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Vnukovo-1 airport building in Moscow. The load bearing steel structures of grid-type roof. Features of design concepts, manufacture and erection.

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Abstract

The Vnukovo-1 air-terminal complex building of irregular curved configuration in plan in Moscow has the following basic overall dimensions: about 600 m in length and from 70 m to 300 m by cross-section. This building construction was begun in 2006. The manufacture and erection of the roof steel structures were started in 2008. The main conditions for design of roof framing in accordance with a design task are the following: warm building; snow is not removed from the roof; organized water outlet from the roof; the roof enclosing structures are partially translucent; the main load-bearing elements of the roof steel structures are made from the tube round billets; production of the roof framings and their erection are executed by the Russian manufacturers and construction and erection organizations. The report acquaints the reader with design features of the given unique structure as well as those of fabrication and erection of the load-bearing steel structures of roof by the example of one temperature block with plan dimensions of 125x100 m.

Kewwords: Grid shell, steel structures, roof, nodal elements, loads, calculations, manufacture, erection.

1. Design features

Construction of Vnukovo-1 air-terminal complex building was begun in Moscow in 2006. The building of irregular curved configuration in plan and throughout the height has the following overall dimensions: about 600 m in length and from 70 m to 300 m by cross-section (Figure 1).

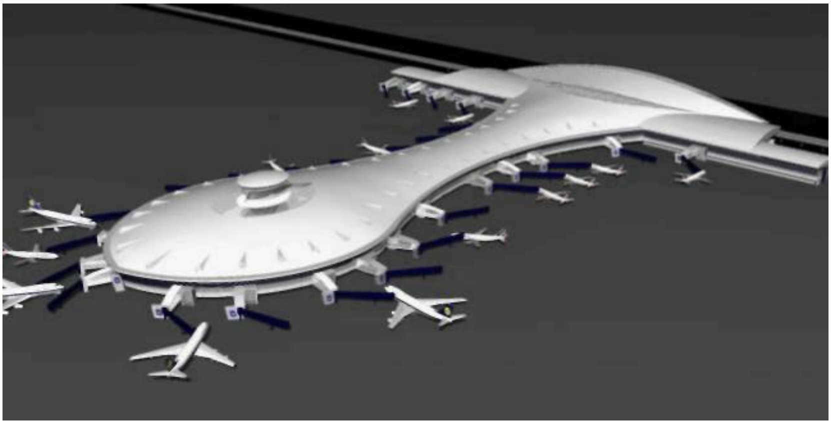


Figure 1. General view of Vnukovo-1 air-terminal complex building in Moscow

The complex three-dimensional configuration of roof (see Figure 1) demanded the special development of its geometry so that later there was made possible not only to fit into this geometry, but also to unify the major part of elements of the load-bearing steel structures.

Geometrically the roof is a rotation surface articulated from 6 different shells of positive, zero and negative Gaussian curvature. It consists of a longitudinal part formed by rotation of compound curve relative to axis lying in the symmetry plane and parallel to a symmetry axis of structure and cylindrical parts with axes of rotation located at right angles to the symmetry plane of structure. At the same time the cylindrical shells mate with the conical one forming the compound intersectional curves (on each side of longitudinal symmetry axis of structure – see Figure 1).

The whole roof construction consists of 9 temperature blocks divided by expansion joints (Figure 2).

