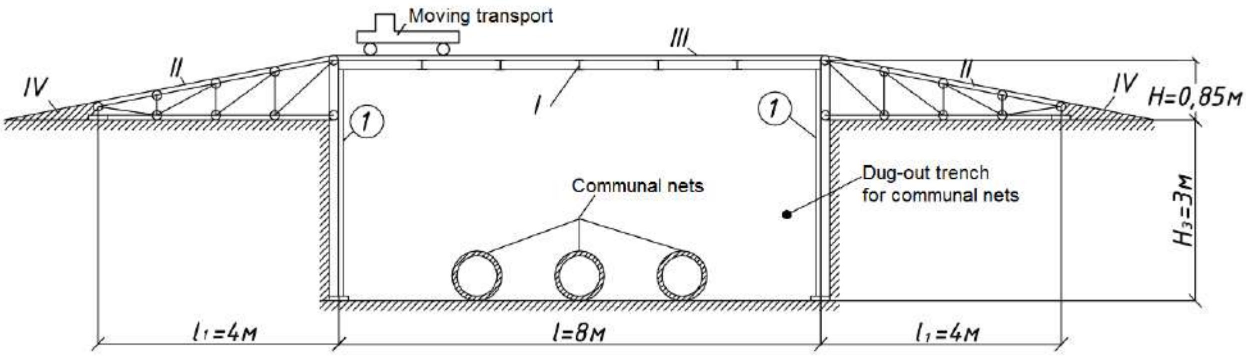
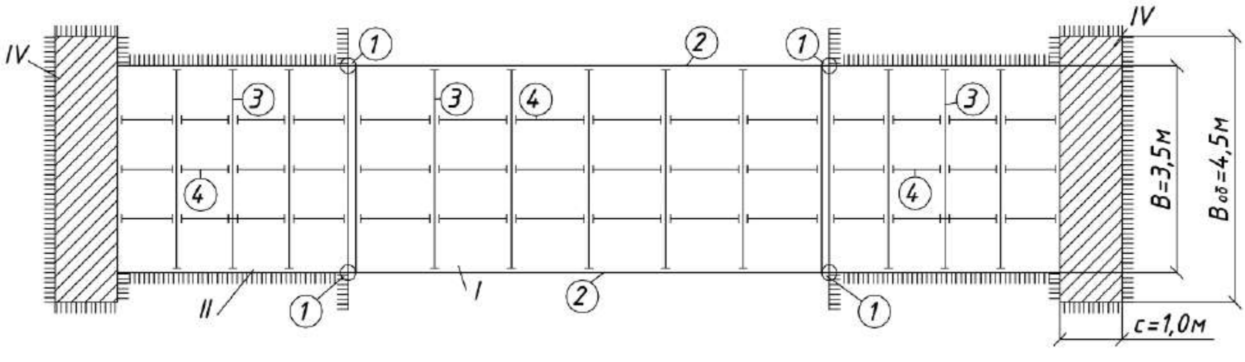


Fig. 1. – 3D model of the overpass in operational position



a) Front view (facade)

b) Top view (plan)



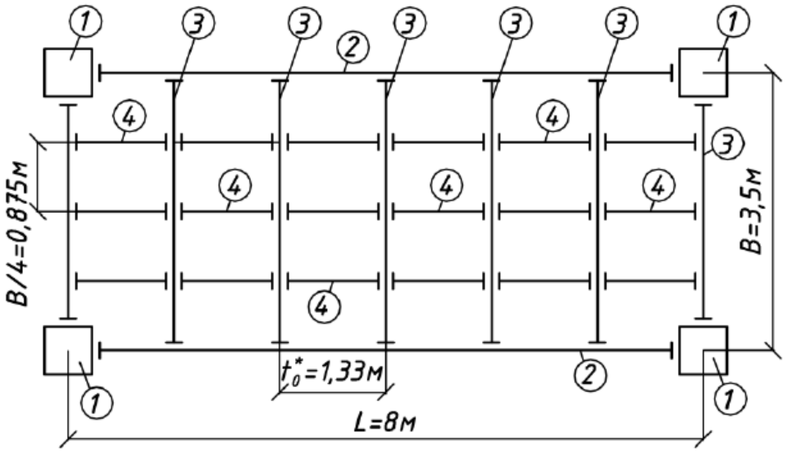
Explication of the elements and modules of the overpass (a, front view):
I – Spatial frame of the structure (the orthogonal module);
II – Pivot-nodal basic supporting-hinged rod-like frame (the inclined module);
III – Metal roadway decking (slabs);
IV – Access ramp.

