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To cite this article: Y Lunev and A Morozov 2018 IOP Conf. Ser.: Mater. Sci. Eng. 456 012021

View the article online for updates and enhancements.
Brief methodology calculation of steel structures freeform grid shell on the example coating Philharmonic building in the park “Zaryadye”

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Abstract. This article describes how to design and calculation of net free-form shell in the park “Zaryadye” in Moscow. Affected aspects of forming plate-rod FEM model computational schemes grid shell. Formation of wind and snow loads on the surface of double curvature, accounting nodes pliability grid shell, the calculation taking into account progressive collapse and overall stability.

1. Description of the project. Preparation for design
“Glass Bark” (Figure 1) - the artificial hill above the Philharmonic building is a shell of double curvature, consisting of triangular panels. “Glass Bark” is integrated organically into the Park concept and reflects the icy expanses of North Russia. The grid shell has dimensions of 130*90 m, its area is 8680 m² and is based only on inclined columns of triangular variable length section.

Figure 1. Operated design “Glass Bark”, April 2018.

According to the initial data from the architects, provided in the form of BIM model, a fully parametric plate-rod calculation model was formed to determine the rational position of inclined variable cross-section columns, optimization of the rod elements length, the shape rationalization and the elements position after series of calculations.
2. Design features and design scheme of the grid shell

The design of the shell contains a number of unique structural elements, namely the presence of a window area with glass edges. As it was mentioned earlier, the grid shell has a size of 130*90 m. It is located in the open air (not heated structure) and has no thermal and deformation seams. The supports of the grid shell are separately standing three-, four-branched columns of triangular cross-section. The distance between the columns branches is from 12 to 20 meters. Overhangs along the perimeter of the cover have a flight up to 6 meters. This arrangement provides maximum horizontal transparency due to the walls/beams lack along the perimeter of the structure, and a significant distance between the supports allows achieving the effect of the maximum open space under the “glass bark”.

In order to minimize cross sections and structural unification of the steel frame elements is designed with different sections:

- rolling section 120×80×7 (used in the ridge area with a minimum load, as well as to give ease of construction);
- rolling section 200×100×8 (these rods are used in the area with an average load in places with a slope of more than 20 degrees relative to the horizontal surface);
- rolled and welded section 300×100×10 (12), section 350×110, 400×160 (these items are used on flat surfaces and in the areas with the largest accumulation of snow);
- bar with variable height cross-section of 200-300×100;200-350×110;300-350×100;300–400×100.

To pair of weld applied beams of various sections (reference sites), and bolt (for ordinary nodes) nodal connectors. All bolted connections are made using two types of nodes: solid section (Figure 4) and the set section (Figure 5). The latter allow you to connect any height elements, while providing metal savings and reducing the production time of structures in the factory. In the most loaded zones (column headings) welded connectors of the stacked section are used (see Figure 6). These units are characterized by an increased height of the section, the use of high-strength steel 10HsND-12, as well as the connection of adjacent pipes in welding, which allows to achieve maximum strength and stiffness performance.

According to the results of aerodynamic tests (Figure 6, 7) the calculated snow load was obtained, which varied from 200 to 500 kg/m² in different zones, and the standard wind load, which varied from -30 to +20 kg/m² in different zones, which correlated well [8].

All climatic loads, including temperature and pulsation, were applied to the grid shell surface by parameterization of the computational model using a visual programming language.

3. Joint calculation ground base and the overall stability

As it mentioned earlier, the grid shell is made as a coating of the Philharmonic building. Shell deformations are directly dependent on the deformation of the whole building. To determine the stress-strain state considering the elastic development, a joint calculation model “grid shell-reinforced
concrete building-ground” was created (Figure 8, 9). Ground base was considered by two coefficients of the bed on Pasternak model.

![Figure 3. Connector of solid cross-section.](image)

![Figure 4. Connector of typesetting section.](image)

![Figure 5. The connector section welded typesetting.](image)

![Figure 6. Park Zaryadye test models in a wind tunnel.](image)

![Figure 7. Park Zaryadye test models in a wind tunnel (plan).](image)

![Figure 8. Calculation model Philharmonic and grid shell of the “grid shell-RC building-soil”, view 1.](image)

![Figure 9. Calculation model Philharmonic and grid shell of the “grid shell-RC building-soil”, view 2.](image)

The calculation of the overall stability was made as a separate grid shell together with the Philharmonic building according to [2], as elastic deformed system. The stability calculation was performed according to the main load combinations [1]. To calculate the overall stability, a number of computational models of the grid shell were created, including the following variable parameters: rigid/hinged joints of rod elements, elastic-yielding joints of rod elements, together with the
underlying structures and rigid supports. Also, for the analysis of local stability, in one of the calculation options, welded columns of variable triangular cross-section in length were included both in the variant of rod elements divided into a set of finite elements, and in the plate formulation (Figure 10, 11). On the basis of the calculation results, the factors of the total stability reserve, the stability forms loss for the determination of the “pulling” and “holding” structural elements were analyzed. The minimum coefficient of system stability reserve was obtained equal to 12.67, which was much higher than the requirements [1].

![Figure 10. Fragment of the computational scheme with columns of variable cross-section by simulated rod elements, a pile bush in the form of an elastic connection.](image1)

![Figure 11. Fragment of the design scheme with columns of variable cross-section, modelled plate elements on the pile bush, also in the form of plate elements.](image2)

4. Calculation for the progressing (avalanche) collapse

According to the architectural concept, the grid shell does not have walls along the contour, and relies only on inclined columns. This fact immediately had a significant impact on the design process, namely the device of additional columns and the calculation of special loads combinations, considering the dynamic factor. The rigidity of the grid shell on inclined columns is provided by the coating disc on rigid welded joints, both hinged in one plane and rigid in another, bolted joints (Figure 3, 4, 5).

To calculate the progressive collapse according to [4- 6], inclined columns of variable triangular cross-section were chosen as the “key” elements. Since the term of the structure operation was laid at least 50 years (with the possibility of increasing to 75 years) for the “key” elements according to [6], additional coefficients of work were introduced. The process of calculation for progressive collapse was a failure consistent calculation of any inclined columns in each “bushes” on the action of constant and long-term loads, considering the dynamism coefficient and the application of special loads for modeling the emergency impact. According to the results of the calculation, it was decided to include additional inclined columns, increase the thickness of walls/shelves, steel beams, and grid shell.

5. Conclusion

In the design and grid shells construction of various types, it is necessary to build accurate parametric design and BIM models changed in the work process. And also, it is necessary to have constant cooperation of construction and design organizations and at the stage of structures design (in the selection of rational form and topology of the grid shell, optimal cross sections, etc.), and at the installation stage (in the selection of slinging equipment, placement of temporary support structures, etc.). At the same time, the best technical and economic indicators of the project on the timing of buildings construction, on the efficiency of decisions are provided. Especially this fact is noticeable in the field of non-standard and unique construction with no previously accumulated experience.
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