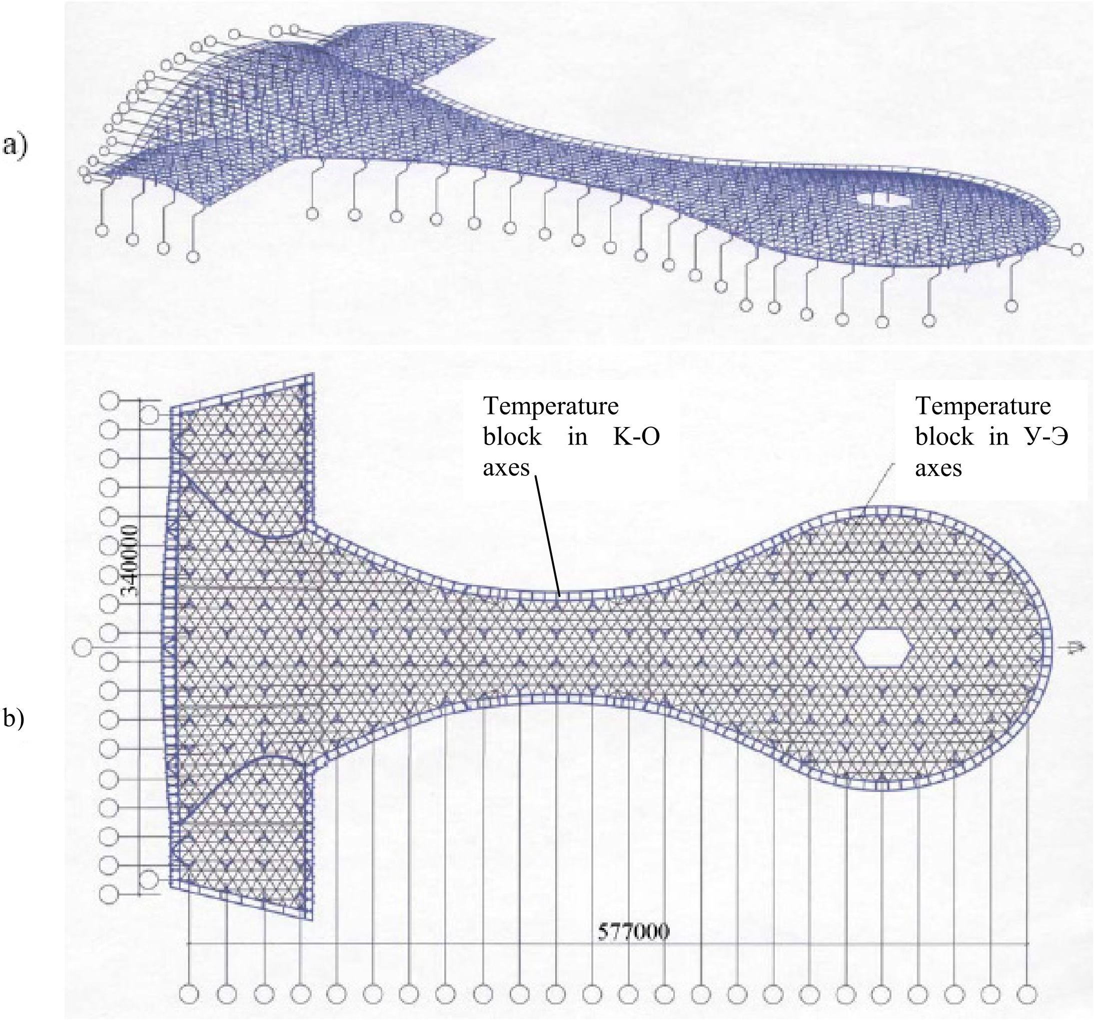


Figure.2. Structural scheme of roof

a) axonometry of roof
b) plan of roof

The overall dimensions of temperature blocks do not exceed the values of 140×100 m, with the exception of block in axes У-Э that measures about 200×200 m (Figure 2a). However, in the last case in the center of temperature block the reinforced concrete control tower, on which according to project the roof elements are held through the hinged movable supports, penetrates through the roof. That is to say, in this block the thermal deformations also occur in the plane of roof along the lengths not exceeding 100 m.

The roof structure of each temperature block is identical and represents a two-chord grid shell with a triangular mesh and lengths of its sides generally from 7 to 8.5 meters. Each of these sides is a flat welded truss 2.5 m in height factory-built from the round tube billets.

The whole construction of roof is held on the reinforced-concrete columns. The column grid is mainly orthogonal and has 20 x 25m parameters.

Supporting of a grid shell on the reinforced-concrete columns is carried out by way of bundles consisting of 3 slant legs made from the round tube billets with apexes of bundles in the nodes of grid shell and on the column. In the aggregate the grid shell and bundles of slant legs generate a three-dimensional frame within a temperature block (Figure 3).

