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Behaviour of load-carrying members of velodromes' long-span steel roof

Работа несущих элементов большепролетного стального покрытия велодрома

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Ключевые слова: арка; ветровая нагрузка; статическая схема

Abstract. Long-span roofs have been of an increased interest within the last sixty years. An arch-type steel roof of velodrome with the maximum span, height, and length equal to 109.50, 23.07, and 126.00 m respectively, is considered as the object of the current investigation. The choice of the preferable structural solution and behaviour analysis of load-carrying members of the long-span arch-type steel roof of the velodrome is considered as the aim of the current study. The distribution of internal forces and stresses in the trihedral lattice steel arch with a triangular web such as displacements under the action of design loads were investigated for fixed, double-hinged, and three-hinged static schemes. It was stated that the preferable structural scheme is the fixed arch.

Аннотация. Большепролетные крыши вызывают повышенный интерес в течение последних шестидесяти лет. Арковидная стальная крыша велодрома с максимальным пролетом, высотой и длиной, равными 109.5, 23.07 и 126 м соответственно, была выбрана как объект исследования. Выбор предпочтительного конструктивного решения и анализ поведения несущих элементов большепролетной арки велодрома является целью исследования. Распределение внутренних усилий и напряжений в элементах стальной арки с трехгранной решеткой, а также перемещения, под воздействием расчетной нагрузки были исследованы для защемленной, двухшарнирной и трехшарнирной статических схем. Было показано, что предпочтительной статической схемой для большепролетной арки является защемленная арка.

Introduction

Long-span roofs have been of an increased interest among civil engineers and architects within the last sixty years [1]. Structures with one span cause a special interest due to the possibility to use the rational internal space for several types of residential and industrial buildings [2]. Sporting halls, indoor swimming pools, velodromes, ice halls, exhibition and concert halls, market halls as well as roofs of railway stadiums, buss stadiums, and airports are examples of such residential buildings [3]. Buildings in the aircraft industry and plants for producing structures with overall dimensions such as storages of bulked materials are examples of such industrial buildings [4]. The length of the buildings spans changes within the limits from 30 to 70 m [5]. The buildings with especially long spans within the limits from 70 to 300 m are used quite rarely [6, 7]. The interior of the velodrome where spans of the roof′s structures change within the limits from 50 to 80 m is shown in Figure 1.

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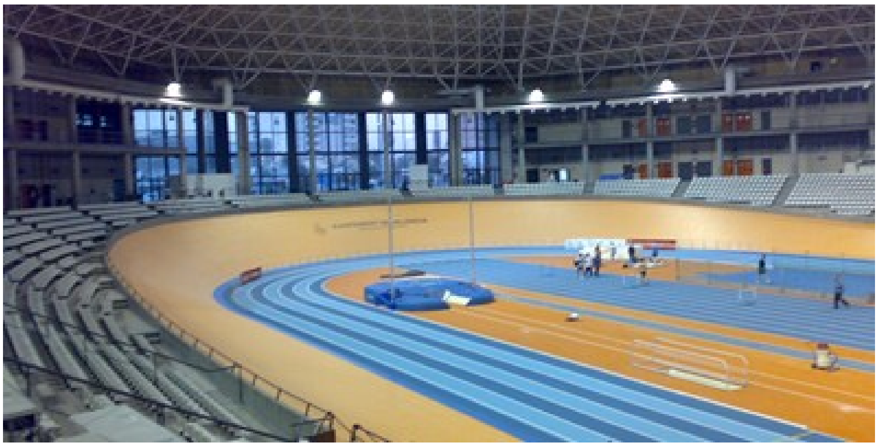
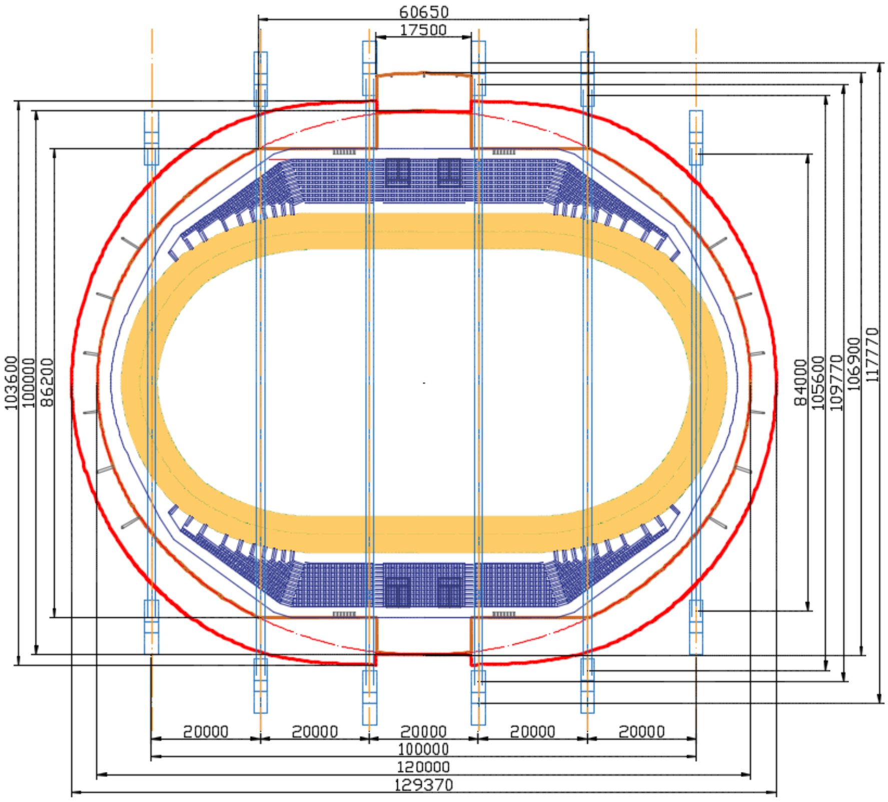


Figure 1. Interior of the velodrome [1]

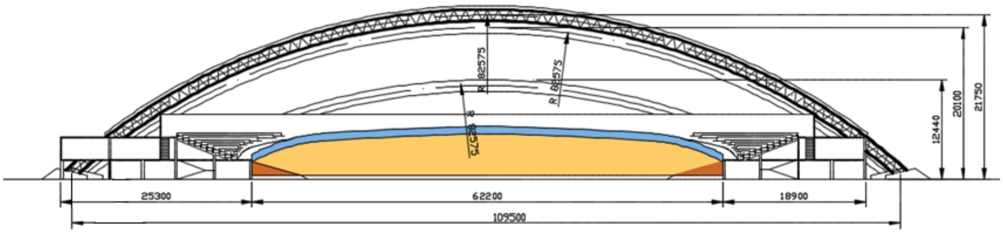
An arch-type steel roof of the velodrome with the maximum span, height, and length equal to 109.50, 23.07, and 126.00 m respectively, is considered as the object of the current investigation. Steel is considered as a structural material based on the existing experience of implementing similar structures [8]. The choice of the preferable structural solution and behaviour analysis of load-carrying members of the long-span arch-type steel roof of the velodrome is considered as the aim of the current study. The distribution of internal forces and stresses in the main load-carrying structural members such as displacements under the impact of design loads must be investigated in the course of the current study.

