RESEARCH OF THE STRESS-STRAIN STATE OF A MOBILE OVERPASS STRUCTURE

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Resume

The research is aimed at solving the problem of traffic congestion during the underground repair work in cities. The goal is to develop and analyze a modular mobile overpass that ensures continuous traffic without bypassing repair areas. The stress-strain state of the spatial steel frame of the orthogonal overpass module was studied using analytical methods of structural mechanics - the displacement method and the force method. Critical forces are determined, relationships between bending moments and stiffness of elements are revealed, optimal parameters ensuring strength and stability of structure are determined. The results confirm the feasibility of the mobile overpass as an effective engineering solution to reduce the transport delays and environmental load, forming the basis for the design of next-generation mobile bridge systems.

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1 Introduction

The constantly growing traffic on urban roads leads to the formation of traffic jams and congestions on roads for various reasons: in the case of car accidents, rush hours, holding any city events - sports, holidays, etc. [1-3].

One of these reasons is the repair of utility networks (heating, water supply, etc.) located under the carriageways of urban roads. This is especially true for the cities of Kazakhstan and the CIS (Commonwealth of Independent States) countries. During the repair of urban utilities, vehicles are forced to go around the repair trenches, along other streets that creates traffic jams and worsens the transport picture of the city (Figure 1). The accumulation of vehicles in traffic jams is especially harmful to the ecology of cities, due to the simultaneous constant emission of pollutants into the atmosphere from exhaust gases. In addition, traffic jams cause social and economic damage to residents and enterprises of the city [4-5].

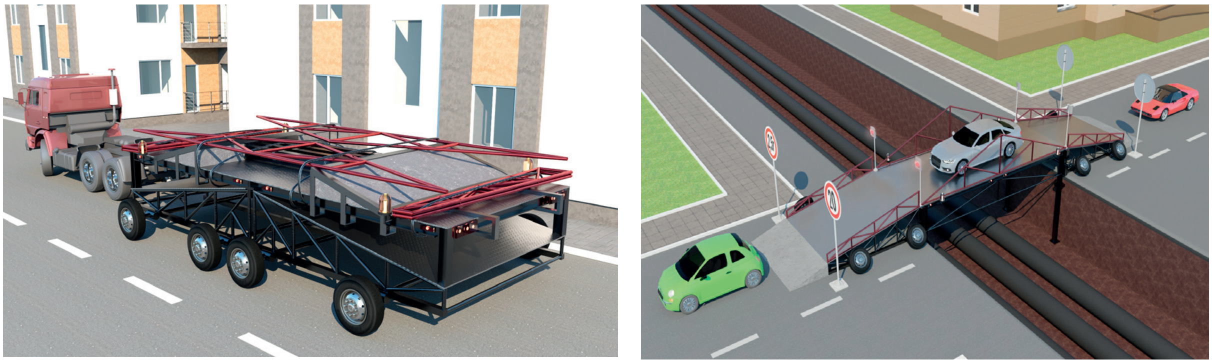
There are many different ways to eliminate the traffic jams and improve the ecology of the city by reducing the emission of harmful substances from exhaust gases [6-8]. One of the possible ideas, that is the use of temporary mobile overpasses, was proposed by authors for the first time [9-11].

The modular overpass is a collapsible temporary bridge structure, which consists of separate parts (modules). This structure is equipped with its own chassis for transportation, as well as special mechanisms for controlling the movement and assembly before operation (Figure 2).

The modular overpass is designed to drive vehicles along it during the repair of underground utilities. Before the start of a repair, the overpass is transported to the place of its operation, then installed above the trench in a perpendicular direction, which allows the transport to cross the trenches along the overpass directly (Figure 2). This eliminates the need to bypass the repair areas and the formation of traffic jams and congestion. After the repair of utility networks is completed, the overpass gets on its wheels and is taken to its place of storage. Transportation can be carried out using the usual tractors.

The idea of using the overpass is to eliminate traffic jams, improve the ecological state of cities by developing and researching the design of a modular overpass. The

Figure 1 *Traffic jam because of repairing the utility networks*



(a) *(b)*

Figure 2 *Municipal modular mobile overpass: a) transport position with folded modules; b) operational position over a trench*

term ‘overpass’ includes equivalent definitions, such as: modular overpass, mobile overpass, communal overpass. The proposed overpass has no analogues in the world as a new type of transport equipment.

As the world survey showed, such structures are practically absent in urban transport construction. Similar designs are found in the engineering forces: tank bridge layers, tracked cross-over trawls, the Bailey bridges, etc. [12]. In addition to specialized military equipment, there is an extensive direction for the construction of temporary bridges, which are stationary collapsible structures, with limited possibility of their transportation: a temporary scissor-type bridge (Japan) [13]; ASTRA temporary bridge for road repair (Switzerland) [14]; deployable arch bridge launched from a vehicle for rescue or military operations (USA) [15].

The founder of the scientific school for the development of mobile overpasses is prof. A. S. Kadyrov and his Ph.D. students: K. G. Balabekova and A. A. Ganyukov.

A. S. Kadyrov and K. G. Balabekova developed a mobile road overpass designed to eliminate the traffic jams in urban conditions at intersections. The disadvantage of this overpass is the impossibility of its use over repair trenches of utility networks [16-17].

One of the analogues of the proposed overpass is a single-span mobile overpass used in the repair of utility networks, developed and studied in the work by Kadyrov and Ganyukov [18-20]. The disadvantage of such an overpass is the limited width of the repaired trenches up to 6 m, due to the lack of additional modules in the structure. This developed modular overpass eliminates this drawback and can overcome trenches of a width of more than 8 m.

The high costs of tank bridge layers and other similar military equipment, as well as temporary stationary bridges, makes it impossible to use them in urban conditions. For these purposes, a modular mobile overpass is proposed that eliminates the above disadvantages.

However, at the moment, researches have not been fully carried out to develop and calculate the structures of the modular overpass, as well as methods for its installation, transportation and operation. In this regard, conducting research on the calculation and design of overpass structures is an actual task.

The proposed solution is a new direction in engineering practice and ensures the elimination of traffic jams in urban conditions during the underground repair of utility networks without the need to block the traffic and bypass the repaired sections.