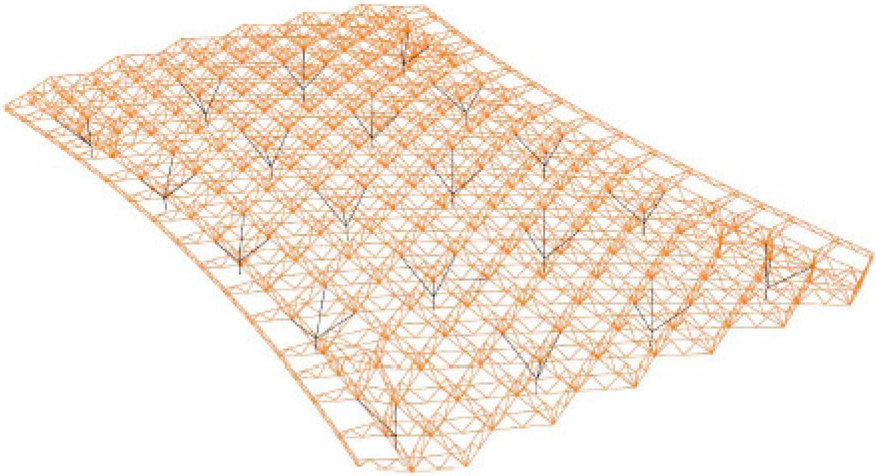


Figure 3. Scheme of grid shell supporting on the reinforced-concrete columns. Axonometry.

The above-described structure realized in geometry of surface of rotation makes it possible to optimize the geometric parameters of grid. So, all the main nodal and rod-type elements lying in a single layer between two adjacent planes traced perpendicularly to the axis of rotation are equal in lengths of rod-type elements and angles between gussets of nodal elements. 2 variants of grid partitioning are made possible: with unification of the nodal elements for angles between gussets and with that for lengths of the rod-type elements. In the first case the number of geometrical types of the main nodal elements lies within 12 – 15. In the second case the number of geometrical types of the main rod-type elements accounts for 21 – 24.

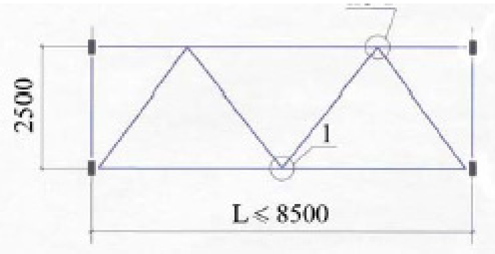
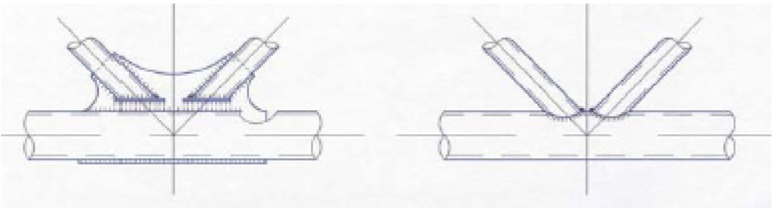
a)	Trusses “Φ” in l 
b)	Node l (Variant 1) Node l (Variant 2) 

Figure 4. Type truss of roof

a) scheme of truss; b) variants of internal nodes of truss

The welded truss 2.5 m in height factory-built from the round tube billets is an element of grid shell (Figure 4).

The grids concur in nodes as a rule in 6 trusses which are fastened by friction joints using high-strength bolts at a level of chords in the factory-built nodal details. The nodal details are hexactinal “stars”, each ray of which is a vertical gusset with bolt-holes (Figure 5).

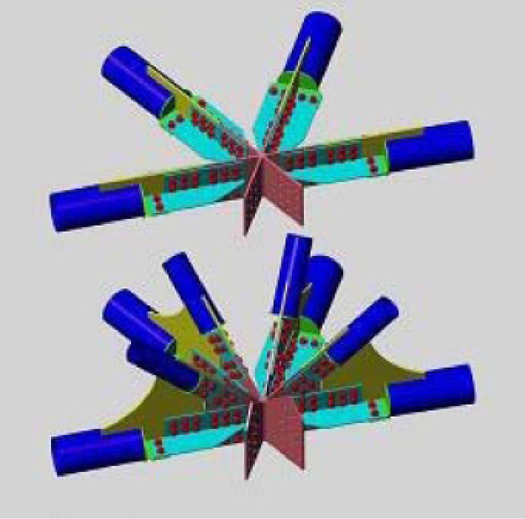
a)	
b)	

Figure 5. Nodal elements of roof grid

a) node of shell frame elements at a level of upper truss chords;
b) node of shell frame elements at a level of lower truss chords

The work of nodal elements in the system was separately investigated by way of bundled software ANSYS and NASTRAN both in the linear statement and with consideration for plasticity (Figure 6).

