DOI: 10.21122/2227-1031-2017-16-6-475-484

UDC 624.074.5

Structural and Design Specifics of Space Grid Systems

G. M. Gasii[1)]

[1)]Poltava National Technical Yuri Kondratyuk University (Poltava, Ukraine)

Abstract. The aim of the study is to identify main trends in the development of space grid structures. In order to reach the purpose it is necessary to conduct a review of the known structural concepts, nodal connections and specifics of the space grid structures and to make conclusions on feasibility improvement of the considered structural concepts that make it possible to develop new solutions without disadvantages residing in the analogues. Analysis of papers written by foreign and national scientists and devoted to theoretical, numerical and experimental studies of stress-strain state, influence of different factors on it and geometrical optimization and designing of space grid structures has been conducted in order to achieve the objectives. Space grid structures and, in particular, flat double-layer grid and most frequent nodes have been studied in the paper. The paper contains a short review of the history on development of space grid structures. It has been found that a rapid development of structural designs was caused by scientific and technical progress and, in particular, improvement of physical and mechanical properties of materials, development of calculation methods, application of software systems for simulating behavior of the structure under load, which significantly increased the calculation accuracy and reduced complexity of design. It has been also established that main parameters that have influence on effectiveness of a structural design are geometric dimensions of its modular elements, ratio of its depth to the span. The world experience on development of connection components has been studied in the paper. The paper presents general classification of nodal connections. Main advantages and disadvantages of existing space grid structures are highlighted and it allows to determine possible methods for their improvement. Theoretical research has permitted to establish that the main direction of spatial grid structures improvement consists in development of new node connection types. Several methods for node improvement have been proposed while taking into account the obtained results.

Keywords: rod, node, welding, bolt, module, span, structure, lattice

For citation: Gasii G. M. (2017) Structural and Design Specifics of Space Grid Systems. *Science and Technique*. 16 (6), 475–484. DOI: 10.21122/2227-1031-2017-16-6-475-484

Особенности конструктивных решений и проектирования пространственных стержневых систем

Канд. техн. наук, доц. Г. М. Гасий[1)]

[1)]Полтавский национальный технический университет имени Юрия Кондратюка (Полтава, Украина)

Реферат. Цель работы – выделить основные направления в развитии пространственных стержневых конструкций. Для этого поставлены задачи: провести обзор известных конструктивных решений, узловых соединений и особенностей проектирования пространственных стержневых конструкций. Сделать выводы о целесообразности усовершенствования рассмотренных конструктивных решений с целью разработки новых, не имеющих недостатков, присущих аналогам. Для решения поставленных задач проведен анализ работ зарубежных и отечественных ученых, посвященных теоретическим, численным и экспериментальным исследованиям напряженно-деформированного состояния и влияния на него различных факторов, а также геометрической оптимизации и проектированию пространственных

Адрес для переписки
Гасий Григорий Михайлович
Полтавский национальный технический университет
имени Юрия Кондратюка
просп. Первомайский, 24,
36011, г. Полтава, Украина
grigoriigm@gmail.com

Address for correspondence
Gasii Grygorii M.
Poltava National Technical
Yuri Kondratyuk University
24 Pershotravnevyi Ave.,
36011, Poltava, Ukraine
grigoriigm@gmail.com

стержневых конструкций. Проанализированы пространственные стержневые конструкции, в частности структурные плиты и наиболее часто встречаемые конструкции их узлов. Проведен краткий обзор истории развития структурных конструкций. Установлено, что быстрому развитию структурных конструкций способствовал научно-технический прогресс, в частности повышение физико-механических свойств материалов, развитие методов расчета, использование для моделирования условий работы на разные виды нагрузок программных комплексов, что существенно увеличивает точность расчета и уменьшает трудоемкость проектных работ. Также установлено, что основными параметрами, которые влияют на эффективность структурной конструкции, являются геометрические размеры его модульных элементов, соотношение его высоты к пролету покрытия. Изучен мировой опыт по разработке узлов соединения. Приведена общая классификация узловых соединений. Выделены основные преимущества и недостатки существующих пространственных стержневых конструкций. В результате проведенного теоретического исследования установлено, что основным направлением усовершенствования пространственных стержневых конструкций является разработка новых узловых соединений. Учитывая полученные результаты, предложено несколько способов усовершенствования узлов.

Ключевые слова: стержень, узел, сварка, болт, модуль, пролет, структура, решетка

Для цитирования: Гасий, Г. М. Особенности конструктивных решений и проектирования пространственных стержневых систем / Г. М. Гасий // *Наука и техника*. 2017. Т. 16, № 6. С. 475–484. DOI: 10.21122/2227-1031-2017-16-6-475-484

Introduction

In the construction of large-span buildings and structures for various purposes often is a problem of the complexity of work and waste of material due to its inefficient use. This situation in the construction has occurred through outdated industry, properties and technical and economic indicators of the existing designs that are a morally and physically outdated over time. These factors have a direct impact on the overall cost and duration of construction of the object, so there is a need to improve and find new load-bearing structures, in particular space frames that would have led to significant savings in materials and reduce the complexity of technological processes of manufacturing and installation.

That was the cause of the ideas to develop of new space systems concept that would be able to combine not only advantages of existing space frames but would have their own original characteristics and their unique benefits and specifics. For that the world experience of studies of space grid structures must be carefully and thoroughly studied.

General information and brief history of the development of space frames

Today, the most well-known space frames systems are the space grid structures. These structures are widely known and disseminated due to well-shaping abilities, which is confirmed by a large number of original and unique objects worldwide [1]. These structures have many advantages and their use provides good cost-effectiveness compared to other more traditional structural solutions [2].

The advantages of the space grid structures that determine their effectiveness in comparison with other designs include [3–5]:

1. Lightweight. It is the most important advantages of a space grid structure. It is mainly due to the load transfer mechanism that is primarily axial tension or compression and as a result all material in any given element is utilized to its full extent. On top of that most space grid structures are constructed from steel or aluminum parts which even more considerably decrease their self-weight.