Description of the object under investigation

The trihedral lattice steel arch with a triangular web is considered as a main load-carrying structure of the steel roof of the velodrome as the most appropriate for the purposes of this building [8]. The top chord of the trihedral lattice steel arch was formed with two round pipes, but the bottom one was formed with only one. Elements of the archs' lattice are also round pipes. The roofing is based on the main trihedral lattice purlins which has the spans equal to 20 m and is placed with the bay equal to 6 m and additional purlins, which are based on the main ones. Additional purlins have double-tee cross-sections. The purlins also play the role of bracings. The plan of the considered arch-type steel roof and its cross-section are given in Figure 2.



a)



b)

Figure 2. Plan *a)* and cross-section
***b)* of the arch-type steel roof of the velodrome [9]**

The hall of the velodrome is covered with the roof, which is based on six trihedral lattice steel arches with a triangular web. The arches differ in spans and can be divided into three pairs with different spans. The central pair has the maximum span equal to 109.50 m. Two other pairs have spans equal to 105.50 and 84 m. This difference in spans is necessary to provide the elliptical shape of the roof in plan (see Figure 3).

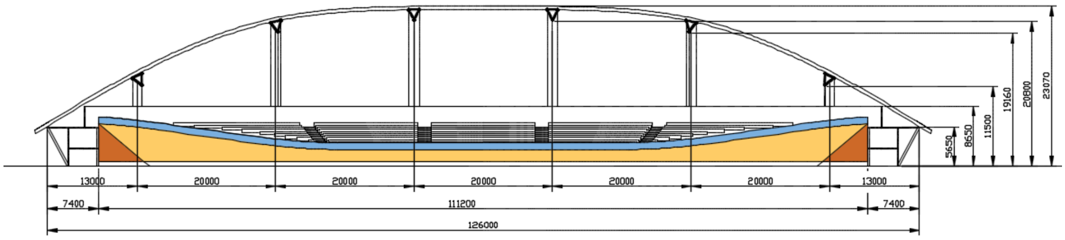


Figure 3. Section of the arch-type steel roof of the velodrome
in a ongitudinal direction [9]

Cross-sections of the arch in the central pair are placed in a vertical position. Cross-sections of two other pairs are placed with inclination, which is necessary to provide the spherical shape of the roof. The behaviour of the central pair will only be considered in the current investigation because this pair has the maximum span, maximum height, and the heaviest load respectively.

Approach to problem solution

The behaviour of the trihedral lattice steel arch with a triangular web was investigated for a static case of loading [10]. The structure is considered under the impact of permanent (dead weight) and variable loads (snow and wind), which were determined by the recommendation of EN 1991. The choice of the preferable structural solution and behaviour analysis for the trihedral lattice steel arch with a triangular web is carried out for three static schemes [11]: fixed arch, double-hinged arch, and three-hinged arch (see Figure 4).

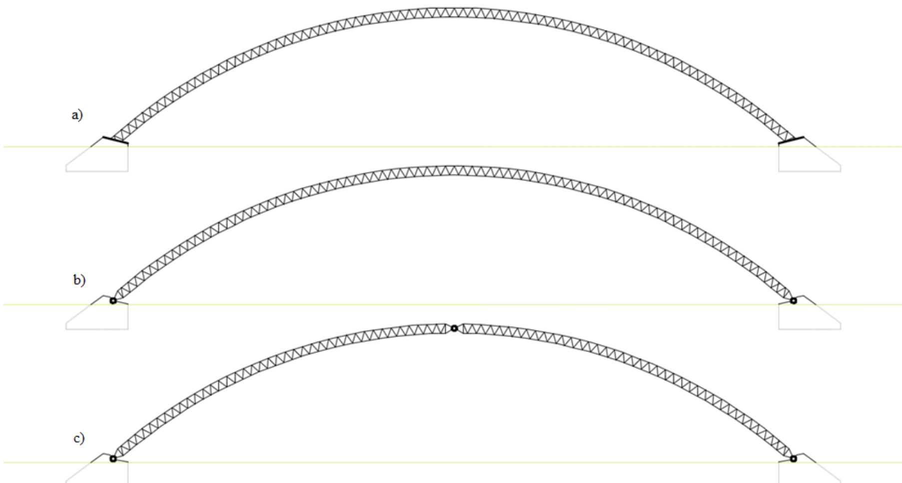


Figure 4. Static schemes of the trihedral lattice steel arch with a triangular web:
***a)* fixed arch; *b)* double-hinged arch; *c)* three-hinged arch [8]**

Three numerical models were created with the software Autodesk Robot Structural Analysis Professional 2015 to investigate the three mentioned variants of the trihedral lattice steel arch with a triangular web [12]. The current investigation is carried out in the following stages:

- Development of a numerical model of the trihedral lattice steel arch;
- Modelling of load actions(symmetric and asymmetric);
- Global analysis of the trihedral lattice steel arch using the developed numerical model;
- Determination of the elements' cross-sections and correction of the developed model if necessary [13];
- Behaviour analysis with the developed numerical model [14].

Internal forces, strains, and stresses, acting in the elements of chords and lattices, such as displacements of the arch's supports and nodes under the impact of the design static loads should be determined in the course of the current investigation [15]. The comparison of the mentioned behaviour enables choosing the best static scheme of the considered steel arch.

Numerical result

Three variants of the trihedral lattice steel arch with a triangular web with the span, height, and radius of the neutral axis equal to 109.5, 20.75, and 82.58 m respectively, are considered within the current study [8]. The width of the top chord of the arch is equal to 1.50 m. The depth of the trihedral cross-section and the lengths of the side grains are equal to 1.50 and 1.68 m respectively. The distances between the nodes of the top and bottom chords are equal to 1.515 and 1.485 m respectively. The radiuses of the top and bottom chords are equal to 83.33 and 81.83 m respectively (see Figure 5).

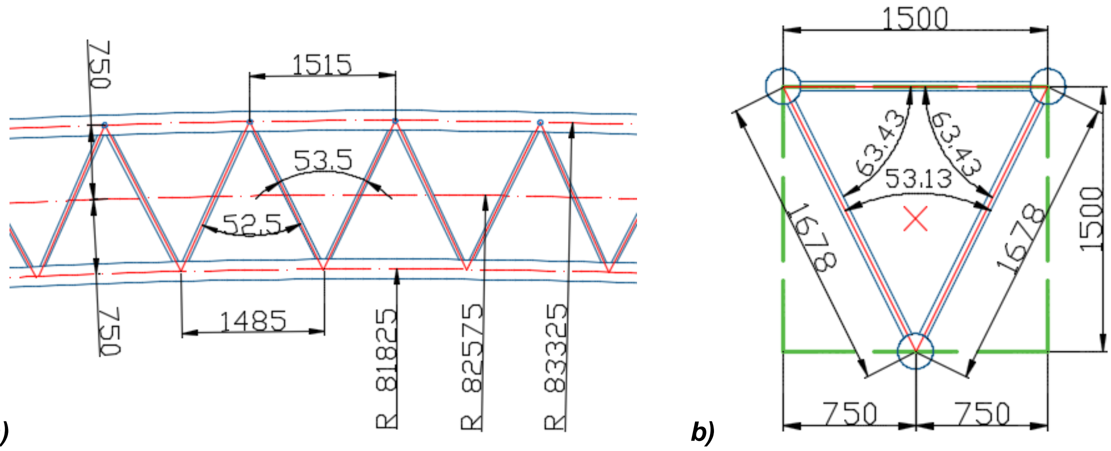


Figure 5. Geometrical scheme of the trihedral lattice steel arch with a triangular web [9]:}
***a)* dimensions of the arch in the longitudinal direction;**
***b)* dimensions of the arch's cross-section**

The length of the arch axis is equal to 119.7 m. Steel of grade S355 is considered as a structural material of the arch [16]. The six steel arches with three different spans are placed with the bay equal to 20 m. The 3D model of the arch-type steel roof is shown in Figure 6.