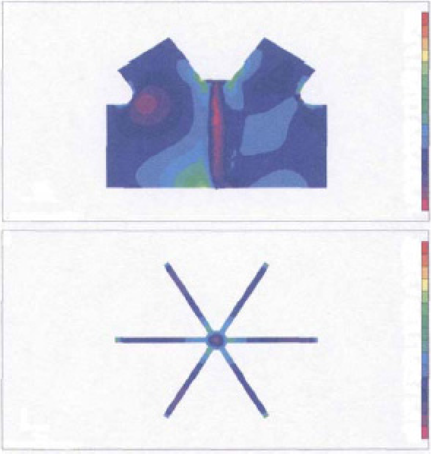


Figure 6. Stressed state pattern in the nodal detail

Besides numerical simulation, there were carried out the full-scale tests of nodal elements which confirmed feasibility of their manufacture and serviceability.

The above-described structure realized in geometry of surface of rotation made it possible to carry out optimization of the geometric parameters of grid with unification of nodal elements for angles between gussets. In this case the number of geometrical types of the main nodal elements lies within 12 – 15.

2. Loads and actions

To calculate the load-bearing steel structures of roof, it is necessary to select the corresponding combinations on the basis of the following design loads:

- constant load, i.e. dead load of roof and its framings: about 205 kg/m^2;
- temporary permanently acting loads, i.e. manufacturing loads and counter ceilings – overall no less than 60 kg/m^2;
- temporary short-duration loads, i.e. climatic loads (wind, snow and temperature).

In our case the wind forces are insignificant for the roof framings.
The design temperature difference was taken equal to ± 50°C.

The design uniform snow load was taken equal to 200 kg/m^2. However, the complicated roof configuration demanded definition of snow deposition on the roof (i.e. definition of coefficients "μ") by means of the wind-tunnel tests of building model at the different angles of wind attack.
One of the obtained results is presented in Figure 7.

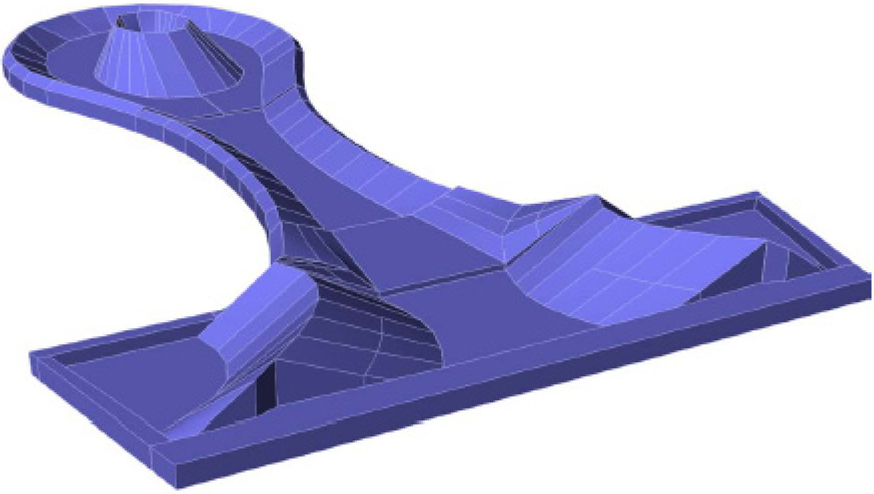


Figure 7. Scheme of snow deposition distribution on the roof
according to results of the wind-tunnel tests of model.
Axonometry

As it follows from Figure 7, in the given case a coefficient μ is ≤ 3.5 (in the valley zone) and ≤ 4 in the projecting control tower - roof mating zone. Thereby, the design snow load is substantially non-uniform and reaches the following values:

$200 \times 3.5 = 700$ kg/m^2 in the valley zone

$200 \times 4 = 800$ kg/m^2 in the zone of control tower.