2. Mass productivity. Space grid structures built from simple prefabricated units, which are of standard size and shape. The units of the structures are produced as usual in the factory so that they can take full advantage of an industrialized system of construction. These units usually are easily transported and quite rapidly assembled on site by semi-skilled labor and erection with conventional equipment and machinery. Consequently, space grid structures can be built at a lower cost.

3. Stiffness. The structures are usually sufficiently stiff despite of its lightness. It is caused its three-dimensional character and to the full participation of its components. The structures also have the good rigidity and great stiffness and exceptional ability to resist unsymmetrical or heavy concentrated load.

4. Versatility. The space grid structures possess a versatility of shape and utilize the modules to generate various space grids, latticed and even free-form shapes. Moreover, the structures have the visual beauty and the impressive simplicity of lines.

The specifics of space grid structures are that they consist of modular mass-produced elements.

Depending on the shape and relative position of the modular elements, the space grid structures can be single-layer, dual-layer lattice shells or flat plates, etc. Using space grid structures allows creating large-span roof system that has sufficiently small depth, which is within the range of 1/16–1/25 of the span. In addition, the space grid structures are characterized as structures with a low weight and reduced sensitivity to seismic actions, for the construction of which small-sized modular standardized elements are used. This greatly facilitates the technological process of transportation, cargo handling works and installation. In addition, the use of modular components allows building architecturally expressive and attractive geometric shapes and surfaces. The advantage of the modular construction has been demonstrated more than a century ago, when it was designed, manufactured and installed the design for The Crystal Palace for The Great Exhibition 1851 in London and The Galleries des machines in Paris in 1889 [3].

Among the general class of space grid structures often highlight flat double-layer grids [6], but there are numerous examples of the implementation of space grid structures with more complex form: the scope, variety of shell, step plates, pyramids, etc. [4, 7]. These structures show great opportunities for the use of steel in the construction of large-span buildings namely, a variety of forms and shapes of which is unlimited. The flat double-layer grids are the most characteristic space grid structures [8, 9]. In most cases for the construction of such structures rods made from tubular steel elements are applied. Less widespread are elements made of steel profiles of other cross sections, such as angles, channels, thin-walled profiles [10, 11].

The first major impetus to the development of the space grid structures was due to the inventor Alexander Graham Bell. In the first decade of the twentieth century he explored the possibility of octahedral and tetrahedral space shapes from rods. He highlighted the double superior of three-dimensional grid elements – it is high load capacity and low weight. However, space grid systems of the first generation have been patented at the end of the 1930s, which later became known as the Unistrut system [12]. Nevertheless, space grid structures were not used widely in construction until the Mero system was designed in the early 40s of the last century in Germany. It should also be noted that Mero system was the first commercialized full spatial structure [13].

Wide implementation of space grid structures had got in the middle of the twentieth century, thanks to the researches in architecture and engineering, whose main objectives were to find the new and original forms and also alternatives to existing joints. Great contribution to the development of space structures was brought by American architect, engineer and inventor Richard Fuller who designed the geodesic dome [14].

In the late 1940s, K. Wachsmannand P. Weidlinger developed a system of spatial structural Mobilar. This system was substantially different from the existing ones, in particular, from Mero system and Unistrut system, so the nodes had not been separated from the rods, and geometry of connection parts were not so rigid and massive. During the 1950s, these systems continued to be improved, which has led to the development of other systems [5, 15–19].

The development of structural designs has not always been so rapid and intense as it is now. Earlier, constraining factor of its development was the degree of static indeterminacy that led to complex and time-consuming calculation. These difficulties were complicated for the analysis to a certain extent slowed down and limited the use of space grid structures. However, the introduction of computers has fundamentally changed the whole approach to the design, which contributed to a new wave of development of such structures. With the using computer software it is possible to analyze very complex dimensional structures with more accuracy and less time [20]. Because of this over the past half-century the development of space grid structures came to an entirely different level. In addition to the development of computer technology, there are other important factors influenced on the rapid development of space grid structures. Firstly, it is the advanced equipment and great opportunities to produce efficient structures. Secondly, it is the requirement for large indoor areas, besides the problem has always been timely and is particularly acute in the design of buildings for mass sport and cultural events, meetings, exhibitions, etc.

The problem of finding new structural forms to cover large areas has always been the main task of architects, engineers and scientists. A large number of theoretical and experimental studies were conducted by many universities and research institutions in different countries. As a result, a considerable part of the results and developments was implemented in practice. New and creative solutions to the space grid structures most commonly implemented in the construction of sports arenas, exhibition halls, transport terminals, computer rooms, hangars for planes [21, 22], etc. There is a large number of different and interest configurations have built worldwide. Each of these structures has its advantages and disadvantages relative to one other, but all are united by one common difference. The difference is that the space grid structures are collected from modular elements which in only on axial compression or tension [23].

Despite the obvious advantages and favorable opportunities for the development space structural systems have one major drawback – the complex manufacture of nodal connections.

The general trend in the development of structural designs is the tendency to minimize the number of sizes of modular elements, reduce the complexity of the technological installation processes and reduce the complexity of the nodal connections.

Design, construction and investigate the space grid structures

Design issues of space grid structures from time to time attracted the attention of scientists all over the world. Previously analysis of the history of the structures development has shown that the appearance and development of each new structural form is devoted to the desire to find the most cost-effective structural concept. Significant number of works of foreign and domestic scientists is devoted to this issue and the study of structural designs. Most of the works are related to the rational designing and finding of relevant geometric parameters [24]. In [25] constructive solutions and schemes, methods of calculation and installation methods have been studied, as well as investigations of the effect of the size and shapes of the structural elements on the stress-strain state and the mass of the structure. Research and further development of constructive solutions for the space grid structures and methods of their calculation have performed by M. N. Kirsanov, V. I. Trofimov, R. I. Hisamov, V. N. Shimanovsky, A. V. Shimanovsky, J. Chilton, J. M. Gerrits, , Z. S. Makowski, G. S. Ramaswamy [26–29] and others.

