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# IMPROVING THE PERFORMANCE PARAMETERS OF METAL CYLINDRICAL GRID SHELL STRUCTURES

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## ABSTRACT

In this article, to improve the performance of metal cylindrical mesh shells used as roofs for modern construction projects, the sub-aperture diaphragms and the corresponding nodal connections are proposed in the context of the problem of the increased vulnerability of individual sections from actual loads. Finite element models are designed taking into account minimization of production and assembly costs, special features of load perception and structural geometry changes in an acceptable range of overall parameters. The effect of sustaining elements located in the direction of the arc of the circle on the percentage of depletion of the bearing capacity and the maximum value of the deflection of circular mesh surfaces with square and rectangular cells are investigated. An economical design solution of IFI type unit is used to increase the bearing capacity and reduce the deformation of rectangular cylindrical multi-element grids. A joint connection which improves operational characteristics of a structure taking into account the features of the geometric formation and spatial design of the structures has been developed. The force factors and deformation parameters of the basic circuits of a cylindrical mesh surface are checked with conventional and developed joint connections. Increased rigidity and stability of the structure due to the introduction of the diaphragms and the use of units with sustaining elements have been achieved.

**Keywords:** joint connection, grid shell, cylindrical surface, roof diaphragm.

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## 1. INTRODUCTION

Today, mesh cylindrical shells are used as roofs for buildings and structures for various purposes. Their geometric shape has long been of interest to customers due to the architectural expressiveness and reliable operation of the structure throughout the life cycle.

Modern technologies allow to create many kinds of meshes for curvilinear surfaces with maximum operational effectiveness of all elements. Materials and labor resources economy is also important here. The variety of mesh forms is impressive, but special attention should be paid to metal mesh shells of circular cylindrical shape with a minimum number of element sizes. However, the idea to obtain an optimal design is associated not only with the choice of the rational geometry of the grid surface. It is also necessary to make the appropriate decision to create simple and reliable nodal connections. Simplicity here means the availability of the minimum possible number of elements and the convenience of assembly during construction.

The history of the development of cylindrical grid shells joint connections is associated with the improvement of the methodology for the lattice surfaces formation. The problem of the effective joint connections for curvilinear grid structures has been discussed by experts from many countries around the world since the 20th century. Most papers on this topic were written in the 1950s, after the World War II, when destroyed objects required to be restored. Many engineers began to develop, design and build grid shell roofs for buildings and structures [1-3]. Considerable interest was given to the application of a minimum number of elements and parts, while meeting the requirements of the geometric stability of lattice surfaces. A huge contribution to the development, design and erection of the shells was made by architects and engineers Vladimir Shukhov and Richard Fuller. Further, an outstanding architect Norman Foster developed unique in dimensions and shape grid shell structures. The lattice shells construction was carried out at a rapid pace and by the mid-1970s [4] a clear understanding of geometric shapes, possible sizes, profiles, design solutions and schemes for rods connection was formed. A serious impetus to the development of lattice roofs was the study of circular shells on a rectangular plane with the improvement of joint connections [5].

Almost every solution [6] suggested by the researchers involves reducing costs and ensuring that the aesthetic and operational qualities of the structure are taken into account. Most of the drawings and the joint connections are devoted to the widespread grid shell structures on the circle plan [7, 8]. The details of cylindrical grid shell structures are not well developed, and the process of assembling such systems assumed the use of the same types of joints as for relatively large domed structures. Obviously, sometimes this leads to a modification of the design solution. Among the most universal joint connections one can name the joint connection systems as follows "IFI" (Germany), "Du Shato" (France), "Triodetic" (Canada). These systems were developed by the engineers of the previous century [9] who proposed the principles of curvilinear systems construction and created the successful design solutions for joints of multi-element buildings and structures roofs.