The overpass on a rigid coupling with a towing tractor is delivered to the place of its operation in the transport position (transport mode) (Figure 2a, Figure 3). After the delivery, it is transferred to the operational position (bridge mode), above the repair trench by

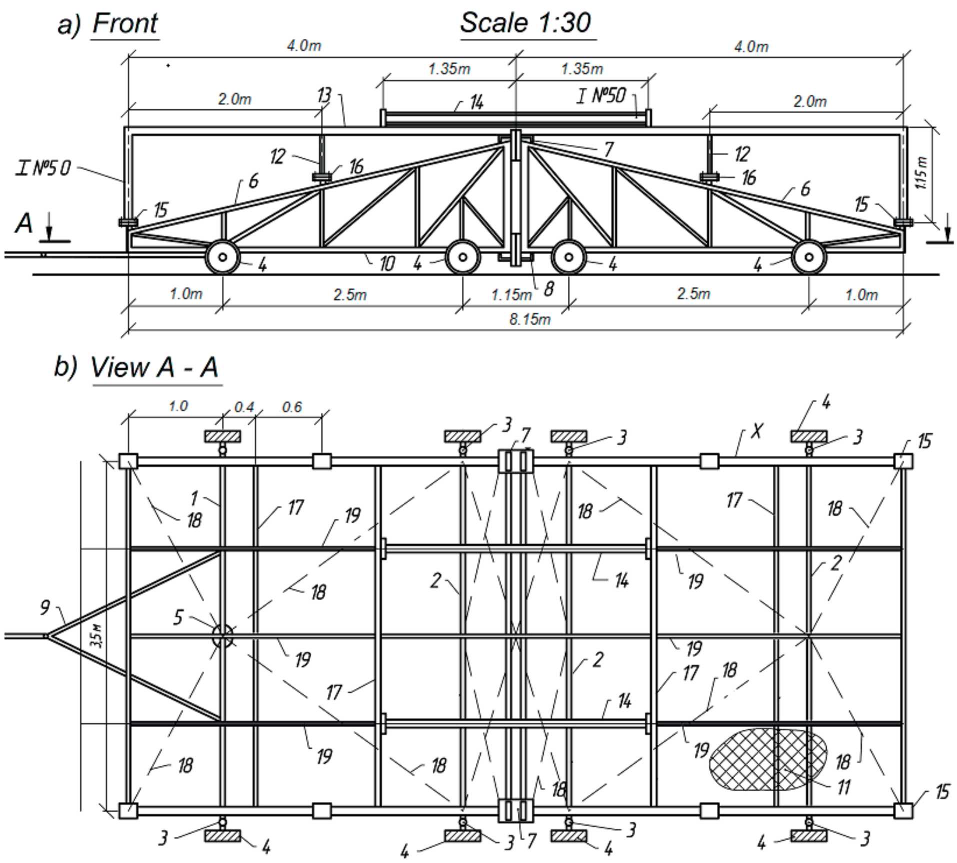


Figure 3 *General view of the modular overpass in the transport position: 1 - front swivel axle; 2 - middle and rear axles; 3 - device for turning wheels; 4 - wheels with low pressure tires; 5 - steering gear; 6 - inclined module with running gear (steel truss); 7 - upper transport locks; 8 - lower transport locks; 9 - towing device; 10 - lower truss chord; 11- metal corrugated flooring; 12 - transportation rack; 13 - an upper portion of an orthogonal Π-shaped module; 14 - lower portion of an orthogonal Π-shaped module; 15 - angular node joint of elements 6 and 13; 16 - intermediate node joint of elements 6 and 13; 17 - transverse beams of chassis frame; 18 - push-pull rods providing rigidity; 19 - longitudinal beams of chassis frame*

specially developed installation methods (Figure 2b, Figure 4) [21]. Thus, the essence of the proposed design is that it is simultaneously a vehicle and a bridge (overpass), which is a new type of transport equipment - a mobile overpass.

The overpass is assembled from unified demountable modules of two types: one orthogonal module (Figure 3, positions 13 and 14; Figure 4, positions 1 and 2) and two inclined modules (Figure 3, position 6; Figure 4, position 3).

The orthogonal module is a spatial steel Π-shaped frame, the base of which is attached to the bottom of the repair trench in special ways (Figure 4, positions 9 and 10). The upper part of the frame is a roadway above the repair trench in the form of an orthotropic slab with stiffeners reinforcing the ribs (Figure 4, positions 4, 7 and 8).

The inclined module (left and right) is a paired steel trusses carrying the roadway, also in the form of an orthotropic slab, and providing entry and exit of vehicles to the roadway of the orthogonal module (Figure 3, position 6; Figure 4 positions 3 and 5). The inclined modules are equipped with undercarriage axles with special mechanisms for raising the wheels and steering (Figure 3, positions 1-5 and 17-20) necessary for transporting the overpass to the place of operation.

The cantilever part of the trusses of the inclined module is founded on reinforced concrete ramps, which ensure the entry of vehicles to the inclined module (Figure 4, position 6) and are made of special concrete that can withstand dynamic loads [22-23]. The hinged part of the trusses is founded on the supporting frame of the orthogonal module using rigid docking units (Figure 4, position 12).

The overall dimensions of the “single-band modules” are as follows: the length of the orthogonal module - 8 m; width - 3.5 m; height (including installation on the trench bottom) - 4.7 m. Inclined module length - 4 m; width - 3.5 m; high height - 0.85 m; lower height - 0.17 m.

After the operation of the overpass is completed, it is dismantled by separate modules and towed to the storage site. For this, the inclined modules are disconnected from the orthogonal one and transferred to the transport position by turning the wheels of the chassis (Figure 4, positions 3 and 4).

The space frame of the orthogonal module is dismantled to the upper space part (Figure 4, position 4; Figure 3, position 13), then the lower racks of the