Explication of constructions of separate modules (b, top view (plan)):
1 – vertical posts (frame supports);
2 – longitudinal crossbars (beams) of the frame;
3 – transversal crossbars (beams) of the frame;
4 – longitudinal (reinforcing) ribs of the roadway.

Fig. 2. – Scheme of the mobile overpass

1. Materials and methods

In the design of the proposed mobile overpass, the roadway is made of steel sheets supported by a system of mutually perpendicular beams of the supporting frame (Figure 2, b, Figure 3). Such a design solution can be mathematically modeled as a structurally orthotropic plate consisting of a steel sheet interacting with mutually perpendicular stiffeners of a certain cross-section.



1 – vertical posts (rolled I-beam No. 50);
2 – longitudinal elements (beams, rolled I-beam No. 45);
3 – transverse elements of the plate (beams, rolled I-beam No. 30);
4 – reinforcing ribs of the plate (steel strip 14x3 cm).

Fig. 3. – Structural diagram of the roadway slab of the overpass

Elements 1–4 in Figure 3 were obtained separately by calculating the spatial frame of the orthogonal module and are beyond the scope of this article.

When designing engineering structures that provide for the crossing of various types of rolling stock, such as the presented overpass, special attention is paid to the design solution of their roadway. Their design solution must ensure, along with the strength of the supporting structures, the rigidity required by the operating conditions to eliminate the phenomenon of "unsteadiness" and "subsidence" [9]. In this regard, calculations are made of the deformability of the supporting structures of the roadway - calculating the displacement of the cargo belt (flooring) from the action of standard operational long-term loads. In this case, the condition of rigidity of the flooring must be met [10]:

$$\frac{W_{\max}}{L} \leq \left(\frac{1}{1000}\right), \tag{1}$$

where $W_{\max}$ – the largest deflection of the middle surface of the deck;

L – the characteristic (calculated) size (span) of the deck (L=8m).

The calculation method for an orthotropic overpass slab must take into account the combined operation of the covering sheet, longitudinal and transverse stiffeners of the slab and the main beams of the span structure. In this case, the problem of calculating such plates in order to identify their stress and strain state arises, according to the results of which they are designed and constructed based on the requirements of rigidity and strength. This paper considers the calculation of deformations (deflections) of overpass slabs from the action of the rolling stock load using the Bubnov-Galerkin variational method for calculating the required structural rigidity according to condition (1).

The calculated rigidity characteristics of structurally orthotropic slabs with one-sided cross-arranged ribs, taking into account the combined work of the covering sheet, longitudinal and transverse ribs of the slab and the main beams of the span structure, are as follows [11, 12]:

$$D_x = \frac{Et^3}{12\left(1-\mu^2\right)} + \frac{EJ_{1y}}{t_1}; \quad D_y = \frac{Et^3}{12\left(1-\mu^2\right)} + \frac{EJ_{2y}}{t_2}; \quad D_{xy} = \frac{Gt^3}{12} + \frac{EJ_{1k}}{t_1\delta}; \tag{2}$$

$$D_\mu = D_1 = \mu D_X = \mu D_y; \quad \delta = 1 - \frac{t_1^2 J_{1y}(t_1 J_{2k} - t_2 J_{1k})}{t_2 J_{2k}(t_1^2 J_{1y} + t_2^2 J_{2k})}$$

where D_x, D_y, D_{xy} – cylindrical rigidities relative to axes during bending and torsion;

D_μ – shear cylindrical rigidity;

δ – generalized stiffness parameter;

E, G, μ – respectively, the modulus of elasticity, the shear modulus and Poisson's ratio;

J_{1k}, J_{2k} – the corresponding torsional moments of elements 4 and 3 (Figure 3);

J_{1y}, J_{2x} – the corresponding axial moments of inertia of elements 4 and 3, relative to their central axes, parallel to the x and y axes, respectively; $t_1 = B/4 = 3{,}5/4 = 0{,}875m$ – step of elements "4"; $t_2 = L/6 = 8/6 = 1{,}33m$ – step of elements "3"; $t = 20mm$ – the previously accepted thickness of the metal sheet deck made of grade 09G2S steel.