## 2. METHODOLOGY

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## 3. MATERIALS AND METHODS OF RESEARCH

The analysis of the development of the grid shell shapes let to underline and generalize existing tools for the circular cylindrical lattice surfaces investigation. The basis for this is the scheme of grid shell structures with forming elements along the length and in the direction of the broken line of roofs. It is taken that the cell has a diagonal rod, which divides each cell into equal-sized triangles. As a result, for each facet, the same lattice is obtained with the braces oriented from the edges to the center. To analyze, the results of the Ruland system design with the same number of panels *n* and facets *m*, with square and rectangular cells are taken. The determined geometry makes it possible to obtain the inclination angle of the diagonal rods to the horizon in the plane of the facets, and this angle is close to or equal to 45°. The length-to-width ratio of the structure is 1.2 and 1.4.

Investigation of grid shell structures was carried out by the constructed finite element models. The detailed design of the improved joint connections is carried out on the basis of the constructive schemes IFI. Within the framework of the study, the factors that allow us to clarify the ratio of the structural elements are determined. The achievements of scientists about the rational schemes of joints are analyzed. The maximum possible number of elements, the correspondence of the angles between the rods, the adaptability of joint connections to the variability of the grid shell geometry and the use of welding and/or bolts are taken into account. We also studied the interchangeability of individual parts and the need for mandatory use of tightening bolts made of high-strength steel. The entire volume of information received is processed by the theory of probability and mathematical statistics. Assessment of the analyzed joint connections adequacy is based on the method of comparative analysis.

Information sources indicate that in the process of a circular single-layered cylindrical surface design we have to determine a radius of curvature and the angle of the shell. With the introduction of a regular grid, the surface should be divided into the required number of cells along the arc and along the direction of the generator. It is desirable that the shape of the cells is in the form of a square, but necessarily with a brace [10], which divides it into two identical triangles. Therefore, the number of elements in the nodes will thus be 2, 4, 5 or 6 (Fig. 1).

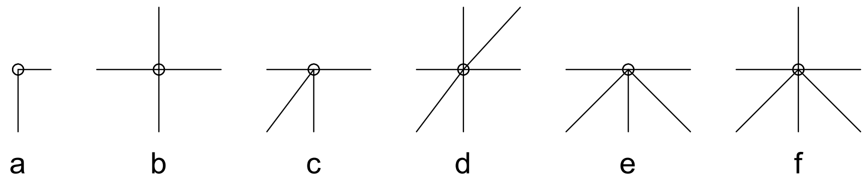


**Fig.1.** The number of elements in the nodes of a single-layered cylindrical grid shell: (a) two; (b), (c) four; (d), (f) six; (e) five. The circles show the nodal inserts

All joints of the lattice shell differ not only in the number of convergent rods, but also in the value of the bearing load. A mandatory requirement in the assembly process is the use of a simple and convenient nodal element that is able to connect and secure the rods of the grid surface with a specified accuracy.

## 4. RESULTS AND DISCUSSION

The realized projects testify to the high performance of the IFI type joint, which provides connection of up to 8 rods and, in the case of a square cell, allows to obtain an angle of 45 °. However, as can be seen from Fig. 1, the number of elements in the joint connection of single-layered cylindrical grid shells varies within the range from 2 to 6. Therefore, one should pay attention to the possibility of this unit being amenable to some adjustment and with the introduction of additional structural elements to increase stability and increase the overall dimensions of the shell. To identify this ability, computer simulations have been carried out and calculations of cylindrical grid shell with a modified "IFI" joint connections have been performed. The use of such type of joints allows to create roof structures for real projects of buildings and constructions. However, the principle of quadratic cells is often ignored in the design due to the desire to draw out a grid with less number of elements. Thus, the use of rods of different length along the arc and along the direction of the generator leads to the creation of an alternative rectangular cell. Then the smallest angle between the diagonal element or the brace and one of these rods is 38 °. In addition, when forming a single-layered grid shell, one should take into account the fact that the angles between elements are defined within each facet. In this paper, four schemes of the shell of a single-layered cylindrical grid roof with a width $B$ equal to the range from 18 m to 36 m are studied. In each scheme investigated standard IFI joint connections and assemblies with inserted parts of diaphragms are used.