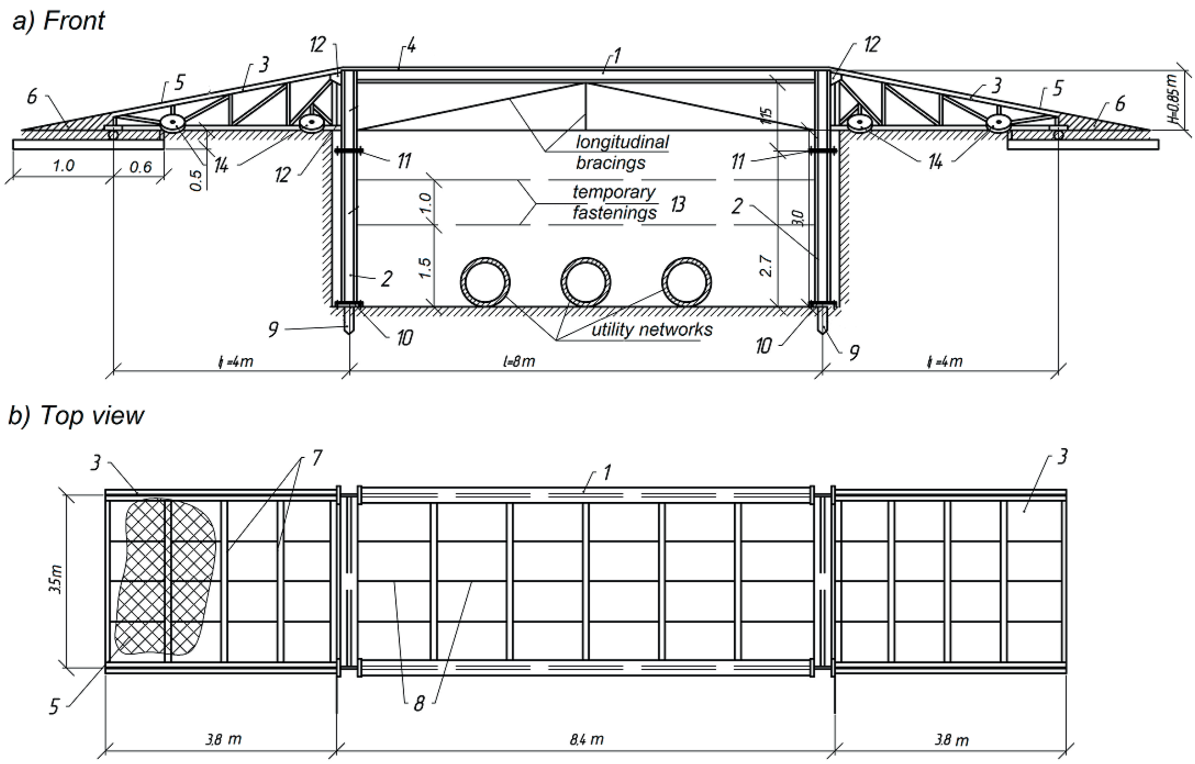


Figure 4 *General view of the modular overpass in operational position: 1 - longitudinal beams of orthogonal module; 2 - vertical racks of the orthogonal module; 3 - inclined modules with a chassis; 4, 5 - metal flooring of orthogonal and inclined modules; 6 - entrance ramps; 7 - transverse bearing beams of the deck; 8 - longitudinal deck beams; 9 - supports of the lower part of the orthogonal module; 10 - support metal mount for racks; 11 - node joint of elements 1 and 2; 12 - node joint of elements 1 and 3; 13 - structures of temporary installation reinforcement of elements; 14 - wheels of undercarriage in turned state*

frame are removed (Figure 4, position 2), disconnecting from the support mounts (Figure 4, position 10). Then the inclined modules are connected with transport locks (Figure 3, positions 7, 8). Further, the upper part of the orthogonal module (Figure 3, position 13) is mounted on the resulting structure from above and fixed using a transport rack (Figure 3, position 12) and a junction joint (Figure 3, position 15). The lower frame posts (4 pcs.) are fixed on the top of the frame (Figure 3, position 14). Entrance ramps, fencing and other additional equipment can also be transported on top of the frame of the orthogonal module [21].

It should be noted that to ensure the safety of transportation, the overpass, being transport equipment, must be equipped with additional equipment: front and rear headlights, side running lights around the perimeter, turn signals, brake lights, flashing yellow beacons and a wheel brake system controlled by the driver of the tractor.

2 Materials and methods

The main bearing structures of the overpass are: a spatial П-shaped frame of an orthogonal module with a roadway slab, reinforced with stiffeners, as well as inclined modules consisting of paired trusses connected by longitudinal and transverse beams (Figure 4). The carriageway of the orthogonal and inclined modules are covered with a corrugated metal flooring, 20mm thick.

In the proposed article, to analyze the stress-strain state of the supporting metal structures of the overpass in terms of strength, stability and rigidity, the calculation of the spatial frame of the orthogonal module is performed (Figure 4, positions 1 and 2).

The purpose of the study was to develop the design and strength calculation of the orthogonal module of the mobile overpass, which is a spatial frame carrying the carriageway of the overpass.

To achieve this goal, it is necessary to complete the following tasks:

- to perform the study of operation and strength calculation of the longitudinal and transverse frame orthogonally to the overpass module, taking into account the dynamics of mobile vehicles;
- to select cross-sections of structural elements of longitudinal and transverse frame of orthogonal overpass module based on strength and stability conditions;
- to assess and calculate the rigidity of the spatial frame of the orthogonal overpass module in accordance with regulatory documents.

The scientific novelty of this research lies in the development, theoretical justification and study of a

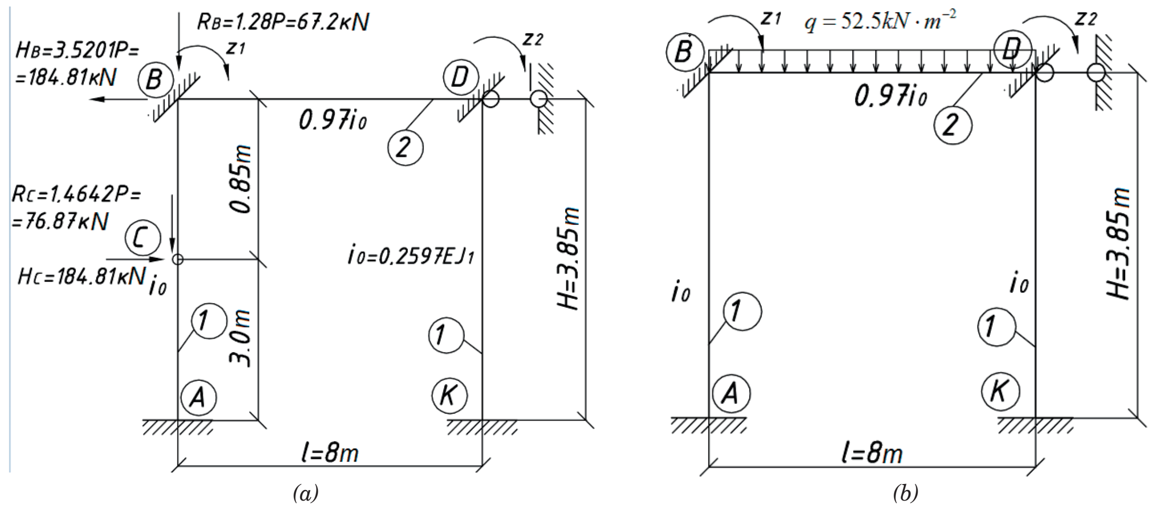


Figure 5 *Calculation scheme of the longitudinal frame by the displacement method with dangerous loading: a) Variant 1: load on inclined module; b) Vvariant 2: load on orthogonal module*

new type of transport equipment - a modular mobile overpass, which is a combined structure of a bridge structure and a vehicle with its own undercarriage and issues in the following:

- for the first time, as a result of the development and study of a mathematical model, the dependencies for calculating a new type of transport equipment - a mobile overpass were obtained;
- the dependences linking the strength and deformed state of the spatial frame of the orthogonal overpass module from the loads of a mobile vehicle in a static position, taking into account the dynamic coefficient have been established;
- the dependence of bending moment at critical points of the structure of the spatial frame of the orthogonal module on the ratio of bending rigidity of the crossbar and the racks is obtained;
- a methodology for calculating the elements of a modular overpass has been developed, taking into account the complex impact of mobile loads, dynamic factors, strength and stability characteristics, which ensures increased accuracy of calculation and reliability of the structure in operating conditions;
- the design was optimized according to the criteria of strength, stiffness and metal intensity, which made it possible to determine the rational parameters of the spatial frame of the orthogonal module and thereby increase the economic efficiency of the designed structure.