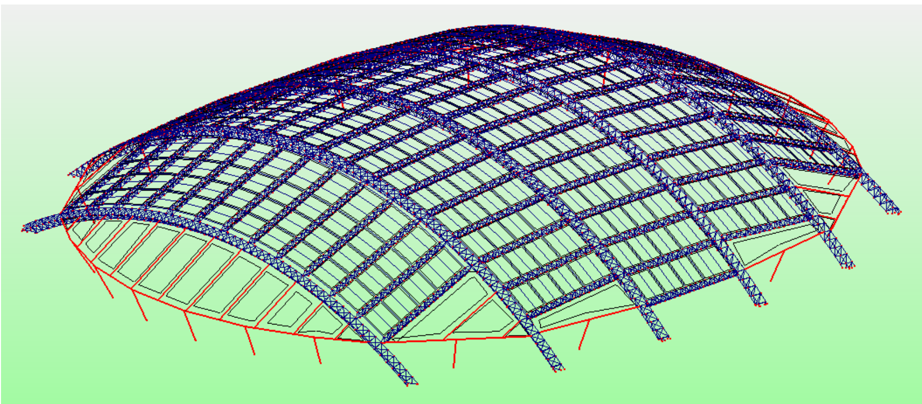


Figure 6. 3D model of the arch-type steel roof [9]

Additional purlins are placed with the bay equal to 2 m. A simple beam is considered as a static scheme of the additional purlins. Cladding panels work in both directions and are based on the main and additional purlins [17].

The structure was analysed at the static action of permanent, snow, and wind loads [18]. Snow and wind loads were determined for the city of Riga. Two variants of the snow load action were considered: undrifted and drifted ones. The design value of the surface snow load was determined by equation 1 [19]:

$$s_d = \mu_3 \cdot C_e \cdot C_t \cdot s_k \cdot \gamma_f \cdot 1{,}34, \quad (1)$$

where s_k is a characteristic value of the snow surface load; C_e is an exposure coefficient; C_t is a thermal coefficient; γ_f is safety factors; μ_3 shows factors, which allow for the roof's shape influence on the snow load; 1,34 are factors, which take into account the influence of the cladding panels' works on the snow load.

Equation 1 is written for the case of the drifted snow load. Factors μ_3 should be replaced with μ_1 in the case of the undrifted snow load. The characteristic value of the snow surface load was equal to 1.25 kPa. The safety factors were equal to 1.50. The thermal and exposure coefficients both were equal to 1.0. Three variants of the drifted snow load were considered (see Figure 7).

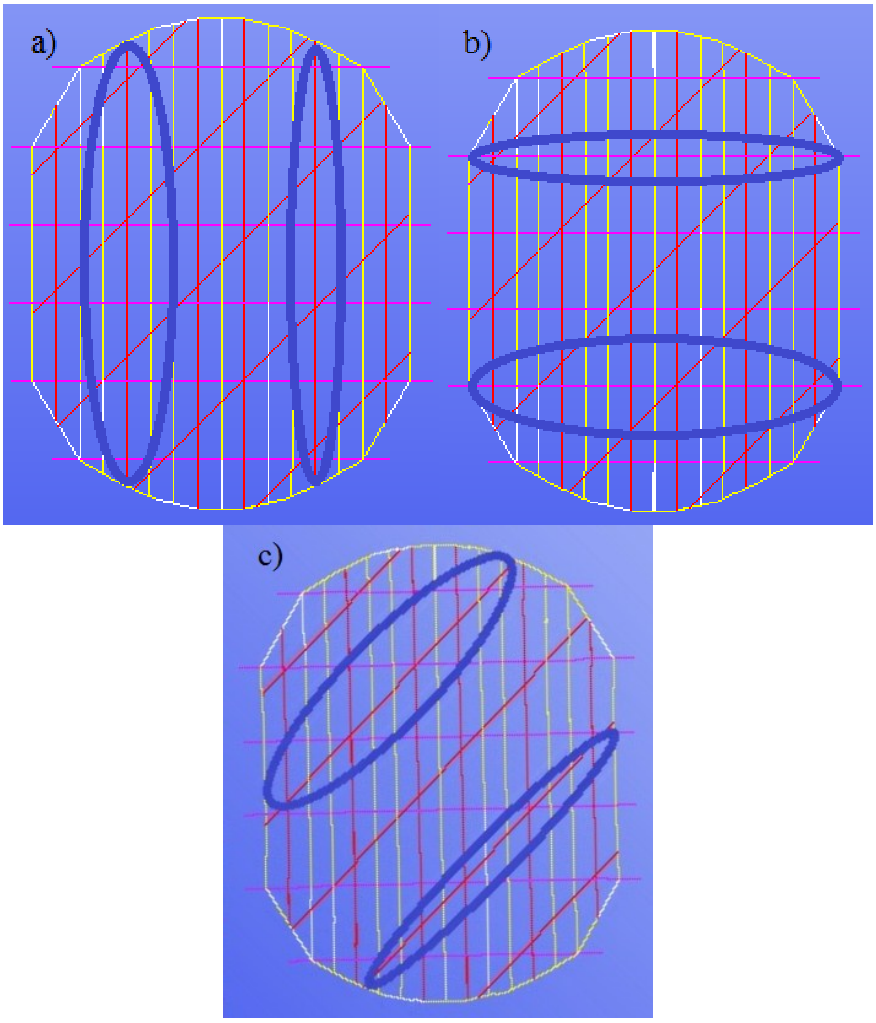


Figure 7. Variants of the drifted snow load: a) wind blows in the longitudinal direction; b) wind blows in the transversal direction; c) wind blows in the diagonal direction [9]

All the variants of snow load were formed under the impact of the wind which blows in the transversal, longitudinal, and diagonal directions respectively [20].

The wind load upon the roof was determined with the software Autodesk Robot Structural Analysis Professional 2015 for the cases when the wind blows in transversal, longitudinal, and diagonal directions which form angles 0°, 45°, and 90° with the longitudinal axis of the structure (see Figure 8) [21].