Thus, 8 finite-element computer models of shells are created. The grid topology for economic reasons is formed by a system of longitudinal and transverse cross ribs with diagonal elements between them. The angle of the circumscribed circle of the cross section of the roof is fixed at a level of α = 120 °. The shape of the cells is given in the form of squares or rectangles separated by braces into adjacent triangles.

Accordingly, the same number of panels along the length and facets along the arc direction of the circle ($n = m = 12$) is obtained.

Geometric parameters (width $B$, length $L$, radius of curvature $r$, cell size $a$ or $l$ x $h$, camber of arch $f$) are calculated in the recommended for the design ratios. The main shaping parameters of the grid shell scheme with the IFI (Scheme 1) connections and the joints with inserted parts of the diaphragm (Scheme 2) are shown in Fig. 2 and in Table 1.

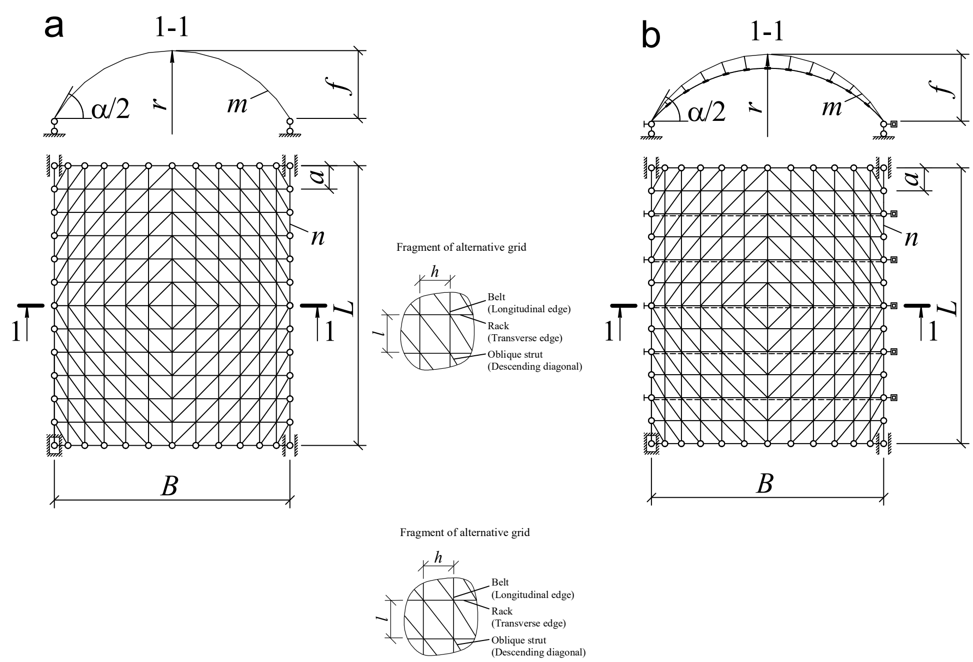


**Fig.2.** Plan and cross-section of the grid shell of the roof with geometric parameters: (a) without reinforcements (Scheme 1) and (b) with reinforcement of the diaphragms (Scheme 2)

**Table 1.** Geometric parameters of roof schemes with square cells

| Number | $B$, m | $L$, m | $r$, m | $a$, m | $f$, m |
|---|---|---|---|---|---|
| 1 | 18 | 21,6 | 10,4 | 1,8 | 5,15 |
| 2 | 24 | 28,56 | 13,9 | 2,38 | 6,87 |
| 3 | 30 | 36,12 | 17,3 | 3,01 | 8,6 |
| 4 | 36 | 43,2 | 20,8 | 3,6 | 10,29 |

The rectangular cells are interesting for a design because of the possibility of simultaneously preserving the determining parameters and increasing the length of the shell. The fragment of the circuit and the corresponding characteristics are shown in Table 2.

The structural solutions of the investigated roof are based on the rods with a cross-section in the form of a shaped seamless tubular profile of S235 steel.

The stiffness characteristics of the elements, including those for reinforcement, are taken from the basic section types.