In the methodological approach of the study, novelty manifests itself in the use of a combination of precise analytical displacement and force methods to calculate the spatial frame as flat structures (longitudinal 8 m and transverse 3.5 m) with the correction factors for the spatial work of the elements, taking into account the dynamics of moving loads according to Eurocodes in two critical cases (on inclined and orthogonal modules), parametric stiffness ratio analysis, and stiffness check, enabling design optimization without complex numerical modeling.

The practical significance of the research is determined by the development of a methodology for calculating the structural elements of the overpass based on the results obtained.

With a sufficient degree of accuracy, the spatial frame of the orthogonal module (Figure 4, positions 1, 2) can be calculated as flat structures: a longitudinal frame with a span (longitudinal crossbar) of 8m and a transverse frame with a span (transverse crossbar) of 3.5m. The longitudinal crossbar of the frame covers the length of the trench; the transverse crossbar is the width of the carriageway of the overpass. In this case, the correction factors are introduced to take into account the spatial work of individual elements of the frame structures [24].

To calculate the framework frame of the orthogonal module, the exact analytical method of displacement and the method of forces are adopted [25-26]. Based on the displacement method, the strength calculation of the longitudinal frame, with a span of 8 m and a height of 3.85 m, was considered (Figure 4, positions 1 and 2). The calculation scheme is presented in Figure 5.

Taking into account the fact that the load on the overpass is mobile (from the movement of vehicles), two variants for the most dangerous loading of the calculated frame were considered: variant 1 - the carriageway is located only on the inclined module (Figure 4, position 3, Figure 5a); variant 2 - only on the orthogonal module (Figure 4, position 1, Figure 5b).

The load on 1 m² of the overpass carriageway, taking into account overloads and the dynamic effect of mobile vehicles, is accepted as $g = 3000\,\mathrm{kg\cdot m^{-2}} = 30\,\mathrm{kN\cdot m^{-2}}$, according to Eurocodes [27-28]. This can provide safe movement, both for light vehicles and lightly loaded vehicles up to 3.5 tons. Then, the linear load on the upper crossbar of the frame would be $q = g \cdot 1.7585250\,\mathrm{kg\cdot m^{-2}}$ or

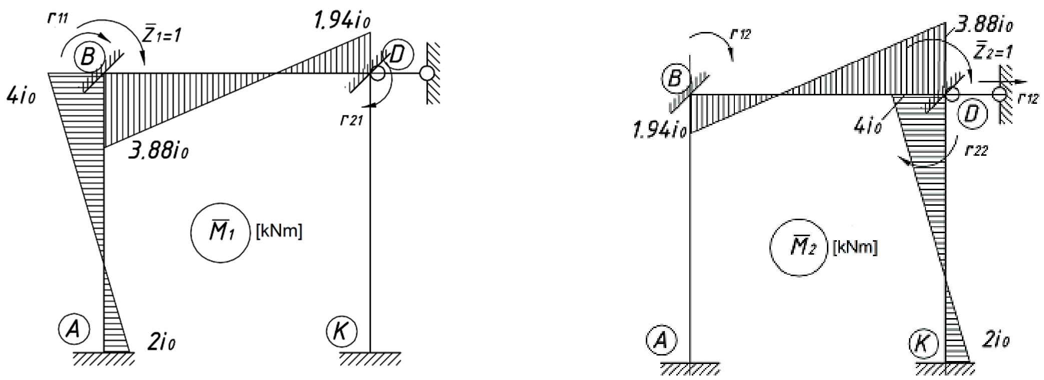


Figure 6 *Diagrams of unit moments* M_1 *and* M_2

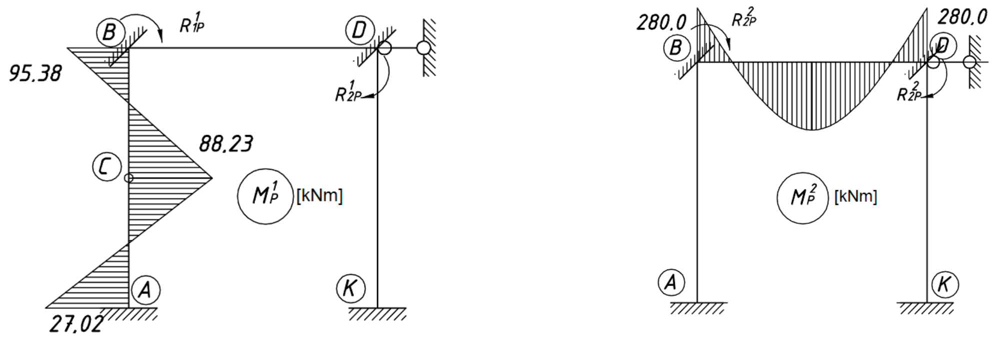


Figure 7 *Loading diagrams of moments* M^1_P *and* M^2_P *from loading variants 1 and 2.*

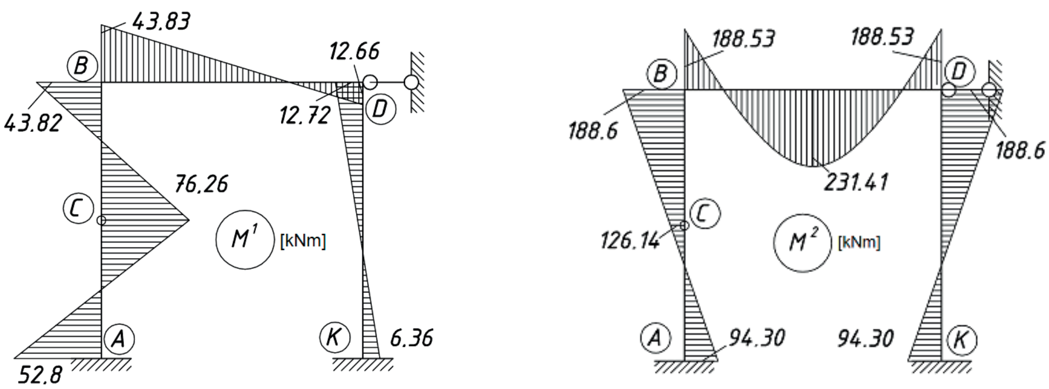


Figure 8 *Moment diagrams from loading variants 1 and 2*

$q = 52.5\,\mathrm{kN \cdot m^{-2}}$ (Figure 5a, 5b). In Figure 5, and at points B and C (points of attachment of the inclined module), the reactions from the inclined module H_B, R_B, H_C, R_C, are applied, which arise from 1 loading variant.