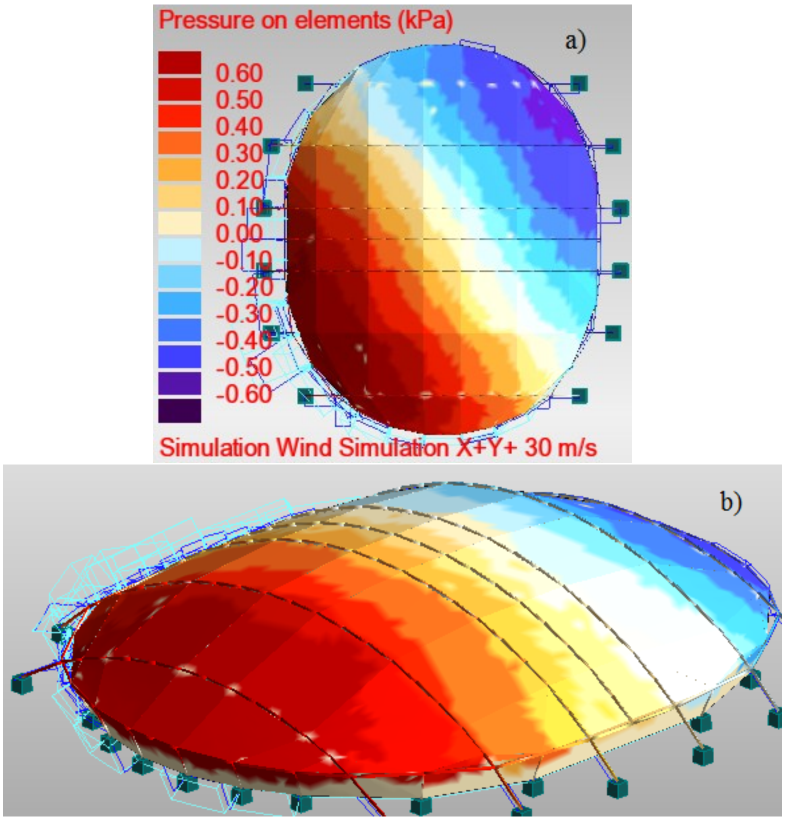


Figure 8. Values of the wind load: a) wind blows in the longitudinal direction; b) wind blows in the transversal direction [9]

The wind load was determined for the basic wind velocity equal to 20 m/s. The corresponding value of the basic wind velocity pressure was equal to 0.24 kPa [22].

The characteristic value of the roofing panels was taken 0.35 kPa [8].

The values of the maximum stresses in the main load-bearing members of the trihedral lattice steel arch were obtained with the software Autodesk Robot Structural Analysis Professional 2015 for the fixed arch, double-hinged arch and three-hinged arch [23]. The values of normal stresses in the bottom chord of the trihedral lattice steel arch are given in Figures 9, 10, and 11 for arches with spans equal to 84, 105.5, and 109.5 m respectively. The values were obtained for the load combination including permanent and accidental snow loads.

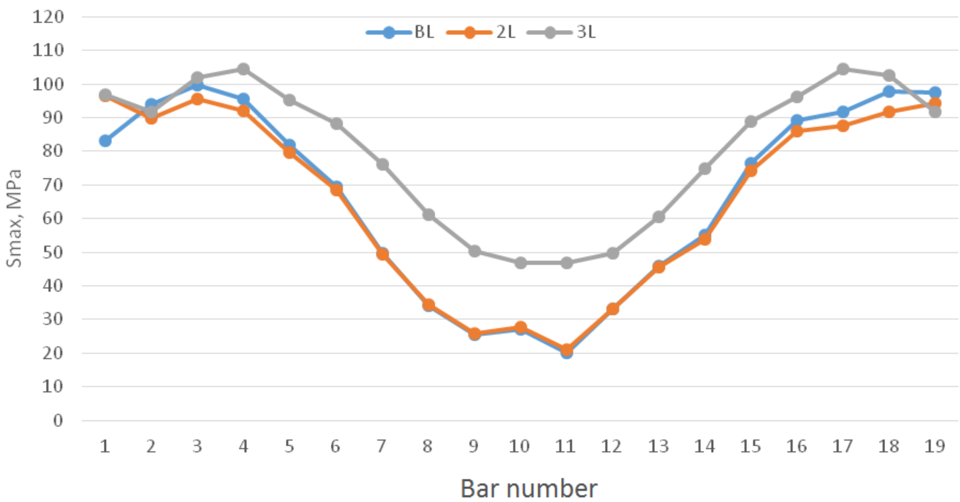


Figure 9. Values of normal stresses in the bottom chord of the trihedral lattice steel arch for the load combination including permanent and accidental snow loads for the arch with the span equal to 84 m; B1 – fixed arch, L2 – double-hinged arch, L3 – three-hinged arch

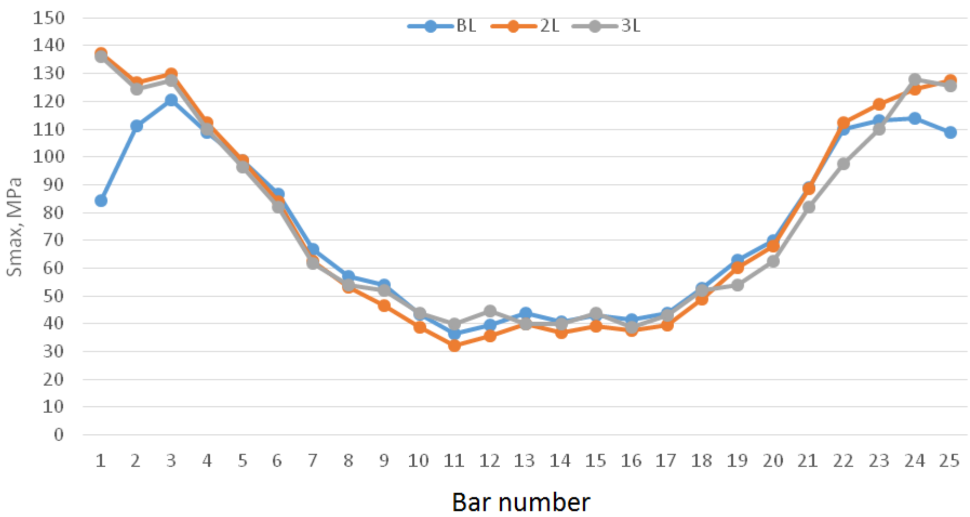


Figure 10. Values of normal stresses in the bottom chord of the trihedral lattice steel arch for the load combination including permanent and accidental snow loads for the arch with the span equal to 105.5 m

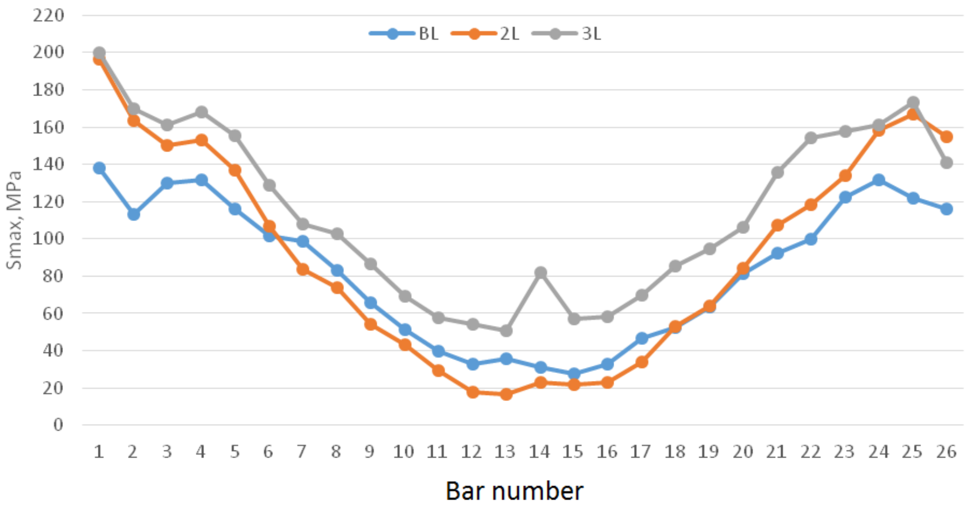


Figure 11. Values of normal stresses in the bottom chord of the trihedral lattice steel arch for the load combination including permanent and accidental snow loads for the arch with the span equal to 109.5 m.