**Table 2.** Geometric parameters of roof schemes with rectangular cells

| Number | $B$, m | $L$, m | $r$, m | $l \times h$, m | $f$, m |
|---|---|---|---|---|---|
| 1 | 18 | 25,92 | 10,4 | $2,16 \times 1,8$ | 5,15 |
| 2 | 24 | 34,32 | 13,9 | $2,86 \times 2,38$ | 6,87 |
| 3 | 30 | 43,32 | 17,3 | $3,61 \times 3,01$ | 8,6 |
| 4 | 36 | 51,84 | 20,8 | $4,32 \times 3,6$ | 10,29 |

Geometric stability is ensured by the fact that along the contour the shell through the support joint connections is hinged with complete prohibition of displacements at one corner point and imposition in two directions in the remaining contour support joints:

$$X_{s.c.} = Y_{s.c.} = Z_{s.c.} = 0\,, \quad X_{s.c.} = Z_{s.c.} = 0 \qquad (1)$$

Finite element models without reinforcements and with diaphragms (shown in Fig. 3) are created with the help of surfaces of rotation, data on the elements, the form and the type of grid filling.

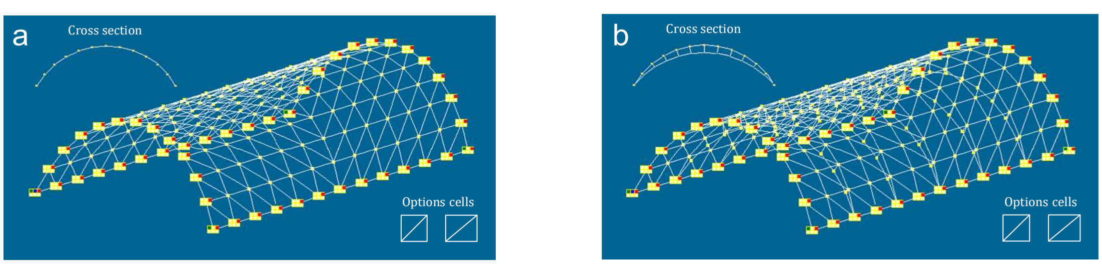


**Fig.3.** Finite-element 3D design model of a grid shell with square and rectangular cells: (a) without reinforcements and (b) with a diaphragm

Modeling takes into account the restrictions on the movement of nodes

$$\delta_i \le \delta_u, \quad \delta_{max} \le \delta_u \qquad (2)$$

where $\delta_i$, $\delta_{max}$, $\delta_u$ are the actual, the maximum and the limit value of nodes displacement respectively.

Climatic impacts are determined taking into account the most dangerous schemes of applying loads and transferred to nodal forces on the basis of calculated load areas for corner, contour and span zones of a coverage respectively.

The weight of the structure is calculated on the basis of the received information on the assigned stiffness characteristics of the elements from the available software range.

The construction of the computational models is carried out with the use of the IFI joints and improved joint connections with inserted parts of the diaphragms (shown in Fig. 4).

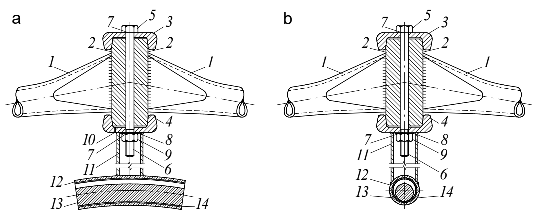


**Fig.4.** (a) and (b) are sections of the developed joint of the reinforced cylindrical grid shell: 1 - tubular rods, 2 - wedge-shaped tips, 3 - upper nodal disc, 4 - lower nodal disc, 5 - tightening bolt, 6 - thread, 7 - hole in the discs, 8 – shim, 9 - screw nut, 10 - a drip for draining water, 11 - cylindrical shell, 12 - curved tubular rod, 13 - diaphragm, 14 - a lining material

The wedge-shaped tips which are welded to the flattened end of the tubular rods and are joined by nodal discs, one of which has a hole for the drip for draining water, are used in the developed joint connections. The elements in the joint are fixed with a tightening bolt, the diameter of which is selected from the condition of strength for axial tension:

$$N_i / A_{bn} \le R_{bt} \quad \text{or} \quad N_i / A_{bn} \le 0.7 R_{bun} / \gamma_n \qquad (3)$$

where $N_i$ is a design stress in the *i*-element; $A_{bn}$ is a cross-section area by the thread; $R_{bt}$ is a design stretching resistance of the bolt, $R_{bun}$ is the least temporary tear resistance of high-strength steel after thermal treatment of the bolt; $\gamma_n$ is a reliability coefficient of the bolt connection.