For the plate shown in Figure 3, the following values were obtained using formulas (1):

$$D_x = 17{,}1452 \cdot 10^2 kNm; \; D_y = 107{,}93 \cdot 10^2 kNm; \; D_1 = 5{,}1436 \cdot 10^2 kNm; \; D_{xy} = 3{,}57 \cdot 10^2 kNm. \quad (3)$$

The uniformly distributed surface load on the slab, taking into account the overload factor and the dynamic effect of movement of a mobile vehicle load weighing up to 3.5 tons along the overpass, is *g = 52.5 kN/m²* [13].

To calculate the slab (Figure 3), we apply the Bubnov-Galerkin variational method [14, 15]. The desired deflection function $W = W(x, y)$ we will look for slabs in the form:

$$W = \sum_{i=1}^{n} a_i \cdot \varphi_i, \quad (4)$$

where a_i – undefined coefficients; φ_i – approximating functions satisfying the conditions of fixing the edges of the plate. Fixing of the plate is clamping along the contour (Figure 4).

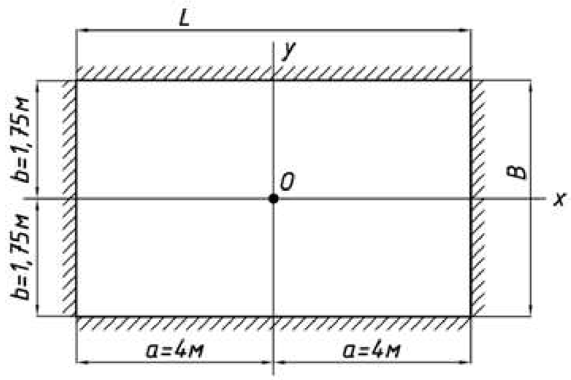


Fig. 4.– Calculation scheme of the slab

The boundary conditions (Figure 4) are written as:

$$\begin{aligned} &\text{a) when } x = \pm a; \; W = 0, \; \partial W/\partial x = 0; \\ &\text{b) when } y = \pm b; \; W = 0, \; \partial W/\partial y = 0. \end{aligned} \quad (5)$$

We will accept the approximating functions in the form of a power series:

$$\begin{aligned} \varphi_1 &= (x^2 - a^2) \cdot (y^2 - b^2); \\ \varphi_2 &= (x^2 - a^2)^2 \cdot (y^2 - b^2)^3; \\ \varphi_3 &= (x^2 - a^2)^3 \cdot (y^2 - b^2)^2. \end{aligned} \quad (6)$$

The initial differential equation of equilibrium of orthotropic plates has the form [12, 15]:

$$\left(\frac{\partial^4 W}{\partial x^4}+\alpha\frac{\partial^4 W}{\partial x^2\partial y^2}+\beta\frac{\partial^4 W}{\partial y^4}-\frac{g}{D_x}\right)=0 \text{ or } \nabla^4 W-\frac{g}{D_x}=0, \tag{7}$$

where α and β – orthotropy coefficients. Taking into account the values (3), α and β will take the values:

$$\alpha = 2\left(D_1+2D_{xy}\right)/D_x = 1{,}453;\ \beta = D_y/D_x = 6{,}295. \tag{8}$$

In the Bubnov-Galerkin method, the left side of equation (7) after substituting series (6) into it must be orthogonal to the functions that form this series, i.e.:

$$\int\int\left(\sum_{i=1}^{n} a_i\nabla^4\varphi_i - g/D_x\right)\varphi_k\cdot dx\cdot dy = 0. \tag{9}$$

By expanding the sum of the integrals in expression (9), we obtain a system of canonical equations of the Bubnov-Galerkin method in the form:

$$\begin{cases} a_1\delta_{11}+a_2\delta_{21}+...+a_n\delta_{n1}=\Delta q_1; \\ a_1\delta_{12}+a_2\delta_{22}+...+a_n\delta_{n2}=\Delta q_2; \\ . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \\ a_1\delta_{1n}+a_2\delta_{2n}+...+a_n\delta_{nn}=\Delta q. \end{cases} \tag{10}$$

In the system (10) $\delta_{ik}=\delta_{ki}=\int\int\left(\nabla^4\varphi_i\right)\varphi_k\cdot dx\cdot dy$ – unit coefficients; $\Delta q_k=\int\int\frac{g}{D_{red}}\varphi_k\cdot dx\cdot dy$ – load coefficients.