The numeration of the elements is given in Figure 12.

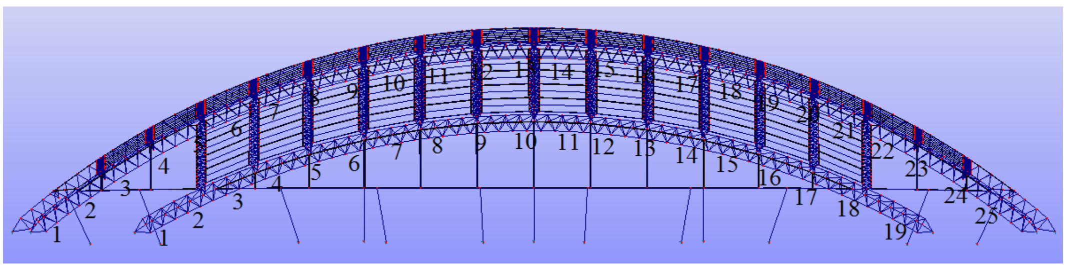


Figure 12. Numeration of elements of the trihedral lattice steel arch [6]

Values of normal stresses in the members of the bottom chord of the trihedral lattice steel arch, with the span equal to 84 m, change within the limits from 20 to 100 MPa, from 20 to 95 MPa, and from 47 to 105 MPa for the fixed, double-hinged and three-hinged arches respectively. The values of normal stresses for the arches with the spans equal to 105.5 and 109.5 m change within the limits from 32 to 138 MPa, and from 19 to 200 MPa respectively. The values of normal stresses in the bottom chord of the trihedral lattice steel arch are given in Figures 13, 14, and 15 for the load combination including the permanent drifted snow load and wind loads.

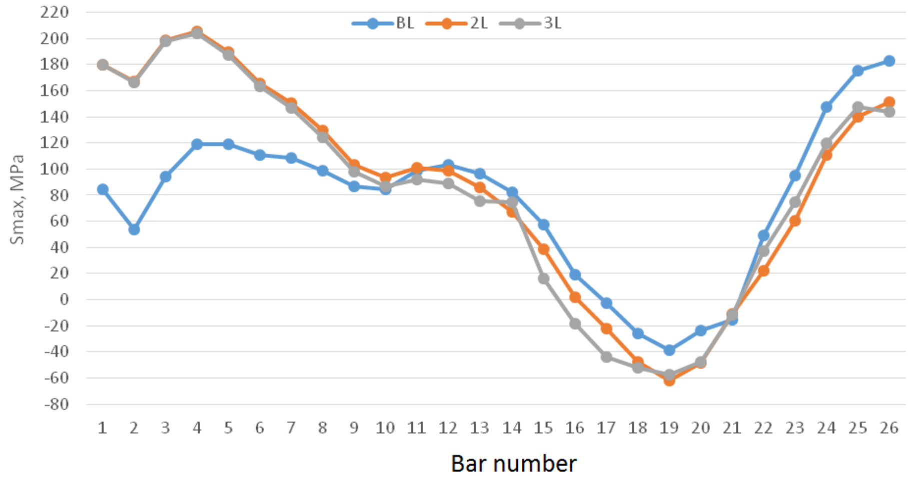


Figure 13. Values of the normal stresses in the bottom chord of the trihedral lattice steel arch for the load combination including the permanent drifted snow load and wind loads for the arch with the span equal to 84 m

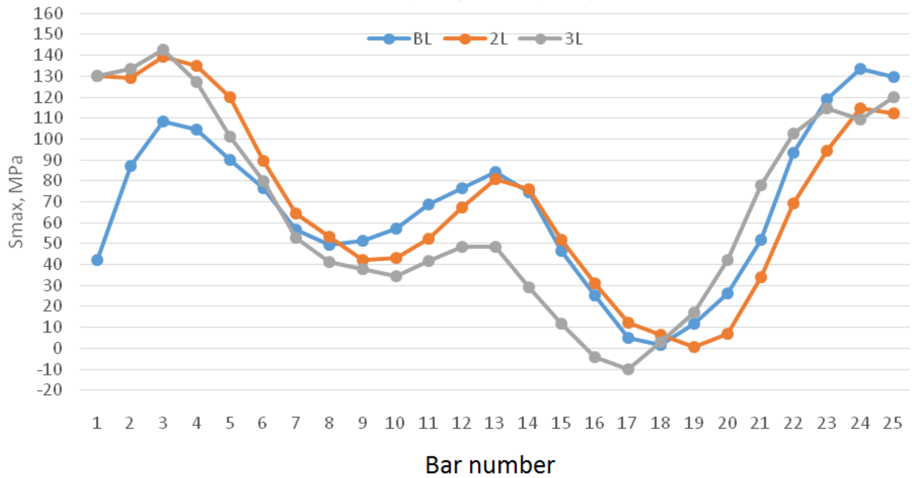


Figure 14. Values of the normal stresses in the bottom chord of the trihedral lattice steel arch for the load combination including the permanent drifted snow load and wind loads for the arch with the span equal to 105.5 m

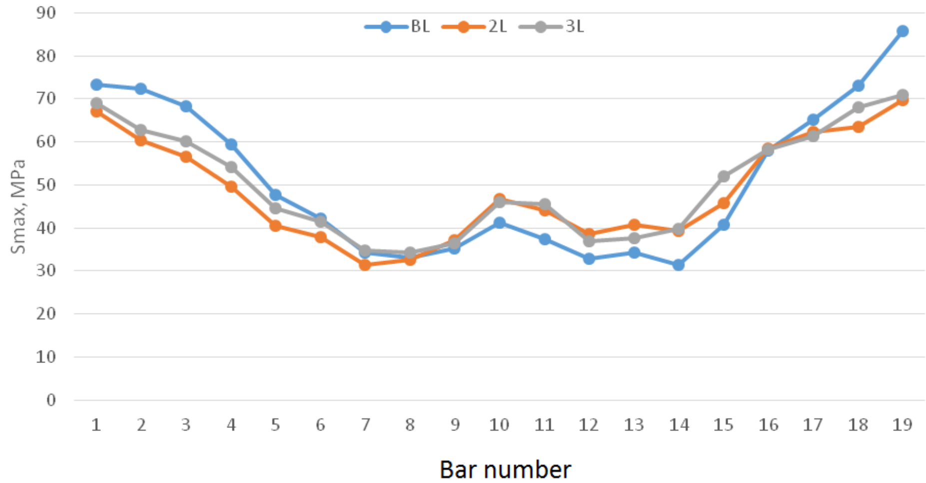


Figure 15. Values of the normal stresses in the bottom chord of the trihedral lattice steel arch for the load combination including the permanent drifted snow load and wind loads for the arch with the span equal to 109.5 m