The direct fixation of the joint parts is carried out by a screw-nut with a shim.

In addition, to reinforce and improve the stability of the structure in the convex direction, the diaphragms are comprised. They are arranged in steps of two panels along the length and are connected to the joints on the inside of the roof. Therefore, each joints connection additionally includes a cylindrical shell, one end of which is welded to the lower nodal disc and the other is connected by welding to a curved tubular rod with the diaphragm and the lining material inside. The curvature of the tubular rod is matched to the radius of the circumscribed circle of the roof.

All these design schemes performance is assessed based on the results of the calculations taking into account unfavorable schemes and combinations of loads. The analysis of the application of the developed joints with the diaphragms is made by comparing the obtained behavior regularities of the reinforced and non-reinforced roof. As a result, maximum values of internal force factors and deformation parameters are determined for each scheme.

The overall stress-strain state of the systems shows a significant improvement in the performance of the roof with the diaphragms and the corresponding joint connections, which is indicated in a more even stresses and displacements distribution along the surface of the structures. Regardless of the shell scheme, the greatest force occurs in the transverse direction. However, if for non-reinforced systems it is noted on the slopes closer to the edges of the roof, then in the case of systems with diaphragms, the maximum force is found in the central support zone. Quite different, but rather predictable situation is with the greatest node displacements. In all schemes, it is detected vertically in the upper central zone and turns to be substantially smaller in roof systems with diaphragms.

In order to estimate the effect of reinforcement elements on the structure performance, charts of dependence of the bearing capacity depletion on the maximum deflection are represented. As can be seen from the obtained results (shown in Figs. 5, 6), as the size of the system increases, the maximum vertical displacement also increases and the difference in the percentage of depletion of the bearing capacity decreases. Here we take into account the correspondence between the normative value of the maximum deflection and the value of the real deflection in the structure.

As it is shown in Fig. 5, in the schemes with square cells the parameter of depletion of the bearing capacity Δ does not reach 100%. However, in the schemes with rectangular cells (shown in Fig. 6), the grid becomes less and in the case of the cell dimensions $3.61\times3.01\,\mathrm{m}$ and $4.32\times3.6\,\mathrm{m}$ the structure collapses ($\Delta=104\%$ and $\Delta=108\%$). The use in this case of the diaphragm and the corresponding joint connections shows a positive result, but only for the roofs with the sizes up $B\times L=30\,\mathrm{m}\times43.32\,\mathrm{m}$. In the case of bigger spans ($B=36\,\mathrm{m}$) the diaphragms influence slightly and the load bearing capacity is exceeded.