Extent of structure responsibility is taken into account using a coefficient $\gamma_n = 1.2$, by which all forces and displacements obtained in the static calculation are multiplied.

3. Some features of calculation

The calculation features of the above-described structural scheme are determined essentially by three main factors:

- an irregular three-dimensional configuration of roof;
- a grid-type structure of the load-bearing steel structure system;
- a very great quantity of nodes and elements in the system.

Since as a result of the wind-tunnel tests of roof model we obtained a very irregular configuration of snow depositions on the roof, there emerged a need to develop a special program on treatment of snow loads and definition of the design nodal snow loads.

The static calculation of structure was carried out with the use of bundled software MicroFE, NASTRAN and KATRAN. In two last versions a block for definition of design forces in respect to the worst combinations of loads was absent. It required a development of special program, where there was realized a principle permitting the user to fix a criterion for selection of Design Force Combinations.

The calculation results for individual loadings obtained from the bundled software, description of the loads-combination coefficients interaction in the form of graph and description of criterions for selection of Design Force Combinations were used as the basic data for this program.

The performed static calculation showed very adverse effects of ±50°C temperature loadings expressed in the great horizontal reactions reaching the values about 200 tf, while the thrust forces from a vertical load did not exceed 50 – 60 tf.

Considering impossibility of further downsizing of temperature blocks the constructive – nonlinear connections were introduced into structure in the form of friction joints of chords and nodal details with out-of-round holes. The connection demonstrates the elastic behaviour, until its force reaches the critical value determinable by the number of bolts, coefficient of friction and bolt tension force. Then slippage occurs within the out-of-roundness of holes and force in the chord does not increase anymore. Locating these nonlinear connections in the places with minimum forces from a vertical load we succeeded in decreasing design thrust forces up to the values of less than 100 tf.

In the design scheme these connections were modeled for MicroFE by standard ones with a work diagram $P/\Delta L$ by type of Prandtl one for an ideal elasto-plastic body and for NASTRAN by special elements with nonlinear elasto-plastic diagram of material σ/ε.

By itself a great quantity of nodes and elements in the system set a task that consists in automation of processes of unification and optimization for sections of the load-bearing construction elements that also demanded a development of the special-purpose programs.

4. Some features of nodal details - "stars" manufacture

As it has been noted above, the nodal details are hexactional "stars", each ray of which is a vertical gusset with bolt-holes.

In addition, depending on angles of approach of the truss chords to the nodal detail 3 structural types of “stars” are manufactured for an object.

The “star” of type 1 (Figure 8) – a core of nodal detail is a hexactinal “star” with short rays that is made by method of pressing through die (hot-worked profile). The gussets with bolt-holes are butt-seam welded with “star” rays of core by the full-strength flat butt welds. In this case the angles between rays are constant and symmetric on the great area of shell – “stars” of type 1 account for about 85% of all nodal details.