Values of the normal stresses in the members of the bottom chord of the trihedral lattice steel arch, with the span equal to 84 m, change within the limits from 74 to 85 MPa, from 32 to 72 MPa, and from 35 to 72 MPa for the fixed, double-hinged, and three-hinged arches respectively. The maximum values of normal stresses for the arches with the spans equal to 105.5 and 109.5 m are equal to 142 and 204 MPa respectively. The values of the normal stresses in the bottom chord of the trihedral lattice steel arch are given in Figure 10 for the load combination including the permanent drifted snow load and wind loads. The wind load is acting in the transversal direction.

The distribution of normal stresses between the top and bottom chords of the trihedral lattice steel arch is given in Figures 16, 17, and 18 for the arch with the span equal to 84 m.

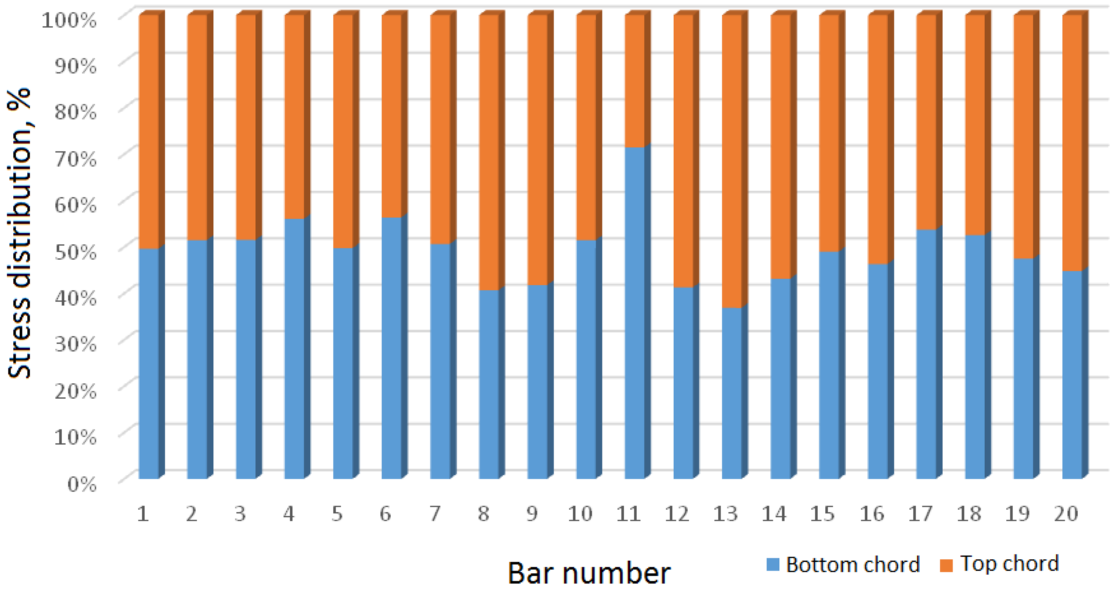


Figure 16. Distribution of normal stresses between the top and bottom chord of the trihedral lattice steel arch with the span equal to 84 m for the load combination including permanent and accidental snow loads for the fixed arch

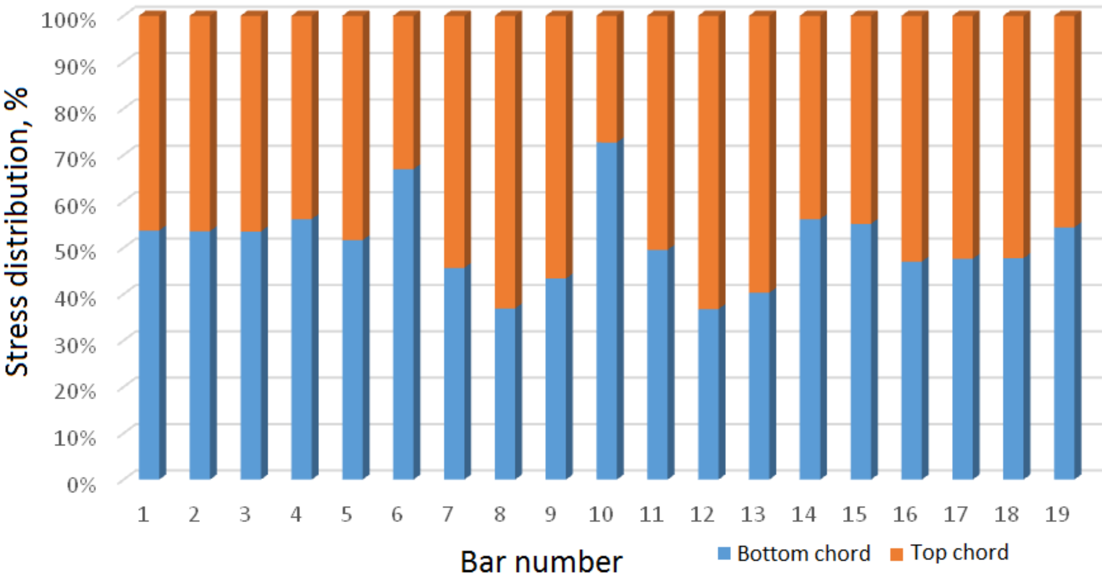


Figure 17. Distribution of normal stresses between the top and bottom chord of the trihedral lattice steel arch with the span equal to 84 m for the load combination including permanent and accidental snow loads for the double-hinged arch