Next are defined the geometric and stiffness relationships of the frames. Indices “1” - indicate vertical racks, indices “2” and “3” - crossbars of longitudinal and transverse frame 3.5 m (Figure 5). The following is obtained: $\alpha_1 = l_1 = H = 3.85\,\mathrm{m}$; $\alpha_2 = l_2/l_1 = L/H = /3.85 = 2.0779$; $\alpha_3 = l_3/l_1 = 3.5/3.85 = 0.9091$. Stiffness ratio of racks and crossbars: $g_1 = EJ_1 = 16.35 \cdot 10^6\,\mathrm{N \cdot m^2}$; $g_2 = EJ_2/EJ_1 = 2.0$; $g_3 = 1.5$. Linear stiffness $i_1 = EJ_1/H = 0.2597EJ_1$; $i_2 = i_1\, g_2/\alpha_2 = 0.25EJ_1$; $i_0 = i_1 = 0.2597EJ_1$; $i_2 = 0.97i_0$.

Taking into account the conditions for coupling the frame rods of the orthogonal module, the number of the main unknowns will be equal to two: the angles of rotation of the upper nodes of the frame B and D - z_1 and z_2. The canonical equations of the displacement method in this case are [25-26]:

$$R \cdot z + R_{kp} = 0\,, \tag{1}$$

where, $R = \{r_{ij}\}, (i = 1,2; j = 1,2)$ - matrix of unit coefficients (N·m) obtained based on diagrams of unit moments $\overline{M}_k (k = 1,2)$ arising from angular displacements z_1 and z_2 (Figure 6); $R_{kp}\{r_{1p}, r_{2p}\}$ - vector of load coefficients (N·m), which are calculated from the load diagrams of moments in accordance with loading variants shown in Figure 5 (Figure 7); $z\{z_1, z_2\}$ - unknown vector of angular displacements of the frame in nodes B and D (Figure 5a).

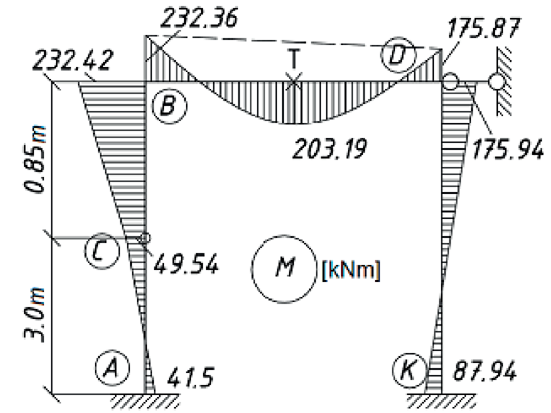


Figure 9 Summary diagram of moments M

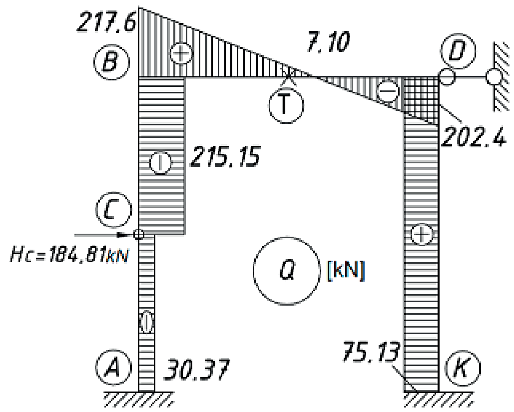


Figure 10 Diagram of shear forces Q

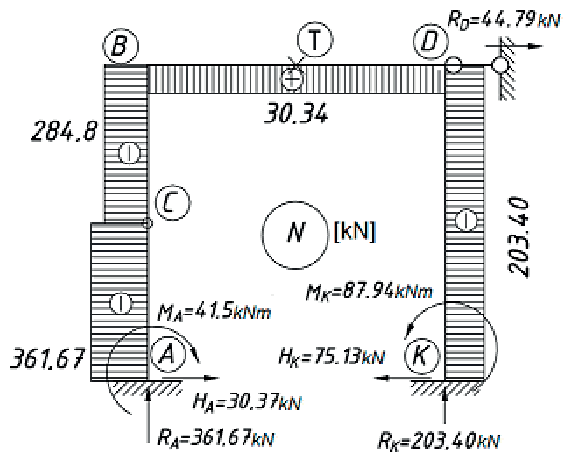


Figure 11 Diagram of longitudinal forces N

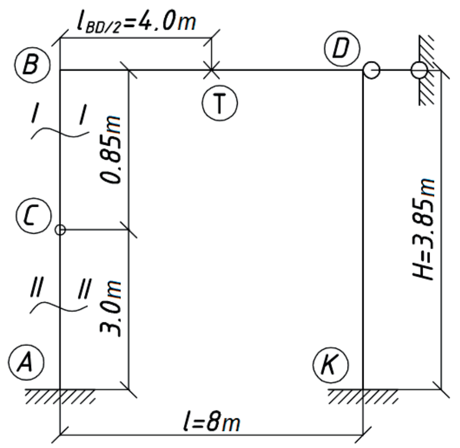


Figure 12 Calculation cross-sections and nodes

After finding R_{kp} and R, the system of linear equations in Equation (1) is solved, and z_1 and z_2 are determined. Further, the diagram of moments from each loading variant is found by the equation [25-26]:

$$M^1 = \overline{M}^l_1 z_1 + \overline{M}^l_2 z_2 + \overline{M}^l_p, \tag{2}$$

where z_1, z_2 are the main unknowns of displacement method found from Equation (1); l - index of frame loading variant (l = 1,2). Diagrams of these moments are given in Figure 8.

The total calculating diagram of moments from both loading variants of the frame specified in Figure 5 is found by addition (Figure 9) [25-26]:

$$M = \overline{M}^1 + \overline{M}^2. \tag{3}$$

3 Results and discussion

The total calculating diagram of moments M from the two loading variants, according to Equation (3), is given in Figure 9. Figure 10 shows the diagram of transverse forces Q (Figure 10), obtained based on the diagram M. Based on the diagram of shear forces Q, the diagram of longitudinal forces N, presented in Figure 11, was obtained.

Based on the values of calculating diagrams M^1 and M^2, shown in Figure 8, a table of unfavorable loads was compiled for the frame of the orthogonal module, from the load of mobile vehicles moving along the carriageway of the overpass (Table 1). Figure 12 shows the positions of the calculating sections when calculating the stability of the frame pillars.