The main geometric parameters of structural designs are height H and the size of the module M. Height it is the distance between the top and bottom chord, and the module it is the distance between the two joints in the top chord (fig. 1). Despite the fact that these parameters seem to be quite simple, properly chosen values can significantly influence the cost of the structure. In turn, the height and size of the module is influenced by several parameters: the mesh type, the distance between supports, the form of the roof, as well as the nodal system. In fact, the height and size of the module are interconnected. The parameter that connects them is the angle α between the rod of the module and its horizontal projection. This angle should be between 30°–60°, but advisory in nature is equal to the angle of 45°.

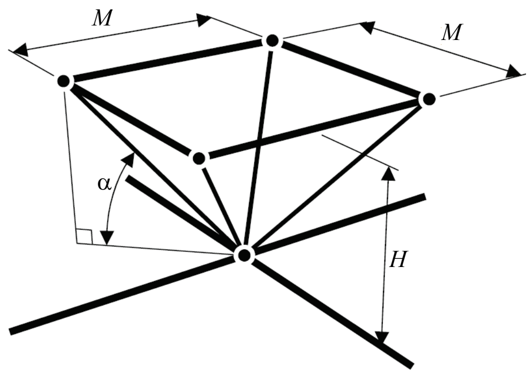

Fig. 1. Basic geometric dimensions of module for space grid structures

Common ratio of height H to the size of the module M does not exist and, as a rule, is determined by practical experience. It is believed that the structural height of the structure is relatively small as compared with conventional structures. However, one must consider the fact that a small structural height with respect to the structures span creates the need for smaller size modules, which will promote the growth of their quantity, and hence the number of nodes, the total weight of the structure and cost structure. Structural optimization is the best way to determine the optimal ratio of height to span. In [30], using the principles of structural optimization the optimal ratio spans search was carried out in the range of 24 to 72 m and a height of the space grid structures. Seven types of gratings were investigated. The size and height of the modules were taken as a variable, and the total value was taken as the objective function, which was the sum of the cost of the elements, joints, roofing and enclosing materials. This approach made it possible to argue about the validity of the data. It has been found that the optimum design parameters for the various systems are different, and the module size generally increases with span. In addition, empirical formula was obtained to determine the optimal ratio of the span and height. Based on these expressions, diagrams of dependence between the span *L* and height *H* of the space grid structures were built (fig. 2) [30]. Also for comparison of the results fig. 2 showing further research in this area, which are discussed in [31].

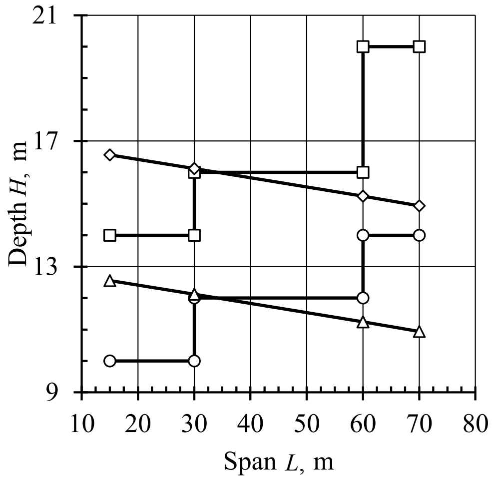

Fig. 2. Relation between depth and span of double-layer grids:
—○— – bottom boundary by Chinese Academy;
—□— – top boundary by Chinese Academy;
—Δ— – bottom boundary by Lan;
—◊— – top boundary by Lan

Besides the optimal geometric dimensions of the modular elements in the design of structural designs the efficient and reliable constructive solution of the nodal connections occupies is also an important place.

Review of existing nodal connections and their research

As mentioned previously structural designs consist of rod members of different cross sections, which are joined at the nodes. Currently there are a large variety of nodal connections solutions but generally they can be divided into groups:

Group I – the nodal connections are made with mounting welding;

Group II – bolt connection or other modular elements are made without any welding. Such connection depend on how the bolts in, can be divided into two subgroups, where nodes bolts working in compression or tension bolts and bolts which resist the shear;

Group III – combined nodal connections. This group includes compounds in which welding is carried out in the factory, and the assembly with bolts on site.

In most cases, manufacturing the nodes requires the use of special connection parts – connectors [32], and they can be manufactured from cast, forged or welded spheres, hemispheres, polyhedrons, and other forms [32].

Each group has its own advantages and disadvantages. The advantages of welded joints should include the ability to combine different number of rods from almost any angle. However, welded joints have a number of disadvantages, among which a large amount of welding; the complexity of the alignment angles and hence higher probability appearance of eccentricity; inability to reassembling and disassembling; inhomogeneity residual weld and welding stress; stringent requirements for a length of rod. Given this, widely spread welds have not received.

Welded node connections include Oktaplatte system, Segmo, SDC and many others. The node system Oktaplatte is the most known among this class of connections. The German company Manessman developed it, and its feature lies in that the node consists of two hemispherical hollow steel parts that in the joint with steel diaphragm made as a disc. The most famous example of the use of Oktaplatte system is a pavilion built for the World New York Exhibition in 1964–1965.

Bolt node connections include Sarton system, Premit, Triodetic, Mero, Space Deck, Envision, Unibat, Nodus, NS, Zachod, Berlin, Pyramitec, БрГТУ, System III, Pyramid Sphere System, Hemisperical Node System, Unistrut, Mostostal, Newbat, TRIDI 2000; ONDDI, Uzay, Montal, Spherobat, Axent, Wuppermann, Orbik and many others.

As can be seen from a review of the existing bolt nodal systems of structural designs in different countries own systems have been developed, which may be structurally differ from one another through connection way of rod elements, crosssectional shape and form of the connector core elements. In the world practice of building space grid structures a nodal connection with axial bolts is widespread. The most popular among these systems as mentioned earlier is Mero system that was proposed by German designer M. Mengeringhausen. This system for connecting of rod shaped elements involves the use of the connector, which is a solid steel spherical polyhedron shape with arranged in it threaded holes. This connector allows you to connect up to 18 of rod shaped elements, which are equipped with axle bolt and sleeve. The node Mero system has a significant number of modifications and improvements [33].