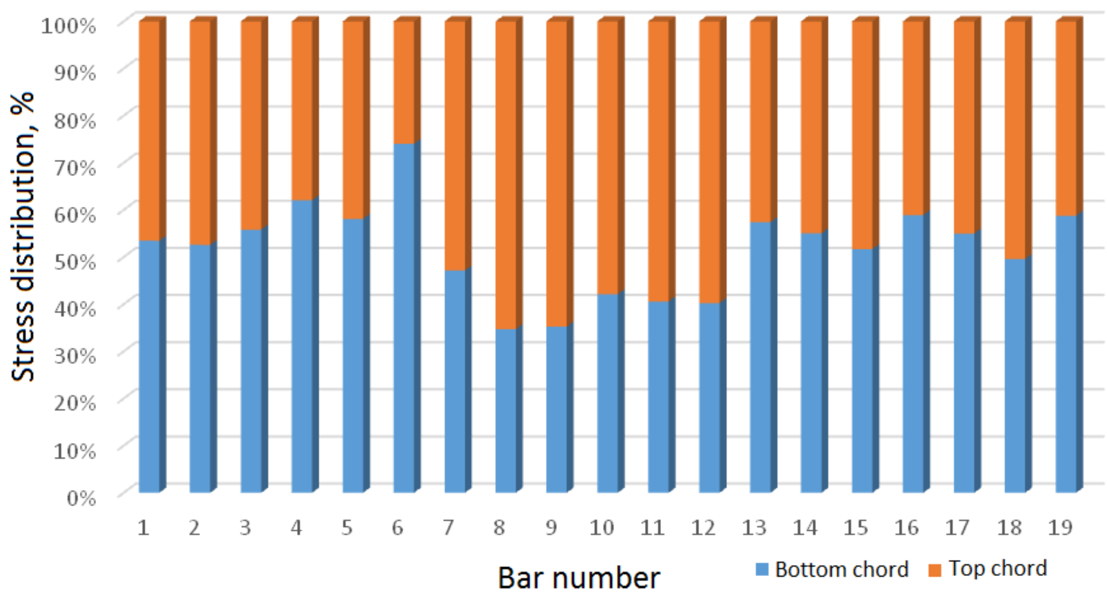


Figure 18. Distribution of normal stresses between the top and bottom chord of the trihedral lattice steel arch with the span equal to 84 m for the load combination including permanent and accidental snow loads for the three-hinged arch

The distribution of normal stresses between the top and bottom chords of the trihedral lattice steel arch with the spans equal to 105.5 and 109.5 m is close to the distribution shown in Figures 16, 17, and 18.

Values of the maximum vertical displacements of the considered steel arches were determined for five load combinations and shown in Figures 19, 20, and 21. The maximum vertical displacements were determined in halves and quarters of the arch spans. The nodes designations, where the maximum vertical displacements were determined, are given in Figure 22.

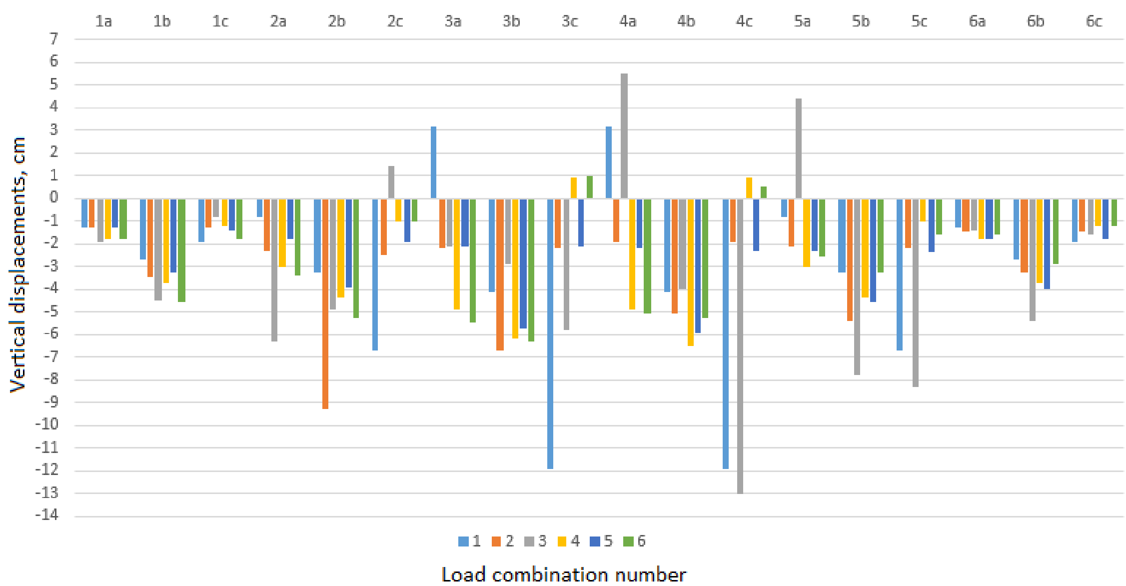


Figure 19. The maximum vertical displacements of the steel arch with the span equal to 84 m for the load combinations including permanent, snow, and wind loads for the fixed arch

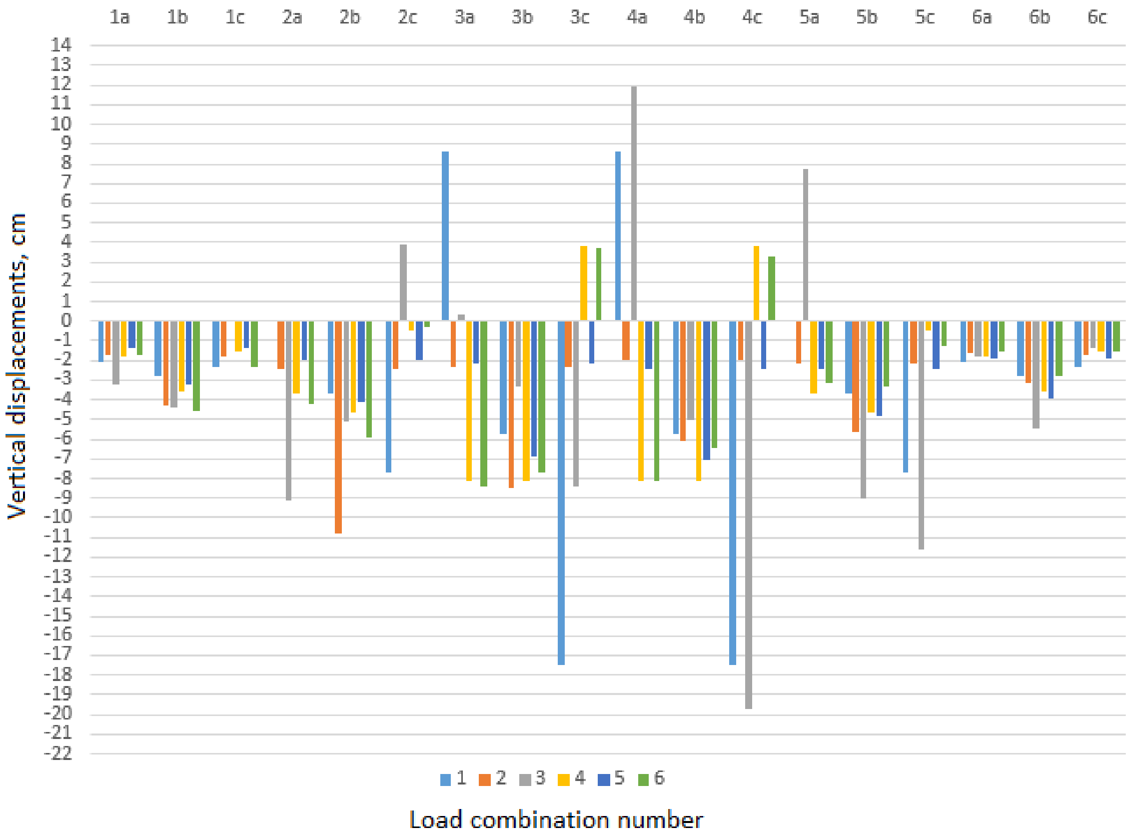


Figure 20. The maximum vertical displacements of the steel arch with the span equal to 84 m for the load combinations including permanent, snow, and wind loads for the double-hinged arch