Table 1 contains data on six calculating points (A, C, B, T, D, K) for the two loading variants of the longitudinal frame of the orthogonal module, as well as total and extreme values of forces (Figures 9, 10 and 11). The critical points of the structure are points B, T and A. At point B, the greatest negative bending moment (-232.42 kNm) and high shear forces (-215.15 and + 214.60 kN) are observed, which makes this point the most loaded. This node requires reinforcement and additional investigation to prevent the shear and additional deformations. At point T, the maximum positive moment (+231.41 kNm) indicates significant stretching of the lower fibers, which requires testing for material strength in this zone. At point A, the maximum

***Table 1** Calculation forces in orthogonal module frame cross-sections*

Calculation points	Values of bending moments M^1 and M^2 (kNm)		Summary moments (kNm)	Calculation moments (kNm)		Values of shear and longitudinal forces (kN)	
	Load variant 1	Load variant 2	$M^1 + M^2$	M_{max}	M_{min}	Q	N
A	-52.8	+94.30	+41.5	+41.5	-52.8	-30.37	-361.67
C	+76.26	-126.14	-49.88	+76.26	-49.54	-30.37 -215.15	-361.67 -284.80
B	-43.82	-188.60	-232.42	-43.82	-232.42	-215.15 +214.60	-284.80 -30.34
T	-28.28	+231.41	+203.19	+231.41	+203.19	+7.10	-30.34
D	+12.72	-188.53	-175.81	+12.72	-175.87	-203.40 +75.13	-30.34 -203.40
K	-6.36	+94.30	+87.94	+94.30	-6.36	+75.13	-203.40

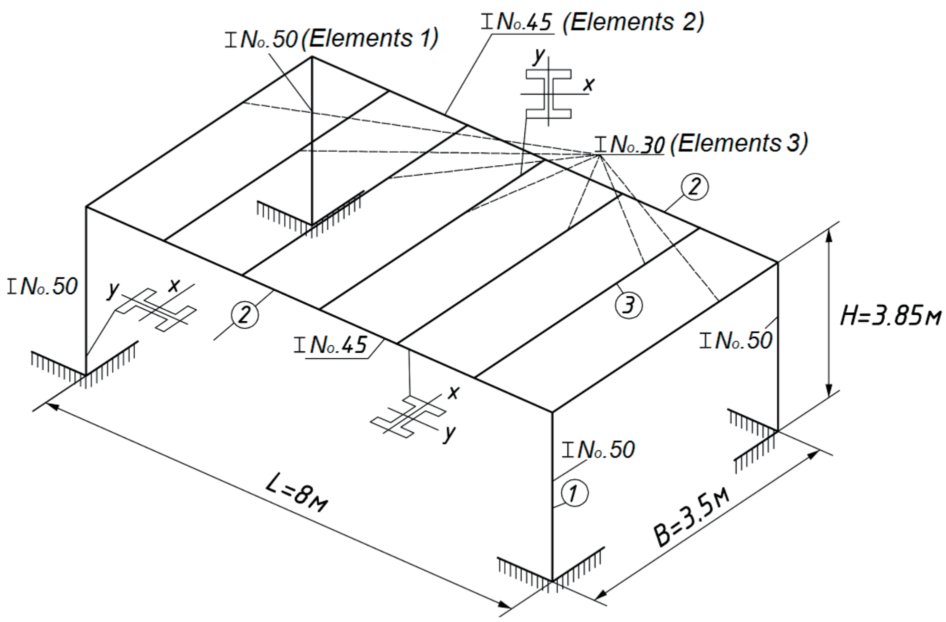


***Figure 13** Obtained set of cross-sections of frame spatial elements of orthogonal module: Elements 1 (vertical racks of the orthogonal module) - I-beam No. 50; Elements 2 (longitudinal beams (girders) 8m long) - I-beam No. 45; Elements 3 (crossbars (girders) with a length of 3.5m) - I-beam No. 30*

compressive force (-361.67 kN) indicates a high axial load, which is important for assessing the stability of the vertical racks of the structure. Similar calculations were made for the transverse frame 3.5 m wide (Figure 13, elements 1 and 3).

Based on the results of the study of the strength state of the longitudinal and transverse frames of the frame, based on the strength and stability of its elements (crossbars and racks), their cross sections were selected as for structures operating under conditions of complex resistance (tension-compression, bending, torsion), taking into account the dynamic effect of mobile vehicles. Vertical racks and crossbars of longitudinal and transverse frames were taken in the form of a rolled I-beam.

The equation of strength condition at eccentric compression-tension reads, [24-26]:

$$\left[\sigma = \pm\frac{N}{A}\left(1+\frac{x_k x_f}{i_y^2}+\frac{y_k y_f}{i_x^2}\right)\right] \leq \frac{\sigma_{adm}\cdot\gamma}{K_d}, \qquad (4)$$

where $\sigma_{adm} = 284\,\mathrm{MPa}$ - allowable stress for steel grade S355JR, according to the European standard EN 10025-2 [27-28]; (x_k, y_k) - coordinates of the design point of the cross section; i_x^2, i_y^2 - squares of the main radii of inertia of the section relative to the corresponding axes; A - cross-sectional area; (x_f, y_f) - coordinates of the point of application of axial longitudinal force N; ($\gamma = 0.9$) - accounting coefficient of spatial work of the structure. The dynamic effect of the movement of the rolling stock along the carriageway of the bridge crossing is taken into account by introducing an empirical dynamic coefficient $K_d = 1.3$. The dynamic coefficient takes into account additional loads from vibrations and shocks

***Table 2** Moments in dangerous node B of the frame depending on parameter "n"*

Values of parameter «n»	Coefficient values					Force values (kN)		Forces in the main system (kNm)			
	a_{11}	a_{12}	a_{22}	b_1	b_2	X_1	X_2	$\overline{M}_1 \cdot X_1$	$\overline{M}_2 \cdot X_2$	$M_{P,B}$	M_B
0.5	4.97	0.485	4.97	-184.6	280	43.05	-49.93	41.76	-24.84	-184.6	-167.68
1.0	5.94	0.97	5.94	-184.6	280	39.83	-53.64	77.28	-53.37	-184.6	-160.69
1.5	6.91	1.455	6.91	-184.6	280	27.78	-48.25	80.84	-72.07	-184.6	-175.83
2.0	7.88	1.94	7.88	-184.6	280	34.25	-43.97	132.89	-85.30	-184.6	-137.01

when moving vehicles along the overpass, increasing the calculated static loads by 30% to ensure the safety of the structure.

The central compression stability is given by the equation [24, 26]:

$$\left(\sigma = \frac{N}{\varphi A}\right) \leq \frac{\sigma_{adm} \cdot \gamma}{K_d}, \quad (5)$$

where φ - coefficient of reduction of the main allowable stress.

For elements of the structure working for bending, the required bending strength moment W of the cross section is determined by the equation [24, 26]:

$$W = \frac{M_{\max}}{\sigma_{adm} \cdot \gamma} K_d, \quad (6)$$

where M_{max} - maximum bending moment on the structure element.

According to the results of calculations according to Equations (4)-(6) based on Table 1 (for longitudinal and transverse frames), the cross sections of the spatial frame of the orthogonal module are taken according to the range. The selected set of cross sections is shown in Figure 13.