Analogues of Mero system are the Orona, Cubotto, Vestrut, Villeroy and other systems. Connectors of such systems may consist of several parts, which are tightened a central bolt.

Based on the overall review of the known nodal connections we can see that the overwhelming number of them have bolts and designed to combine elements with tubular section. In most of these nodes bolts works in considerable axial tension or compression force. However, assembly errors, accidental damage or deformation can lead to bending moments that can cause the destruction of the bolts in the thread-free section. In [34] it suggested that the node connection of the tubular elements for space grid structures, which excludes the risk of the destruction bolt must working on a bend. The paper also refers to the universality of the developed connection and the possibility of its widespread use for covering various buildings and structures, also in the construction of arch type and domes, as well as in covers over the stands of stadiums. The efficiency of the developed node according to studies [34] is that it has been designed to use standard bolts, which in double cross shear that increases by 2.0–2.5 times the load-bearing capacity in comparison with special bolts used in Mero system.

After analyzing specifics of the existing nodes of space grid structures and studies, from the perspective of ease of assembly, the most effective are the nodal connections with welded sheet. Such constructive solutions of nodes allow making their shapes simpler, and hence to reduce production costs. Less complex and more reliable are the node elements what constituted a single solid part: stamped, milled or bent because such nodes are not weakened due welds.

Complexity level of nodal connections significantly influences on the total cost of space grid structures, and consequently on the technical and economic feasibility of their application, because they account for 20 % of steel. Without exception, all space grid structures consist of rods and junctions, so the mass of bars and nodal elements determines the total weight of the structure. According to [35], the total weight of the modular cell of space grid structures is determined by multiplying the construction coefficient of space grid structures and rods weight. Moreover, weight of rods, depending on the type of lattice structure is defined by different formulas [35]. Also, in the mentioned work at graphs are displayed construction coefficients that were calculated for the most common nodal solutions and were set their values depending on span of the structures. With these graphs it is possible to define the geometric parameters in which a particular type of node connections is efficient to use, for example, according to [35] for large spans covers Mero, Unistrut and KIBI are not rational systems of nodal connections because construction coefficients of these systems with increase span have been rising, and when the span more than 40 m is much greater than the coefficient for flat trusses.

The nodal connections, except weight, are characterized by pliability that has effect on stress-strain state of structures. In space grid structures with a high degree of redundancy, pliability of nodal connections leads to a deviation of the actual behavior of structures from the design scheme resulting in a redistribution of stresses in the structure. In addition, for the space grid structures, which combine elements of bolt normal accuracy, pliability bolted connections should be considered also because it leads to increase a structure deflection [36]. In this case, the total deflection, which are obtained for a system with fixed connections, it is recommended to increase by 30 %, if the difference between the diameter of the bolt and hole 2–3 mm, and 20 % when the difference is 1.5 mm [37].

Also, the pliability of node connections, depending on the type of space grid structures has varying degrees and shape of influence on its behavior. Accounting pliability of nodal connections for example for a mesh dome has allowed reducing the stresses in rod elements up to 15 % [38], but in the space grid slabs pliability has another effect. It was found that the redistribution of stresses in space grid slabs is extremely uneven: in some elements pliability of bolt connection causes minor changes, in others the change stresses can reach up from 20 to 60 %, in addition in some elements the stresses can change the sign [36]. Therefore, the calculation of structures with bolted connections with their possible pliability should be taken into account for the purpose to obtain realistic behavior scheme.

Pliability of nodal connections is possible to taken into account in several ways: by replacing the elastic modulus of the nodal connections; installation of elastic elements on the ends of the rods; modeling nodal connections as polygons. Accounting pliability of nodal connections by any of the methods shows the increase of structure deformability [38]. Pliability of nodes may also be eliminated or reduced by improving the quality of prefabricated elements or parts and the welded joints [35].

In addition, the choice of node connections and components of space grid structures should be carry out based on the integrity and reliability of the entire system. Errors that may occur during the design lead to increased consumption of materials, erection difficulties, inefficient operation and undesirable initial efforts. That is why the load-bearing capacity of node connections should exceed the load-bearing capacity of the most stressful rod member in tension thereby making the necessary reserve load-bearing capacity of structure. In this case, even in case of accidental failure of most stressful element or node, the situation is not dangerous, as there is a redistribution of stresses. In the case where at designing have the inequality that indicates the most stressful load bearing capacity has more than load bearing capacity of node so there is overrun of steel [35].

That is why it is so important the choice of the nodal connections need to make comprehensive analysis of it in all points.

Analysis of the results of research and the search for ways to improve the nodes

Considering the above and after a number of various nodal connections of space grid structures have been considered. It was established that the determining factor in the making of the cost of the erection of the structures is the complexity of the connection node. This statement has been made based on that in general, the load-bearing capacity of space grid structures is dependent on the bearing capacity of the node, and when the node is designed with a significant reserve of strength, it is accompanied by the overrun of steel. Hence, than the node is simpler in to manufacture and assembly, the less time-consuming, and therefore inherent safety factor will not cause large expenditure of steel. In addition, a small labor and material intensity positive effect on reducing the total cost of coverage.

As noted above depending on the way of assembly, the nodes are classified in bolted, welded and combined, but bolted nodes are used widely because they have factory readiness and faster assembly procedure. However, it should be noted that the welded joints can be used quite effectively. For example, if the components made in lap joint [39] instead of butt joints, it is possible to reduce the accuracy requirements for the lengths of rods. Also, for welded assemblies, at light loads, as the rods of the lattice can be used steel rods of round or square cross-section (fig. 3).