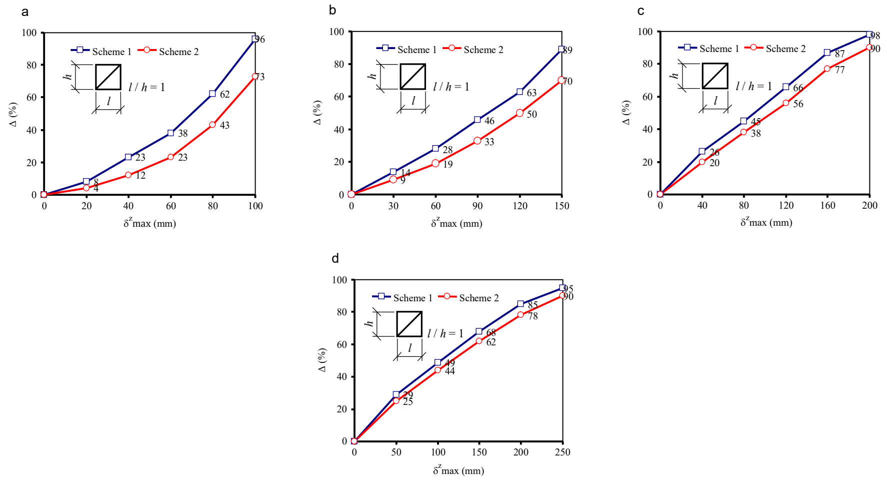


**Fig.5.** The effect of the introduction of joints with diaphragm elements on the percentage of depletion of the bearing capacity Δ (%) and the maximum deflection $\delta^{z}_{max}$ (mm) of single-layered cylindrical grid shells with square mesh size: (a) 1.8 m, (b) 2.38 m, (c) 3.01 m, (d) 3.6 m

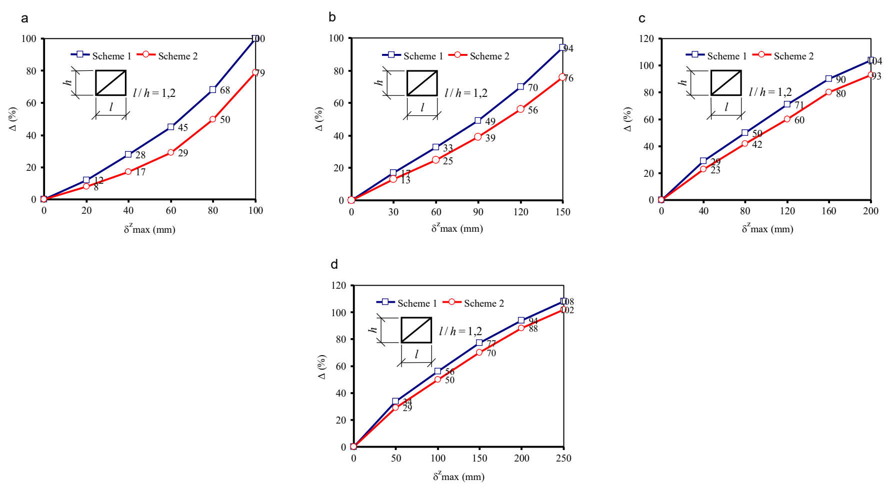


**Fig.6.** The effect of the introduction of joints with diaphragm elements on the percentage of depletion of the bearing capacity Δ (%) and the maximum deflection $\delta^{z}_{max}$ (mm) of single-layered cylindrical grid shells with rectangular mesh size: (a) 2.16×1.8 m, (b) 2.86×2.38 m, (c) 3.61×3.01 m, (d) 4.32×3.6 m

## 5. CONCLUSIONS

On the basis of common requirements and approaches to metal cylindrical grid shells design the problematic issues of the particular zones vulnerability under the loads are discussed. Finite-element models of circular contour systems with cross orthogonal ribs and downward braces in an acceptable range of overall parameters are created.

The features of cylindrical grid shell structure performance along with the impact of the changes in of these structures geometry are revealed, taking into account the most dangerous schemes and combinations of external load application.

On the base of the obtained numerical results, a better distribution of force factors and deformation parameters of cylindrical grid shells is represented by introducing the curved diaphragms of rigidity and corresponding joint connections.

The connection of the rods in the span part of the structure with more effective performance and minimal manufacturing and assembly costs is developed.

The influence of reinforcing elements on the percentage of depletion of the load-carrying capacity Δ and the maximum value of deflection of curvilinear grids with square and rectangular cells is identified.

It is shown that depletions of the load-carrying capacity Δ for different cylindrical grid shell schemes differ and that the most effective scheme is the one with an equal dimension ration of the sides. It is found that the structure with the ration between length and height equal to 1.2 ($l/h=1.2$) and with the span more than 30 m ($B \geq 30\mathrm{m}$) is destroyed. The use of sub-aperture diaphragms and particular joint connections with reinforcement elements has a positive impact on the cylindrical grid shell structures, but only up to a certain size of the shell ($B \times L = 30\mathrm{m} \times 43.32\mathrm{m}$).

**6. ACKNOWLEDGMENTS**

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