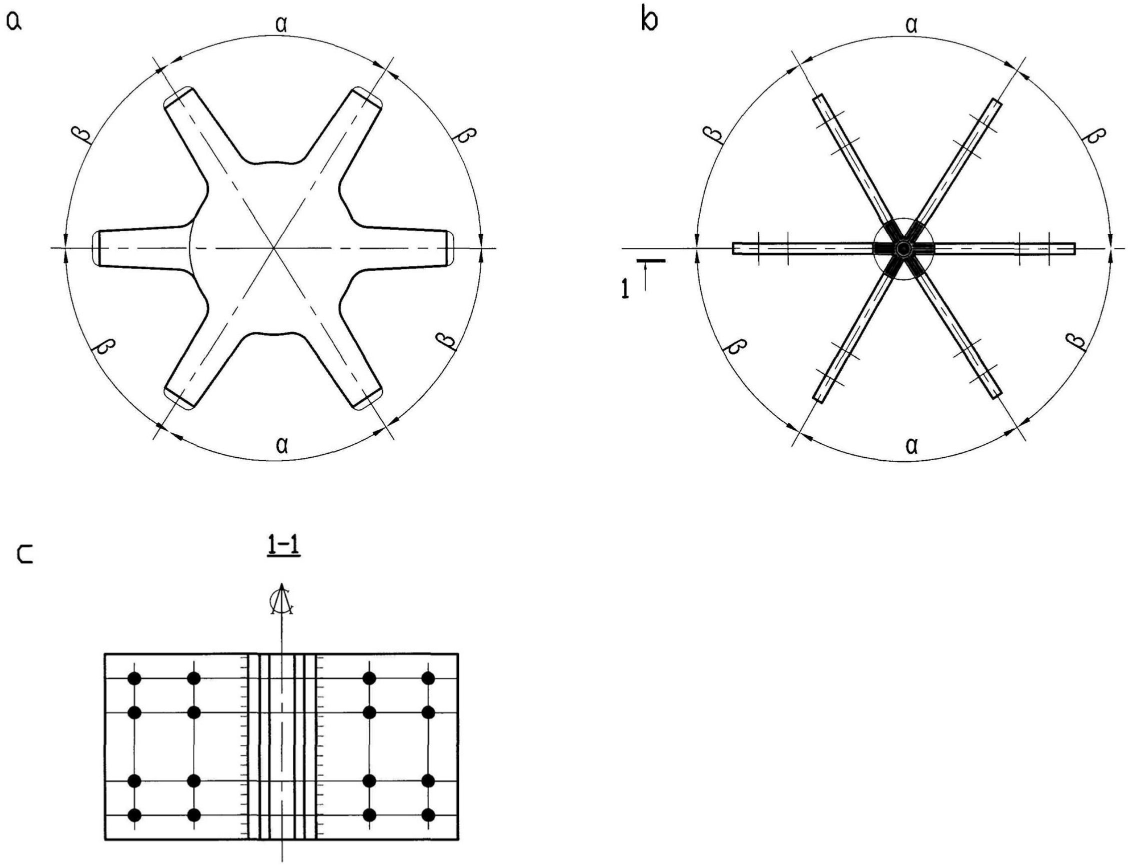


Figure 8. “Star ” of type 1
a) hot-formed core
b, c) “star” of type 1 after manufacture

The “star” of type 2 (Figure 9) – a core of nodal detail is a solid round rod 100 mm in diameter (hot-rolled stock), to which gussets with bolt-holes are fay-welded by the edge welds. In this case the angles between rays are variable and asymmetric - “stars” of type 2 account for about 10% of all nodal details.

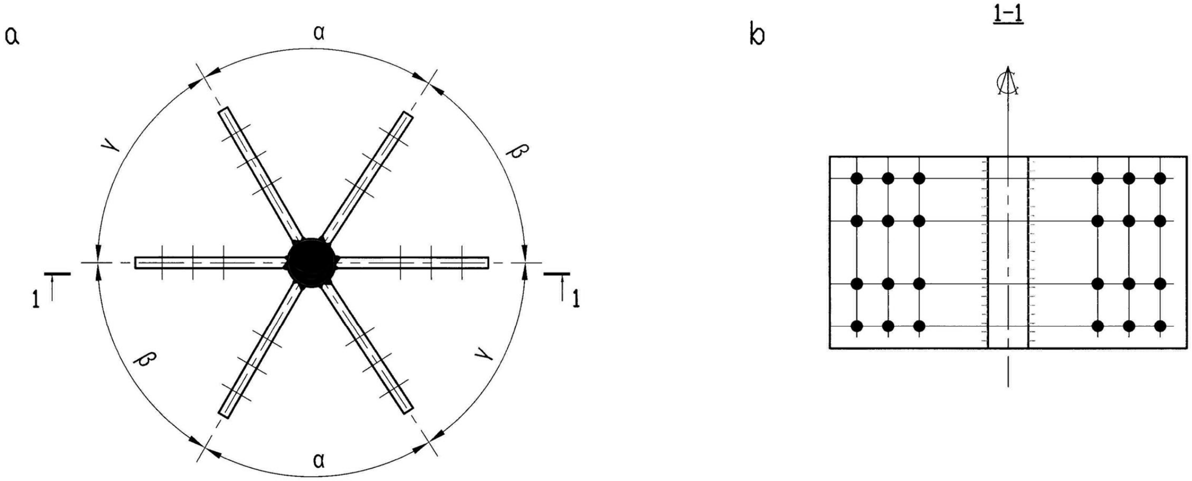


Figure 9. “Star” of type 2 with a core in the form of round rod

The “star” of type 3 (Figure 10) – a core of nodal detail is a thick-walled pipe about 200 mm in diameter, to which gussets with bolt-holes are fay-welded by the fillet welds. In this case the angles between rays are variable and asymmetric and some of them are so small that practically do not allow carrying out welding of gussets on the round rod 100 mm in diameter. At the same time, usage of pipe demands its reinforcement by horizontal diaphragms on top and below to protect from deformations under the influence of compression – tension forces in the chords approaching to the truss node. The “stars” of type 3 account for about 5% of all nodal details.