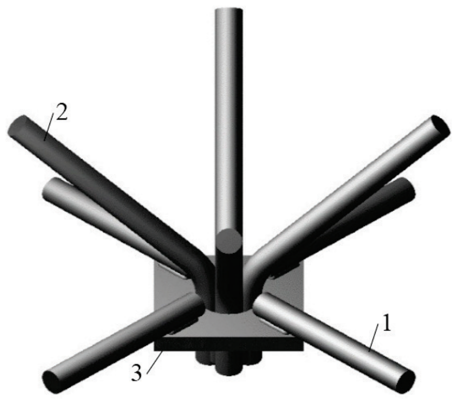

Fig. 3. Welded node of space grid structure: 1 – bottom chord; 2 – slanted rods; 3 – steel plate

It has been proposed several ways to improve the space grid structures based on the information received, that caused a development of a concept new space rod system. The specifics of this system are in providing collaboration not only grid modular elements, but also plates, made with durable and efficient building materials, including translucent. Constructively these systems consist of top and bottom cords and space lattice. At the same time, top chord is made of rigid plates that in compression and transverse force, the bottom chord is made of flexible linear elements [40]. It should also be noted that this structure is modular, that is assembled from space structural modules which are completely produced at factory [41]. These systems have three types of modules. They are support and span space modules and line modules from which make a flexible chord. This structural concept allows constructing cover with different forms and shapes, including a variety of shells [42]. Structural concept of such systems involves usage specially designed nodes for connection modules in the integral structure [43, 44].

The results of theoretical, numerical and experimental studies of this system enable us to assert about its efficiency and reliability, as well as resources saving, which is especially relevant in today's construction industry [45].

CONCLUSIONS

Considering the above, it was found that the nodal connections are members of structures that determine the cost of material consumption and complexity of installation work for space grid structures. Nodes are classified on bolted, welded and combined ones. Bolted and combined nodes are most widely used. It should be noted that a significant number of existing nodes connections, including welded, involve the use of special steel connectors. Usage connectors, generally adds weight and complexity of assembly, and also requires the production of works with high accuracy. The analysis of theoretical and experimental studies have established that the most effective nodal connections are combined with gussets due to simplicity of manufacture, low weight and absence of axial bolts. However, these nodes have significant drawbacks. There are a large number of bolts and the complexity of using tubular rod elements and in the case of welding there is a significant total length of the assembly weld. Therefore, as a result of the theoretical studies highlighted effective nodal connections, but it remains a certain number of problematic issues that require further research. Hence has been developed the concept of the new space grid system, the constructive solution that will save both material and human resources in the construction of covers of different forms and shapes for large-span buildings.

REFERENCES

1. Furche A. (2016) *Tragkonstruktionen: Basiswissen für Architekten*. Springer Vieweg. 210 (in German).
2. Shimanovsky O. V., Bespalov. S. M. (2002) Peculiar Features in Designing of Long Span Roof Structures on the Basis of Structural Plates. *Budivnitstvo Ukrainy* [Construction of Ukraine], (5), 21–24 (in Ukrainian).
3. Chilton J. (2000) *Space Grid Structures*. Boston, Architectural Press. 180. DOI: 10.4324/9780080498188.
4. Kancheli N. V. (2009) *Building Space Structures*. 3rd ed. Moscow, Publishing House "ASV". 112 (in Russian).
5. Lan T. T. (1999) *Space Frame Structures*. Boca Raton, CRC Press LLC. 129. DOI: 10.4324/9780080498188.
6. Allen E., Iano J. (2013). *Fundamentals of Building Construction. Materials and Methods*. 6th ed. Wiley. 1024.
7. Parke G. A. R., Disney P. (2002) *Space Structures 5*. London, Thomas Telford Ltd. 1613. DOI: 10.1680/ss5 v1.31739.
8. Lubo L. N., Mironkov B. A. (1976) *Plates of Regular Spatial Patterns*. Moscow, Stroyizdat Publ. 105 (in Russian).
9. Morozov A. P., Vasilenko O. V., Mironkov B. A. (1977). *Space Structures of Public Buildings*. Leningrad, Storyizdat Publ. 168 (in Russian).
10. Gemmerling A. V. (2014) Structural Constructions from Efficient Roll-Formed Sections. Saarbrücken, Lap Lambert. 137 (in Russian).
11. Mitrofanov S. V. (2012) Operation of Unit-Forming Elements in Structural Construction. *Metalevi Konstruktsiï = Metal Constructions,* 18 (1), 17–25 (in Ukrainian).
12. Condit C. W. (1961) *American Building Art: the Twentieth Century*. Oxford University Press. 427.
13. Schueller W. (1983) *Horizontal-Span Building Structures*. John Wiley and Sons. 594.
14. Edmondson A. C. (2007) *A Fuller Explanation: the Synergetic Geometry of R. Buckminster Fuller*. Pueblo, Emergent World Press. 339.
15. Bai Y., Yang X. (2012) Novel Joint for Assembly of All-Composite Space Truss Structures: Conceptual Design and Preliminary Study. *Journal of Composites for Construction*, 17 (1), 130–138. DOI:10.1061/(asce)cc.1943-5614.0000304.
16. Gerrits J. M. (1998) An Architectonic Approach of Choosing a Space Frame System. *Lightweight Structures in Architecture, Engineering and Construction*, 2, 992–999.
17. Makowski Z. S. (2002) Development of Jointing Systems for Modular Prefabricated Steel Space Structures. *Proceedings of the International Symposium*. Warsaw, IASS Polish Chapter, 17–41.
18. Andrade de S. A. L., S. Vellasco da P. C. G., Silva da J. G. S., Lima de L. R. O., D'Este A. V. (2005) Tubular Space Trusses with Simple and Reinforced End-Flattened Nodes-an Overview and Experiments. *Journal of Constructional Steel Research*, 61 (8), 1025–1050. DOI: 10.1016/ j.jcsr. 2005.02.001.
19. Yang X., Bai Y., Ding F. (2015) Structural Performance of a Large-Scale Space Frame Assembled Using Pultruded GFRP Composites. *Composite Structures*, 133, 986–996. DOI: 10.1016/j.compstruct.2015.07.120.
20. Gorodetsky A. S., Evzerov I. D. (2005) *Computer Models of Structures*. Kiev, Fakt Publ. 344 (in Russian).
21. Liu X., Zhao Q., Liu H., Chen Z. (2011) Innovations in Design and Construction of the New Stadiums and Gymnasiums for the 2008 Beijing Olympic Games. *Journal of the International Association for Shell and Spatial Structures*, 52 (1), 39–52.
22. Kholopov I. S., Balzannikov M. I., Alpatov V. Yu. (2012) Application of Grid Metal Structures in Roofing of HPP (Hydro Power Plant) Machine Halls. *Vestnik Volgogradskogo Gosudarstvennogo Arkhitekturno-Stroitel'nogo Universiteta. Ser.: Stroitel'stvo i Arkhitektura* [Bulletin of Volgograd State University of Architecture and Civil Engineering. Series: Civil Engineering and Architecture], 47 (28), 225–232 (in Russian).
23. Engel H. (2009) *Structure Systems*. Ostfildern, Hatje Cantz. 352.
24. Tashakori A., Adeli H. (2002) Optimum Design of Cold-Formed Steel Space Structures Using Neural Dynamics Model. *Journal of Constructional Steel Research*, 58 (12), 1545–1566. DOI: 10.1016/s0143-974x(01)00105-5.
25. Trofimov V. I., Begun G. B. (1972) *Structural Constructions*. Moscow, Stroyizdat Publ. 172 (in Russian).