The analysis of the obtained solutions (Table 1) showed that during the operation of the overpass in the operational position (transport movement), the crossbar of the longitudinal frame of the orthogonal module (Element 2, Figure 13) experiences the greatest static and dynamic loads. This results in the highest loads and hazardous cross sections at the corner joints of the vertical posts (Figure 13, element 1) and the girder (Figure 13, element 2) (Figures 9, 10 and 11, nodes B, T and A).

In this regard, a study was conducted of the effect of stiffness characteristics on the selection of the cross section of the crossbar (Figure 13, Element 2) of the longitudinal frame orthogonally to the module, taking into account the forces in the dangerous unit B, in which the greatest forces occur (Figures 9 and 10). For these purposes, the force method was used, which is an analogue of the displacement method and has a similar canonical equations in Equation (1), in which unit nodal displacements are replaced by the corresponding unit nodal forces X_1 and X_2 [24-26].

Then, the following value of linear stiffnesses are taken: vertical elements of the longitudinal frame (rack) (Figures 5 and 13, element 1) $i_1 = i_0 = 1$; horizontal frame elements (girders) (Figures 5 and 13, element 2) $i_2 = 0.5$; 1.0; 1.5; 2.0. Denote the ratio of linear stiffnesses of the longitudinal frame struts by $n = i_2/i_1$ (Figure 5).

Then, the coefficients of the canonical equations in Equation (1) $R = \{r_{ij}\}$ and the vector of load coefficients $R_{kp}\{r_{1p}, r_{2p}\}(i = 1,2; j = 1,2; k = 1,2)$ in the general form, will take the following form:

$$a_{11} = r_{11} = 4i_0 + 1.94 \cdot n \cdot i_0 = (4 + 1.94 \cdot n) \cdot i_0;$$
$$a_{12} = r_{12} = r_{21} = 0.97 \cdot n \cdot i_0; a_{22} = r_{22} = (4 + 1.94n)i_0;$$
$$b_1 = -184.62 = R_{1P}; b_2 = R_{2P} = 280.00. \quad (7)$$

Solving, in general, the system in Equation (1) taking into account the expressions in Equation (7), one obtains:

$$X_1 = \frac{-b_1 - a_{12}^2 \cdot \left[\frac{-b_1 + b_2\left(\frac{a_{11}}{a_{12}}\right)}{(a_{12}^2 - a_{11} \cdot a_{22})}\right]}{a_{11}};$$
$$X_2 = \frac{\left[-b_1 + b_2\left(\frac{a_{11}}{a_{12}}\right)\right] \cdot a_{12}}{(a_{12}^2 - a_{11} \cdot a_{22})}. \quad (8)$$

Using Equation (8), one finds the values of the main unknown methods of forces X_1 and X_2, having previously determined the coefficients of equations in Equation (7) when varying the parameter n = 0.5; 1.0; 1.5; 2.0. By analogy with Equation (2), the resulting moment M_B at the dangerous node B is defined as:

$$M_B = \overline{M}_{1,B} \cdot X_1 + \overline{M}_{2,B} \cdot X_2 + M_{P,B}. \quad (9)$$

The results of these calculations are shown in Table 2. According to Table 2, the dependence is obtained of the bending moment in the dangerous node B of the longitudinal frame (Figure 5) on the ratio $n = i_2/i_1$ (Figure 14).

The analysis of the dependence in Figure 14 shows that the ratio of the linear stiffnesses of the frame girder and its racks (parameter n) has a significant effect on the value of the bending moment M_B in node B (Figure 5), where the crossbar and the left rack are connected. Maximum absolute value of bending moment M_B occurs at values n within n = 1.5. Optimum value of ratio of cross-bar (i_2) and rack (i_1), at which the minimum values of moment M_B occur is determined within n = 2.0. This allows taking into account the design parameters of the

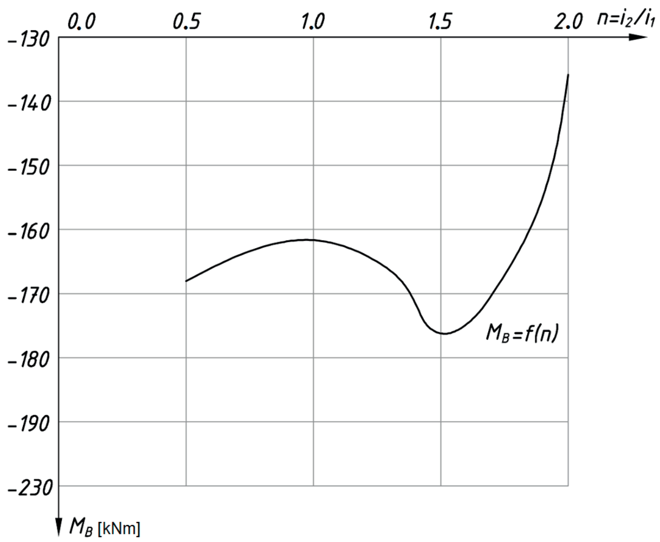


***Figure 14** Dependence of the bending moment M_B on ratio of bending stiffness of crossbar (i_2) and rack (i_1) of longitudinal frame*

longitudinal frame when designing and calculating the orthogonal module of the overpass and reduce the metal consumption of structural elements.

Studies of the operation of the spatial frame of the overpass under the loads of mobile vehicles (taking into account the dynamic coefficient) made it possible to select structure parameters taking into account strength, stability and dynamic impact (Equations (4)-(6)). Additional calculation of orthogonal module frame stiffness is required for the safe operation. Stiffness is a key parameter that determines the resistance to deformations and ensures the reliability of the structure in accordance with the standards of bridge construction [26-28].

During the operation of the overpass in the orthogonal overpass module, the crossbar of the longitudinal frame (Elements 2, Figure 13) and the crossbar of the transverse frame (Elements 3, Figure 13) are subjected to the greatest loads. In this regard, it is necessary to check the stiffness of elements 2 and 3 (Figure 13).

The transverse frames of a width of 3.5 m (Elements 3 and 1) are statically defined frames. Elements 3 (crossbars, Figure 13), length l = 3.5 m, are subjected to a load, the value of which is determined as follows: $q_n = g \cdot c \cdot K_d = 30 \cdot 1.33 \cdot 1.3 = 52\,\mathrm{kN \cdot m^{-1}}$. Where $g = 30\,\mathrm{kN \cdot m^{-1}}$ is the load per 1 m^2 due to the mobile transport; c = 1.33m - beam pace; K_d = 1.3 - dynamic coefficient. The cross section of element 3 is I-beam No. 30. Moment of inertia of the _=beam's cross-section is J_x =7080 cm^4. Modulus of elasticity of material is E = 2·105 MPa (for steel).