Since the accuracy of structure assembling during erection depends to a large extent on that of the nodal detail manufacture, the higher demands on this parameter are made to them.

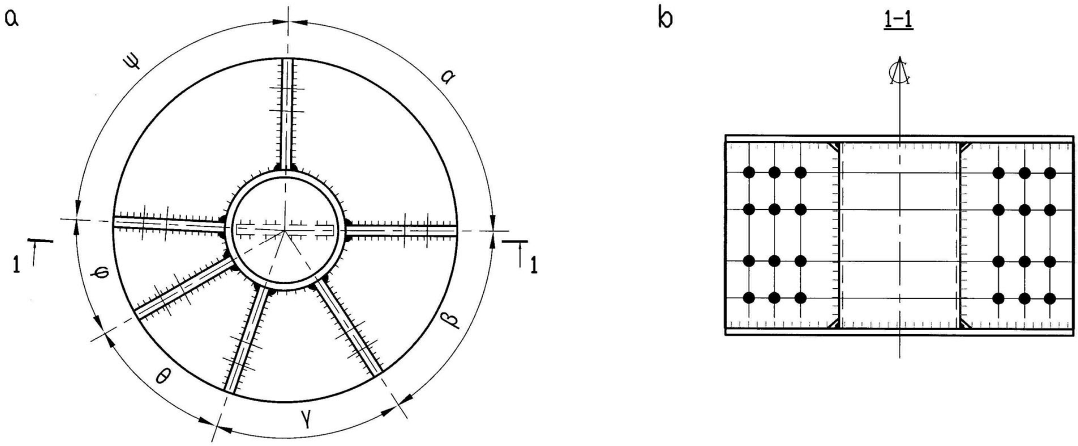


Figure 10. “Star” of type 3 with a core in the form of pipe

The factory manufacture of the nodal elements – welded “stars” is carried out in the jigs. In this case:

1. Maximum deviations of the welded “star” rays for angle of place in plan should not exceed 0 ÷ ±0.1°.

Maximum deviation of the central element of “star” made from a hot-pressed profile for angle of place in plan should not exceed 0 ÷ ±0.5°.

2. Maximum deviations of the hole marks for angle of place in the vertical plane should not exceed 0 ÷ ±0.15°.
3. Maximum deviations from lock-on of hole groups should not exceed 0 ÷ ±0.5°.
4. Maximum deviations from lock-on of hole in the group should not exceed 0 ÷ ±0.2 мм.
5. Maximum deviations in the hole diameter should not exceed 0 ÷ ±0.2 мм. Hole spacing and making are carried out in jig.

In the process of factory manufacture the nodal details are subject to the following heat treatment:

1. The billets in the form of hot-worked profile and hot-rolled rounds of D = 100 mm for a “star” central element are subject to heat treatment: quenching with the following deep drawing. Quenching is carried out in water with temperature of +10 ÷ +30°C after heating to temperature of +890 ÷ +920°C. Drawing is carried out at temperature of +680 ÷ +720°C with ageing of 1.5 ÷ 2.0 hours and the following air cooling.
2. The mechanical properties of heat-treated billets are inspected by tests of check

test pieces for each party of heat treatment.

3. All “stars” with a central element made from round and pipe are subject to heat treatment after welding to remove stresses (drawing): heating to temperature of ±590 ÷ ±620°C with ageing of 1.5 ÷ 2.0 hours and the following air cooling.

Taking account of special responsibility of structure and particular importance of nodal details under consideration for provision of the roof bearing capacity in whole, the “stars” of every type are selectively subject to the full-scale mechanical design force tests.