26. Kirsanov M. N. (2011) Static Calculation and Analysis of Spatial Rod System. *Inzhenerno-Stroitelny Zhournal* [Construction-Engineering Journal], 24 (6), 28–34 (in Russian).
27. Shimanovsky V. N., Gordeev V. N., Grinberg M. L. (1987) *Optimal Design of Space Grid Roofing*. Kiev, Budivelnik Publ. 223 (in Russian).
28. Makowski Z. S. (1992) Space Frames and Trusses. *Constructional Steel Design. an International Guide*. London, Elsevier, 791–843.
29. Ramaswamy G. S., Eekhout M., Suresh G. R. (2002) *Analysis Design and Construction of Steel Space Frames*. London, Thomas Telford Ltd. 262. DOI: 10.1680/adacossf.30145.
30. Lan T. T., Qian R. (1986) A Study on the Optimum Design of Space Trusses-Optimal Geometrical Configuration and Selection of Type. *Shells, Membranes and Space Frames. Proc. IASS Symp*. Amsterdam, Elsevier, 191–198.
31. Chen W. F., Lui E. M. (2005) *Handbook of Structural Engineering*, Second Edition. CRC Press. 1768. DOI: 10.1201/9781420039931.
32. Inzhutov I. S., Dmitriev P. A., Deordiev S. V., Zakharyuta V. V. (2013) Analysis of Existing Interface Nodes in Space Structures and Development of Pre-Assembled and Dismountable Nodal Element. Vestnik MGSU [Moscow State University of Civil Engineering Bulletin], (3), 61–71 (in Russian).
33. Stephan, S., Sánchez-Alvarez J., Knebel K. (2004) Reticulated Structures on Free-Form Surface. *Stahlbau*, 73 (8), 562–572. DOI: 10.1002/stab.200490149.
34. Kaganovsky L. O. (2010) New Solutions for Nodal Connections of Rods in Structural and Single-Layer Latticed Constructions. *Zbirnik Naukovikh Prats' Ukraïns'kogo Naukovo-Doslidnogo ta Proektnogo Institutu Stalevikh Konstruktsii Imeni V. M. Shimanovs'kogo* [Collection of Research Papers of V. Shimanovsky Ukrainian Research and Design Institute of Steel Construction], (5), 192–198 (in Russian).
35. Khisamov R. I. (1981) *Calculation and Design of Space Frames*. Kiev, Budivelnik Publ. 79 (in Russian).
36. Zueva I. I., Zuev V. V. (2010) Effect of Bolt Connection Compliance on Stress-Strain Strain of Structural Constructions. *Vestnik of Perm National Research Polytechnic University. Stroitel'stvo i Arhitektura = PNRPU Construction and Architecture Bulletin*, (1), 40–46 (in Russian).
37. Zueva I. I., Ivanova S. L. (2013) Specific Features in Designing of TsNIISK-Type [Central Research Institute of Construction Structures] Structural Constructions. *Vestnik of Perm National Research Polytechnic University. Stroitel'stvo i Arhitektura = PNRPU Construction and Architecture Bulletin*, (1), 91–97 (in Russian).
38. Tur V. I., Tur A. V. (2014) Influence of Nodal Joint Compliance on Stress-Strain State of Metal Net Dome. *Fundamentalnye Issledovania = Fundamental Research*, (6), 1165–1168 (in Russian).
39. Storozhenko L. I., Gasii G. M., Gapchenko S. A. (2015) *Space Steel-Reinforced Concrete and Structural Cable Roof*. Poltava, Publishing House TOV “ASMI”. 216 (in Ukrainian).
40. Storozhenko L. I., Gasii G. M. (2016) Peculiar Features in Structural Concept and Designing of Full-Length Experimental Model of Steel-Reinforced Concrete and Structural Cable Roof. *Zbirnik Naukovikh Prats'. Seriya: Galuzeve Mashinobuduvannya, Budivnitstvo* [Collection of Research Papers. Series: Industrial Mechanical Engineering, Civil Engineering]. Poltava, Poltava National Technical Yuri Kondratyuk University, 46 (1), 52–60 (in Ukrainian).
41. Storozhenko L. I., Gasii G. M., Gapchenko S. A. (2014) New Steel-Reinforced Concrete and Structural Cable Constructions. *Zbirnik Naukovikh Prats'. Seriya: Galuzeve Mashinobuduvannya, Budivnitstvo* [Collection of Research Papers. Series: Industrial Mechanical Engineering, Civil Engineering]. Poltava, Poltava National Technical Yuri Kondratyuk University, 40 (1), 91–96 (in Ukrainian).
42. Gasii G. M. (2016) Fundamentals of form Making and Designing of Space Roof Made from Steel-Reinforced Concrete and Structural Cable Constructions. *Stroitelstvo, Materialovedenie, Mashinostroyenie: Sb. Nauch. Trudov* [Civel Engineering, Material Science, Mechanical Engineering: Collection of Research Papers], (87), 48–53 (in Ukrainian).
43. Gasii G. M. (2016) Analysis of Stress-Strain State of Trapezoidal Steel Plate in Node Used for Connection of Bottom Chord Elements in Experimental Steel-Reinforced Concrete Structural Cable and Barrel Shell. *Zbirnik Naukovikh Prats' Ukraïns'koï Derzhavnoï Akademiï Zaliznichnogo Transportu* [Ukrainian State University of Railway Transport Collection of Research Papers]. Kharkiv: UkrSURT, (162), 41–47 (in Ukrainian).
44. Gasii G. M. (2016) Stress-Strain State of Rectangular Steel Plate in Node Used for Connection of Rod Elements in Steel-Reinforced Concrete Structural Cable and Barrel Shell. *Visnik Odes'koï Derzhavnoï Akademiï Budivnitstva ta Arkhitekturi* [Odessa State Academy of Civel Engineering and Architecture Bulletin]. Odessa: Publishing House “Zovnishreklamservis”, (62), 215–219 (in Ukrainian).
45. Gasii G. M. (2014) Experimental Investigations on Structural and Steel Cable Roof. *Zbirnik Naukovikh Prats'. Seriya: Galuzeve Mashinobuduvannya, Budivnitstvo* [Collection of Research Papers. Series: Series: Industrial Mechanical Engineering, Civil Engineering]. Poltava, Poltava National Technical Yuri Kondratyuk University, 42 (3), 47–51 (in Ukrainian).