The maximum deflection in the middle of the beam (Element 3, Figure 13) is calculated by the formula [29]:

$$\upsilon_{\max} = \frac{5 \cdot q_n \cdot l^4}{384 \cdot EJ_x} = 0.715 \cdot 10^{-2}\mathrm{m} = = 0.715\,\mathrm{cm} = 7.15\,\mathrm{mm}. \quad (10)$$

The stiffness check is performed by the equation [30]:

$$\frac{\upsilon_{\max}}{l} \leq \left[\frac{1}{f}\right], \quad (11)$$

where $\left[\frac{1}{f}\right] = \frac{1}{400}$ - normative allowable deflection of beams according to the conditions of safe operation of elements of steel structures. By Equation (11) one obtains:

$$\frac{0.715 \cdot 10^{-2}}{3.5} = \frac{1}{4895} \leq \left[\frac{1}{400}\right].$$

Thus, the stiffness of the beam (Element 3, Figure 13) is provided with a large margin.

Elements 2 (girders of longitudinal frames, Figure 13), length l = 8.0m, are subjected to the load, which is determined as follows: $q_n = g \cdot c \cdot K_d = 30 \cdot 1.75 \cdot 1.3 = 68.25\,\mathrm{kN \cdot m^{-1}}$, where c = 1.75 m is the distance equal to half the width of the transverse frame 3.5m to collect loads on the girders of the longitudinal frames (Elements 2).

Crossbars of longitudinal frames (Elements 2, Figure 13) are statically indeterminate beams. To determine the maximum deflection of such beams, the Vereshchagin method was used, based on the multiplication of the coordinates of the centers of gravity of the curves of the resulting moment M (Figure 9) and moments M_1 from the unit force of the longitudinal frame (Figure 15) and determined by the equation [25, 30-31]:

$$\upsilon_{\max} = \upsilon_T = \frac{K_d}{EJ_{1x}}(M) \times (\overline{M}_1), \quad (12)$$

where J_{1x} = 39290 cm^4 - moment of inertia of I-beam No. 50 for the longitudinal frame rack (Element 1, Figure 13).

The diagram of moments $\overline{M}_1$ from a unit force $\overline{P} = 1$, applied in the middle of the longitudinal frame

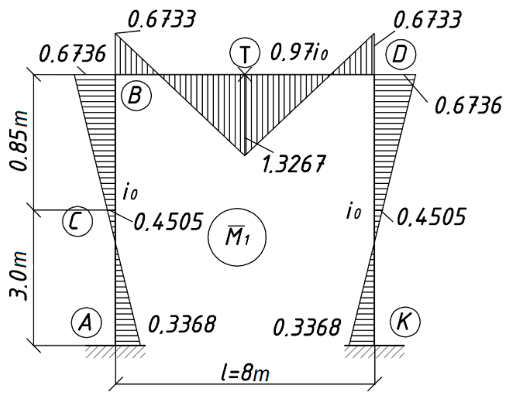


Figure 15 *Diagram of moments* $\overline{M}_1$ *of longitudinal frame from unit force* $\overline{P} = 1$

girder in section BD is shown in Figure 15. Performing calculations by Equation (12) one gets:

$$\upsilon_{\max} = \upsilon_T = \frac{2941.45}{EJ_{1x}}. \tag{13}$$

To take into account the effect on the resulting stiffness of element 2 (Figure 13), its supporting transverse and longitudinal elements 3 (Figure 13) and 4 (Figure 4), a correction coefficient 0.5 is introduced [27-28]. Taking into account the correction coefficient, next is checked the fulfillment of the condition of rigidity of elements 2, which are longitudinal beams with a span l = 8 m with an I-beam section No. 45. According to Equation (13), the maximum deflection is determined as:

$$\upsilon_{\max} = \upsilon_T = 0.5 \cdot \frac{2941.45 \cdot 10^{-3}}{2 \cdot 10^8 \cdot 39.290 \cdot 10^{-8}} = \\ = 0.0187\ \text{m} = 1.87\ \text{cm} = 18.7\ \text{mm}. \tag{14}$$

Stiffness of element "2" can be checked by Equation (11) considering 14:

$$\left(\frac{1.87}{800} = \frac{1}{428}\right) < \left(\left[\frac{1}{f}\right] = \frac{1}{400}\right) \text{or } \frac{1}{428} \leq \frac{1}{400}. \tag{15}$$

According to Equation (15), the condition of rigidity of element 2 (Figure 12) - longitudinal beams with span l = 8 m consisting of I-beams No. 45 is provided.

4 Conclusion

The presented research demonstrated the first analytical model of a modular mobile overpass - a new class of transport equipment that integrates the functions of a temporary bridge and undercarriage. The conducted studies describe the relationship between the force and deformation characteristics of the overpass structure under moving loads and make it possible to optimize the main parameters according to the criteria of strength and stability.

The design of the orthogonal module, as a key bearing element of the overpass, has been developed, which is a spatial Π-shaped steel frame with an orthotropic slab of the carriageway and stiffening ribs. Its analytical force calculation was performed using the displacement method, taking into account the two most unfavorable dynamic loading schemes from mobile vehicles (q = 52.5 kN/m; g = 30 kN/m², with a dynamic coefficient of 1.3, according to Eurocodes [27-28]).

The critical internal forces are determined: the maximum bending moment in the junction of the girder and the strut (point B) - M_B = -232.42 kN·m (option 1) and M_B = 280.0 kN·m (option 2); transverse force Q_B = 214.6 kN; axial compressive force in the support N_A = -361.67 kN.

Optimal cross-sections of frame elements made of steel EN 10025-2 ($\sigma_{adm} = 284$ MPa) are selected:

- vertical struts - I-beam No. 50 (h = 500 mm, b = 200 mm, t = 15.5 mm);
- longitudinal girders with a span of 8 m - I-beam No. 45 (h = 450 mm);
- transverse girders with a span of 3.5 m - I-beam No. 30 (h = 300 mm).

The checks confirmed the fulfillment of the conditions for stiffness: the maximum deflection of the crossbar = 18.7 mm < [f] = L/400 = 20 mm, which guarantees the rigidity of the structure.

For the first time, the analytical dependence of peak bending moments at critical nodes on the ratio of rigidity of the crossbar and struts $n = i_2/i_1$ was established (Figure 14). The optimal value of n = 2.0 provides a decrease in maximum moments and total metal consumption by 9% compared to the equal-rigidity scheme (n = 1), which increases the efficiency and manufacturability of the design. These two results determine the basic scientific novelty of this research.

Further work can be directed to finite element modelling of the complete system (with inclined modules), field tests and the development of automated installation/dismantling mechanisms. The results obtained form the scientific and methodological basis for the design of a family of modular mobile overpasses adapted to various urban conditions. The implementation of the proposed solutions is important for improving the transport and construction technologies and increasing the efficiency of the use of urban space.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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