5. Erection principles

The main principles of the load-bearing steel structures of roof can be demonstrated on the example of central temperature block of roof with overall dimensions of 125x100 m (Block in axes of К - O – see Figure 2).

In connection with irregular three-dimensional configuration and geometry of the roof shell the control assembly of roof is carried out at the manufacturer before output of structures by means of “cards” on the ground with check of space form in the “card”. Dimensions of every “card” in plan correspond to column grid, i.e. 20x25 m.

Figure 11 shows a scheme of К - O block partitioning into assembly “cards”. Enumeration of “cards” shows sequence of erection as well as that of the “cards” structures output from manufacturer.

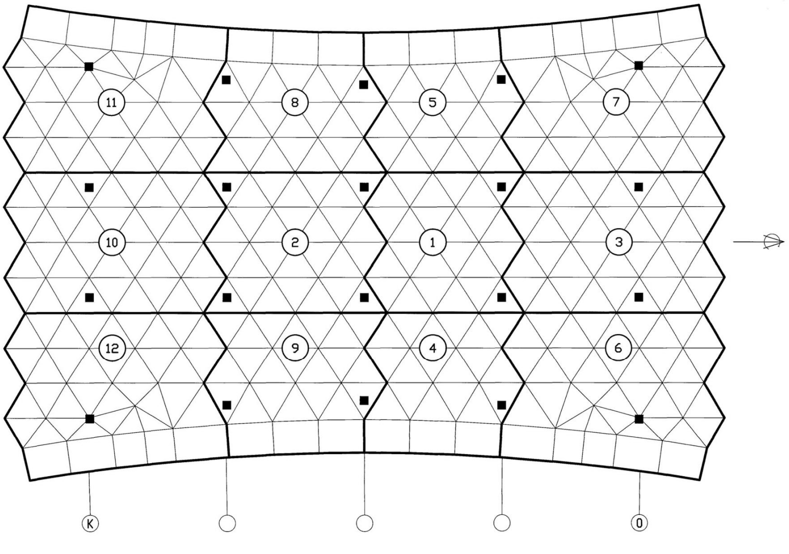


Figure 11. Temperature block in axes К-O. Partitioning into assembly “cards”

1, 2 – enumeration of erection sequence

■ – cast-in-situ reinforced concrete columns

The erection of load-bearing steel structures of roof starts from the floor after casting of the cast-in-situ reinforced concrete columns and alignment by elevation marks and position in plan for the roof steel structure seats.

The erection begins from the central zone of temperature block ("card 1" in Figure 11) and the buildup of structure in plan is uniformly made by "cards" in all directions.

The erection sequence is described by the following algorithm:

1. The solid reusable scaffolds are installed on the floor at the central block zone ("card 1").
2. The supporting triangular blocks from the supporting roof trusses are mounted in design position on the solid reusable scaffolds above the corresponding reinforced concrete columns.
3. After alignment of spatial altitude of the supporting triangular blocks, the steel slant legs of supporting pyramids are brought close to the supporting nodes of their lower chords from below and mounted on their seats on the reinforced concrete column heads.
4. After installation of slant legs and check of design spatial altitude for the upper and lower chord nodes of supporting blocks, grouting of all supporting pyramid erection joints is performed (i.e. all high-strength bolts are tightened and all erection joints are welded up).
5. After completion of works according to item 4 the buildup of roof structures between the reinforced concrete columns is made up to complete assembly of "card 1". The buildup is performed by triangles on the solid reusable scaffolds with check of design spatial altitude of each following node of truss connection.
6. After complete assembly of the roof "card" and control check of spatial altitude of the formed grid nodes, all internal erection joints in the "card" are to be grouted, i.e. the high-strength bolts are to be tightened up to a full rated force.
7. After completion of works according to item 6 the solid reusable scaffolds can be used for assembly of the following roof "cards".
8. The used erection scaffolds must have sufficient strength and stiffness to keep geometrical parameters of mountable structures up to moment of scaffolds dismantling.

The geodesic inspection of design spatial altitude both for every supporting node and for each following node of truss connection during their assembly is of the special importance.

6. Conclusions

In general, the performed mathematic investigations as well as development of unified structural concepts on their basis with minor quantity of nominal sizes of the main load-bearing elements resulted in feasibility of the given project realization by forces of the Russian building complex on the world state-of-the-art.