Received: 27.10.2016
Accepted: 06.01.2017
Published online: 28.11.2017

ЛИТЕРАТУРА

1. Furche, A. Tragkonstruktionen: Basiswissen für Architekten / A. Furche. Springer Vieweg, 2016. 210 p.
2. Шимановський, О. В. Особливості проектування великопрогонових просторових покриттів на основі структурних плит / О. В. Шимановський, С. М. Беспалов // Будівництво України. 2002. № 5. С. 21–24.
3. Chilton, J. Space Grid Structures / J. Chilton. Boston: Architectural Press, 2000. 180 p.
4. Канчели, Н. В. Строительные пространственные конструкции. 3-е изд., доп. и перераб. / Н. В. Канчели. М.: АСВ, 2009. 112 с.
5. Lan, T. T. Space Frame Structures / T. T. Lan. Boca Raton: CRC Press LLC, 1999. 129 p.
6. Allen, E. Fundamentals of Building Construction. Materials and Methods: 6th ed. / E. Allen, J. Iano. Wiley, 2013. 1024 p.
7. Parke, G. A. R. Space Structures 5 / G. A. R. Parke, P. Disney. London: Thomas Telford Ltd, 2002. 1613 p.
8. Лубо, Л. Н. Плиты регулярной пространственной структуры / Л. Н. Лубо, Б. А. Миронков. М.: Стройиздат, 1976. 105 с.
9. Морозов, А. П. Пространственные конструкции общественных зданий / А. П. Морозов, О. В. Василенко, Б. А. Миронков. Л.: Стройиздат, 1977. 168 с.
10. Геммерлинг, А. В. Структурные конструкции из эффективных гнутых профилей / А. В. Геммерлинг. Саарбрюкен: Lap Lambert, 2014. 137 с.
11. Мітрофанов, С. В. Робота вузлових елементів структурної конструкції / С. В. Мітрофанов // Металеві конструкції. 2012. Т. 18, № 1. С. 17–25.
12. Condit, C. W. American Building Art: the Twentieth Century / C. W. Condit. Oxford University Press, 1961. 427 p.