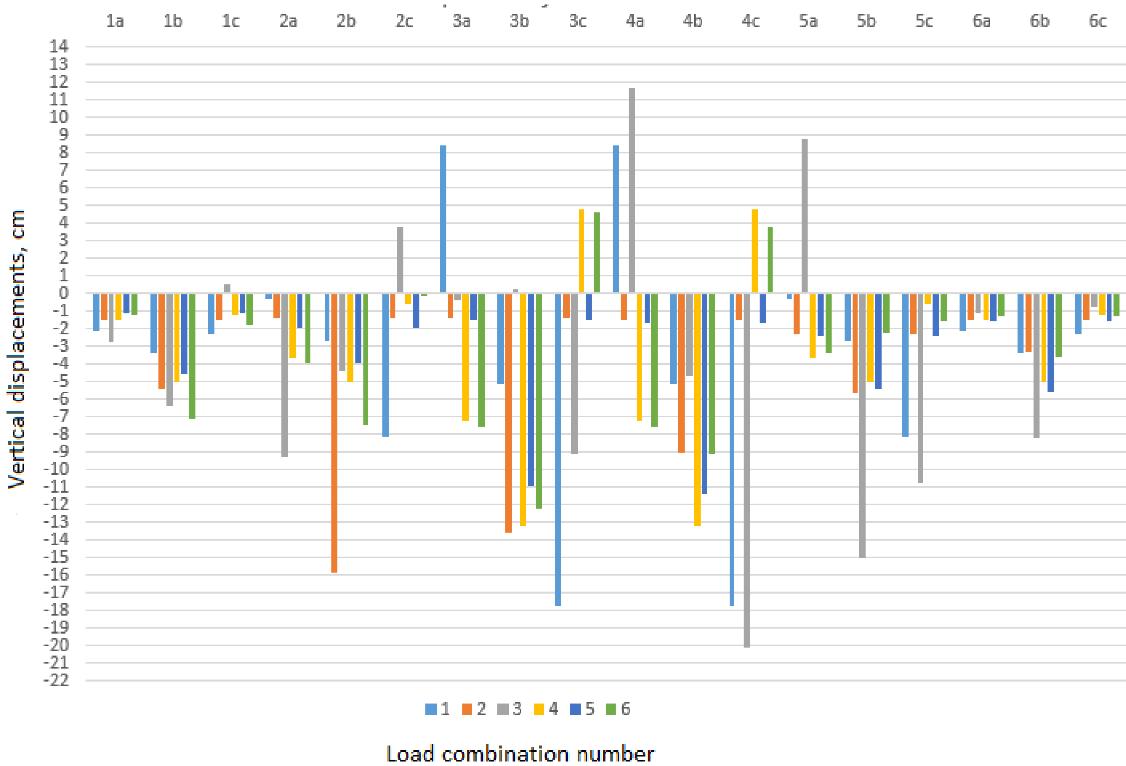


Figure 21. The maximum vertical displacements of the steel arch with the span equal to 84 m for the load combinations including permanent, snow, and wind loads for the three-hinged arch

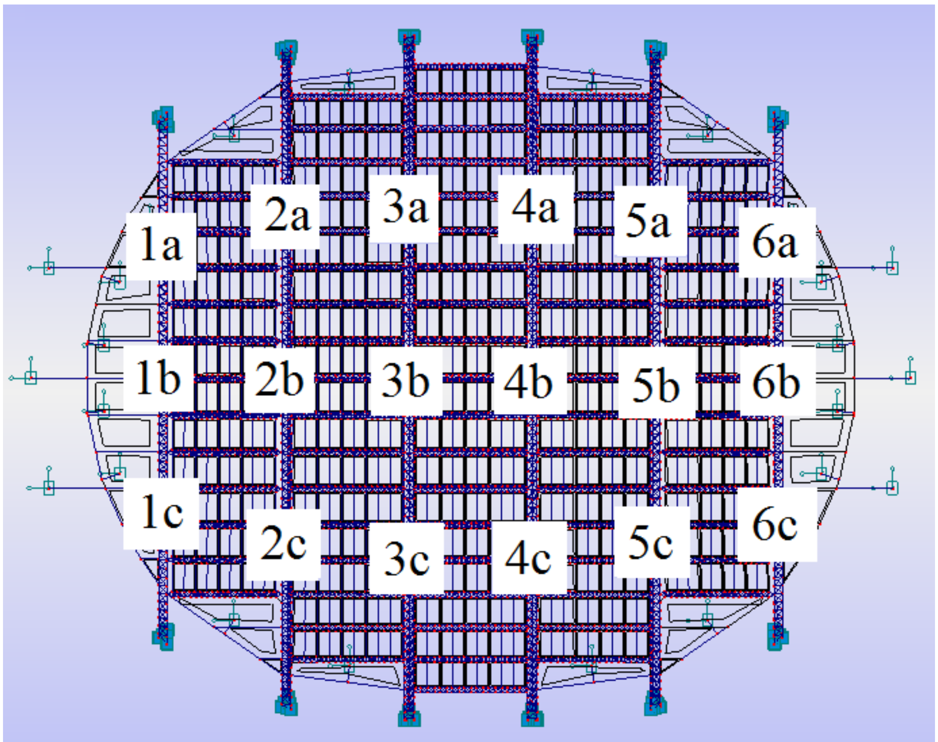


Figure 22. Nodes designations, where the maximum vertical displacements were determined [6]

Five combinations of the loads were formed on the basis of permanent load, drifted and undrifted snow load, and wind, which blows in the transversal, longitudinal, and diagonal directions. The first load combination includes the dead weight of the structure, drifted snow in the longitudinal direction, and wind in the diagonal direction. The second load combination includes the dead weight, undrifted snow load in the longitudinal direction, and wind in the transversal direction. The third load combination includes the dead weight of the structure, drifted snow in the longitudinal direction, and wind in the transversal direction. The fourth load combination includes the dead weight, wind in the diagonal direction, and undrifted snow in the transversal direction. The fifth load combination includes the dead weight, wind in the longitudinal direction, and undrifted snow in the longitudinal direction. The maximum vertical displacements were determined for the fixed arch, double-hinged arch, and three-hinged arch.

The obtained values of the maximum vertical displacements of the steel arches change within the limits of 12 cm up to 20 cm down. The maximum values of the vertical displacements were obtained for the three-hinged arch. The maximum values of the vertical displacements for the double-hinged arch are comparable with the values obtained for the three-hinged arch.

The results of the conducted static analysis allows us to make a conclusion that the preferable structural scheme is the fixed arch.

Conclusions

The structural solution for the arch-type steel roof of the velodrome was chosen. The trihedral lattice steel arch with a triangular web and the maximum span equal to 109.5 m is considered as the main load-carrying structure of the steel roof of the velodrome and as the most appropriate for the purposes of this building. The distribution of internal forces and stresses in the trihedral lattice steel arch with a triangular web such as displacements under the impact of the design loads were investigated for the fixed, double-hinged, and three-hinged static schemes. It was stated that the preferable structural scheme is the fixed arch.

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