Next, for a comparative analysis of the results and verification of the correctness of the calculations, we will consider two options for implementing the Bubnov-Galerkin method for the overpass slab shown in Figure 3:

1 – calculation based on actual values of rigidity characteristics (expressions (2));

2 – calculation based on the reduced (conditional) bending rigidity D_{red}, which is an equivalent value in terms of strength between a given structural orthotropic plate (Figure 3) and a fictitious isotropic plate of thickness t_{red}.

This approach implements the method of mathematical modeling in calculating the rigidity of an orthotropic overpass slab, which allows selecting the design parameters of the structure during its design.

To simplify the calculations, only one member of the series (6) will be retained, i.e.

$$\varphi_1=\left(x^2-a^2\right)\cdot\left(y^2-b^2\right). \tag{11}$$

Let us consider the calculation based on the actual values of the rigidity characteristics (option 1). In this case, the system of equations (10) will take the form (for *n=1*):

$$a\cdot\delta=\Delta q \text{, from here } a=\Delta q/\delta, \tag{12}$$

where

$$\delta_{11}=\int_0^a\int_0^b\left(\frac{\partial^4\varphi}{\partial x^4}\varphi+\alpha\frac{\partial^4\varphi}{\partial x^2\partial y^2}\varphi+\beta\frac{\partial^4\varphi}{\partial y^4}\varphi\right)dxdy;\quad \Delta q=\int_0^a\int_0^b\frac{g}{D_{прив}}\varphi\cdot dx\cdot dy. \tag{13}$$

The corresponding derivatives in expressions (13) taking into account expression (11):

$$\frac{\partial^4\varphi}{\partial x^4}=24\left(y^2-b^2\right)^2,\ \frac{\partial^4\varphi}{\partial y^4}=24\left(x^2-a^2\right)^2,\ \frac{\partial^4\varphi}{\partial x^2\partial y^2}=16\left(3x^2-a^2\right)\left(3y^2-b^2\right). \tag{14}$$

By performing mathematical operations, as well as double integration of expressions (10) and (13), we obtain:

$$\delta = 20{,}8051a^5b^5\left(b^4 + 0{,}5714\cdot\alpha\cdot a^2b^2 + \beta\cdot a^4\right),\ \Delta q = 1{,}1378a^5b^5\,\frac{g}{D_x}. \quad (15)$$

Taking into account the values (8), we obtain from expressions (15), taking into account the load from transport $g = 52.5\ kN/m^2$:

$$\delta = 34557{,}73;\ \Delta q = 59{,}7345 / D_x\ . \quad (16)$$

Using expression (12), we calculate the value of the coefficient "*a*" taking into account expression (1b):

$$a = \Delta q / \delta = \frac{59{,}7345}{34557{,}73\cdot D_x} = 0{,}00173 / D_x\ . \quad (17)$$

Substituting the value (17) into equation (4), taking into account (11), we obtain the desired slab deflection function:

$$W(x,y) = a\cdot\varphi = \frac{0{,}00173}{D_x}\cdot\left(x^2 - a^2\right)^2\left(y^2 - b^2\right)^2. \quad (18)$$

For the plate (Figure 3) ($D_x = 17{,}1452\cdot 10^2\ кHm$, *a=4m, b=1.75m*) at *x=y=0* according to equation (18) we obtain the maximum deflection:

$$W_{\max} = 0{,}00242m = 0{,}242cm = 2{,}42mm\,. \quad (19)$$

Let's consider the calculation according to option 2. In expressions (13) and (15) we take $D_x = D_{red}$, $\alpha = \beta = 1$. Then instead of (18) we get the expression:

$$W = a_1\cdot\varphi_1 = \frac{2{,}8711\cdot\left(x^2 - a^2\right)^2\left(y^2 - b^2\right)^2}{D_{red}\left(b^4 + 0{,}5714a^2b^2 + a^4\right)}\ . \quad (20)$$

In expression (20) the value of the reduced (conditional) cylindrical rigidity D_{red} remains undefined. To determine it, we use the theory of strength of resistance of materials. According to the hypothesis of specific potential energy of shape change, we have [16]:

$$D_{red} = \sqrt{D_x^2 + D_y^2 + 3\cdot D_{xy}^2}\ . \quad (21)$$

Substituting the values of (3) into expressions (21), we obtain

$$D_{red} = 10^2\sqrt{(17{,}1452)^2 + (107{,}93)^2 + 3\cdot(3{,}57)^2} = 109\cdot 10^2\,kNm\,. \quad (22)$$