13. Schueller, W. Horizontal-Span Building Structures / W. Schueller. John Wiley and Sons, 1983. 594 p.
14. Edmondson, A. C. A Fuller Explanation: the Synergetic Geometry of R. Buckminster Fuller / A. C. Edmondson. Pueblo: Emergent World Press, 2007. 339 p.
15. Bai, Y. Novel Joint for Assembly of All-Composite Space Truss Structures: Conceptual Design and Preliminary Study / Y. Bai, X. Yang // Journal of Composites for Construction. 2012. Vol. 17, No 1. P. 130–138.
16. Gerrits, J. M. An Architectonic Approach of Choosing a Space Frame System / J. M. Gerrits // Lightweight Structures in Architecture, Engineering and Construction. 1998. Vol. 2. P. 992–999.
17. Makowski, Z. S. Development of Jointing Systems for Modular Prefabricated Steel Space Structures / Z. S. Makowski // Proceedings of the International Symposium. Warsaw: IASS Polish Chapter, 2002. P. 17–41.
18. Tubular Space Trusses with Simple and Reinforced End-Flattened Nodes-an Overview and Experiments / de S. A. L. Andrade [et al.] // Journal of Constructional Steel Research. 2005. Vol. 61, No 8. P. 1025–1050.
19. Yang, X. Structural Performance of a Large-Scale Space Frame Assembled Using Pultruded GFRP Composites / X. Yang, Y. Bai, F. Ding // Composite Structures. 2015. Vol. 133. P. 986–996.
20. Городецкий, А. С. Компьютерные модели конструкций / А. С. Городецкий, И. Д. Евзеров. Киев: Факт, 2005. 344 с.
21. Innovations in Design and Construction of the New Stadiums and Gymnasiums for the 2008 Beijing Olympic Games / X. Liu [et al.] // Journal of the International Association for Shell and Spatial Structures. 2011. Vol. 52, No 1. P. 39–52.
22. Холопов, И. С. Применение решетчатых пространственных металлических конструкций в покрытиях машинных залов ГЭС / И. С. Холопов, М. И. Бальзанников, В. Ю. Алпатов // Вестник ВолгГАСУ. Сер. Строительство и архитектура. 2012. Т. 47, № 28. С. 225–232.
23. Engel, H. Structure Systems / H. Engel. Ostfildern: Hatje Cantz, 2009. 352 p.
24. Tashakori, A. Optimum Design of Cold-Formed Steel Space Structures Using Neural Dynamics Model / A. Tashakori, H. Adeli // Journal of Constructional Steel Research. 2002. Vol. 58, No 12. P. 1545–1566.
25. Трофимов, В. И. Структурные конструкции / В. И. Трофимов, Г. Б. Бегун. М.: Стройиздат, 1972. 172 с.
26. Кирсанов, М. Н. Статический расчет и анализ пространственной стержневой системы / М. Н. Кирсанов // Инженерно-строительный журнал. 2011. Т. 24, № 6. С. 28–34.
27. Шимановский, В. Н. Оптимальное проектирование пространственных решетчатых покрытий / В. Н. Шимановский, В. Н. Гордеев, М. Л. Гринберг. Киев: Будівельник, 1987. 223 с.
28. Makowski, Z. S. Space Frames and Trusses / Z. S. Makowski // Constructional Steel Design. an International Guide. London: Elsevier, 1992. P. 791–843.
29. Ramaswamy, G. S. Analysis Design and Construction of Steel Space Frames / G. S. Ramaswamy, M. Eekhout, G. R. Suresh. London: Thomas Telford Ltd, 2002. 262 p.
30. Lan, T. T. A Study on the Optimum Design of Space Trusses-Optimal Geometrical Configuration and Selection of Type / T. T. Lan, R. Qian // Shells, Membranes and Space Frames. Proc. IASS Symp. Amsterdam: Elsevier, 1986. P. 191–198.
31. Chen, W. F. Handbook of Structural Engineering, Second ed. / W. F. Chen, E. M. Lui. CRC Press. 2005. 1768 p.
32. Анализ существующих узлов сопряжения пространственных конструкций и разработка сборно-разборного узлового элемента / И. С. Инжутов [и др.] // Вестник МГСУ. 2013. Вып. 3. С. 61–71.
33. Stephan, S. Reticulated Structures on Free-Form Surface / S. Stephan, J. Sánchez-Alvarez, K. Knebel // Stahlbau. 2004. Vol. 73, No 8. P. 562–572.
34. Кагановский, Л. О. Новые решения узловых соединений стержней структурных и однослойных решетчатых конструкций / Л. О. Кагановский // Збірник наукових праць Українського науково-дослідного та проектного інституту сталевих конструкцій імені В. М. Шимановського. 2010. № 5. С. 192–198.
35. Хисамов, Р. И. Расчет и конструирование структурных покрытий / Р. И. Хисамов. Киев: Будівельник, 1981. 79 с.
36. Зуева, И. И. Влияние податливости болтового соединения на напряженно-деформированное состояние структурных конструкций / И. И. Зуева, В. В. Зуев // Вестник ПНИПУ. Строительство и архитектура. 2010. № 1. С. 40–46.
37. Зуева, И. И. Особенности проектирования структурных конструкций типа «ЦНИИСК» / И. И. Зуева, С. Л. Иванова // Вестник ПНИПУ: Строительство и архитектура. 2013. Вып. 1. С. 91–97.
38. Тур, В. И. Влияние податливости узловых соединений на напряженно-деформированное состояние металлического сетчатого купола / В. И. Тур, А. В. Тур // Фундаментальные исследования. 2014. № 6. С. 1165–1168.
39. Стороженко, Л. І. Просторові сталезалізобетонні структурно-вантові покриття / Л. І. Стороженко, Г. М. Гасій, С. А. Гапченко. Полтава: ТОВ «АСМІ», 2015. 216 с.
40. Стороженко, Л. І. Особливості конструктивного рішення та проектування повнорозмірного експериментального зразка структурно-вантового сталезалізобетонного покриття / Л. І. Стороженко, Г. М. Гасій // Збірник наукових праць. Сер. Галузеве машинобудування, будівництво / Полтавський національний технічний університет імя Ю. Кондратюка. Полтава: ПолтНТУ, 2016. Вип. 46, № 1. С. 52–60.
41. Стороженко, Л. І. Нові сталезалізобетонні структурно-вантові конструкції / Л. І. Стороженко, Г. М. Гасій, С. А. Гапченко // Збірник наукових праць. Сер. Галузеве машинобудування, будівництво / Полтавський національний технічний університет імя Ю. Кондратюка. Полтава: ПолтНТУ, 2014. Вип. 40, № 1. С. 91–96.
42. Гасій, Г. М. Основи формотворення і проектування просторових покриттів із структурно-вантових сталезалізобетонних конструкцій / Г. М. Гасій // Строительство, материаловедение, машиностроение: сб. науч. тр. 2016. Вип. 87. С. 48–53.
43. Гасій, Г. М. Аналіз напружено-деформованого стану трапецієподібної сталевої пластини вузла з'єднання елементів нижнього пояса експериментальної структурно-вантової сталезалізобетонної циліндричної оболонки / Г. М. Гасій // Збірник наукових праць УкрДУЗТ. Харків: УкрДУЗТ, 2016. Вип. 162. С. 41–47.
44. Гасій, Г. М. Напружено-деформований стан сталевої пластини прямокутної форми вузла з'єднання стрижневих елементів структурно-вантової сталезалізобетонної циліндричної оболонки / Г. М. Гасій // Вісник ОДАБА. Одеса: Зовнішрекламсервіс, 2016. Вип. 62. С. 215–219.
45. Гасій, Г. М. Експериментальні дослідження структурно-вантових покриттів / Г. М. Гасій // Збірник наукових праць. Серія: галузеве машинобудування, будівництво / Полтавський національний технічний університет імя Ю. Кондратюка. Полтава: ПолтНТУ, 2014. Вип. 42, № 3. С. 47–51.

Поступила 27.10.2016
Подписана в печать 06.01.2017
Опубликована онлайн 28.11.2017