Using the values (22), one can determine the reduced thickness of the roadway deck of the overpass t_{red} fictitious isotropic steel plate, equivalent in strength to a given structural orthotropic plate (Figure 3) [12]:

$$t_{red} = \sqrt[3]{\frac{12\left(1-\mu^2\right)\cdot D_{red}}{E}} = \sqrt[3]{\frac{12\left(1-0{,}3^2\right)\cdot 109\cdot 10^2}{2\cdot 10^8}} = 0{,}0817m.$$

Comparing the result, we get that $\left(t_{red} = 0{,}0817m = 8{,}17mm = 81{,}7mm\right) > \left(t = 20mm\right)$. The actual adopted thickness of the steel plate of the roadway of the overpass is ($t = 20mm$).

Substituting the values (22) into expression (20), we obtain the values of the greatest deflection in the center of the plate at *x=y=0, a=4m, b=1.75m* (Figure 4):

$$W_{\max} = \frac{2{,}8711\cdot a^4\cdot b^4}{109\cdot 10^2\left(b^4 + 0{,}5714a^2b^2 + a^4\right)} = \frac{2{,}8711\cdot(4)^4\cdot(1{,}75)^4}{109\cdot 10^2\left((1{,}75)^4 + 0{,}5714\cdot(4)^2(1{,}75)^2 + (4)^4\right)} = 0{,}002155m$$

Thus

$$W_{\max} = 0{,}002155m = 0{,}2155cm = 2{,}155mm. \quad (23)$$

2. Results

By checking the values (19) and (23) according to condition (1), we obtain the required rigidity of the deflection of the roadway slab of the overpass:

$$\left(\frac{0{,}242}{800} < \frac{1}{1000}\right) \text{ and } \left(\frac{0{,}2155}{800} < \frac{1}{1000}\right). \quad (24)$$

Comparing the results of values (19) and (23), we see that they are quite close, which indicates that structurally orthotropic slabs can be calculated using the Bubnov-Galerkin variational method, both by the actual orthotropy parameters (coefficients α, β in expression (8)), and by the reduced (conditional) cylindrical rigidity D_{red} (expression (21)). The difference in the values of deflections W_{max} of about 10% is explained by the small number of terms of the approximating functions adopted here, which, however, gives a good result already in the first approximation. With an increase in the number of terms of power series in the approximating functions (6), the percentage of error will decrease and at a certain stage will reach a stable final percentage of divergence.

From expressions (24) it is evident that with the adopted thickness $t = 20mm$. The slab decking, supported by a system of calculated stiffening ribs (elements 1-4, Figure 3), ensures the required rigidity of the slab and, accordingly, the safe operational function of the roadway of the overpass.

3. Discussion and conclusion

It should also be noted that it is possible to determine the value of the minimum required cylindrical rigidity D_x from the condition of the standard required rigidity of the slab (1): $W_{max}/L=1/1000$. Hence $W^*_{max}=800/1000=0.8$ *cm*. Then from expression (18) at $x=y=0$, we obtain:

$$W_{\max} = 0{,}00173 \cdot a^4 \cdot b^4 / D_x . \quad (25)$$

Let's equate the values $W_{max} = W^*_{max}$, and we get the expression:

$$D_x = \frac{0{,}00173 \cdot a^4 \cdot b^4}{0{,}008} = 0{,}21625 a^4 b^4 \cdot \quad (26)$$

For $a=4m$, $b=1.75m$, using expression (26) we obtain:

$$D_x = \frac{0{,}00173 \cdot (4)^4 \cdot (1{,}75)^4}{0{,}008} = 5{,}192 \cdot 10^2 < \left(D_x^* = 17{,}1452 \cdot 10^2\right),$$

where $D_x^* = 17{,}1452 \cdot 10^2$ – the value adopted for the plate (Figure 3).

The method proposed in this article, applied for "manual" calculation, can be transferred to calculations using software on personal computers, which will allow performing calculations of various structural-orthotropic slabs with a wide variation of their structural and rigidity parameters with greater accuracy. This will allow selecting the structural parameters of the roadway slab of the mobile overpass to be optimal, rigid and durable. The presented studies on the calculation of the orthotropic slab by the variational method will be included in the calculation methodology of the overpass.

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