Energy efficient building structures based on gridshell

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Abstract. To reduce energy resource consumption in construction industry, housing and utilities infrastructure, it is necessary to maximize the new structural solutions use for the buildings and structures. The bearing and enclosing structures functions separation allows using the optimal design scheme with minimal steel spread for the supporting structures and effective modern thermal insulation materials for the enclosure. The advantages of grid shell structural system are durability, seismic stability, easy installation, dismantling, transportation, re-installation without the heavy equipment use; it also can be used in remote and hard-to-reach places. The authors propose the modules that can be used as exhibition pavilions, shops, cafes with the room height up to 6 m. Mass production of grid shell domes became possible with the advent of computer-aided design, allowing to perform the calculation and the structure three-dimensional model.

Introduction

General trends have been in the modern civilization development - the growth of energy consumption, increasing demand and prices for energy resources over the past decades. Considering the global fuel and energy resources growing consumption, the situation may lead to deficit of these resources. Due to the high demand for energy, the development of energy-saving technologies around the world is becoming increasingly important, including Russia. In this regard, one of the priorities is to limit the energy resources consumption growth rate by increasing the energy facilities efficiency in construction, industry, housing and utilities and transport, the introduction of energy-saving technologies and materials.

In many countries, much attention is paid to “green buildings”, in which electricity cost is on average, 20-30% lower than usual. Energy efficient act entered into force in Russian Federation in 2018. The aim of the Act is to increase energy saving and energy efficiency in the construction, which will contribute to the introduction of new architectural solutions, modern construction technologies, energy efficient building materials, etc. For the effective implementation of the tasks to reduce the amount of energy spent on buildings, it is necessary to clearly define the parameters of the building elements affecting these costs:

- increasing the enclosure thermal resistance (exterior walls, roof, basements bridging) to the technically possible maximum level;
- minimizing the thermal bridges quantity and thermal conductivity;
- ensuring the building structure necessary air density relative to the outdoor air;
- increasing to the maximum technically possible level of translucent constructions thermal resistance;
- creating ventilation for fresh air supplying, removing exhaust air, distributing heat in the room and organizing the ventilation air heat recovery.

**Roof structure analysis**

One of the directions in the creation of energy-saving "houses of the future", with the energy-efficient technologies use, can be the development and implementation of buildings based on metal mesh shells.

Grid shells were invented and patented in the 1896 by Russian engineer Vladimir Shukhov in constructions of exhibition pavilions of the All-Russia industrial and art exhibition in Nizhny Novgorod. Then such constructions became the basis of many projects created by famous architects.

The roof of «Vyksa Steel Works», made by Shukhov in 1898 (Figure 1) have an important place in the history of construction. The design in the form of a steel grid shell dome with double curvature, based on three-hinged arches, allowed to significantly reduce the metal consumption compared to the traditional frame of roof. Shukhov created a classic vaulted roof of rolled steel profile that were new at that time [1]. Interbreeding rods (angles), based on the arch-trusses, formed a rigid frame on which the roof is arranged. For that time, it was a qualitatively new industrial building – high, spacious light (the facades of the building were translucent constructions from the base to the roof).

![Figure 1. Supporting structures of «Vyksa Steel Works»](image)

During the first half of the 20th century, grid shells were most often used in industrial construction. The production and exhibition halls were bridging by grid shells with minimal metal costs on such large spans. At present, grid shells are one of the promising directions in construction design. This is evidenced by the growing number of structures made with this technology and the customers’ interest.

Grid shell has unlimited possibilities for creating new architectural forms, its characteristic feature is the absence of massive supporting elements, due to the uniform distribution of loads on all rods of the frame. The growing number of buildings and structures made using this technology indicates the prospects for applying it in special circumstances such as arctic, seismic and remote areas.

The elements delivery to the construction site is carried out in a disassembled and compactly packed form. On the construction site, elements without special tools are quickly mounted in sections outside or inside the building. Grid shells can be used in the reconstruction of the facades, in the construction of stadiums, museums, hotels, airports, car parks and many other structures. In addition, dismantling and re-assembly of structures is available, which is especially important for temporary and seasonal structures.

**Grid shell’s field of application**

The grid shell field of application is not limited to large-span structures [2-4]. It is possible to use such technologies in low-rise individual construction. The advantages of such houses on the basis of mesh domes are largely based on the properties of the sphere:
the maximum internal volume with the same usable area with a “rectangular” structure, therefore, the best aeration and insolation of the premises;
− the minimum area of the outer surface with the same usable area with a “rectangular” structure, which causes less sound absorption outside, optimal thermal insulation (the greatest heat loss occurs through the outer corners of the building);
− grid shell dome house has high seismic stability as there are no heavy floors and roof;
− the ability to withstand large snow loads (the most rational structure for the Arctic areas);
− the shape of the dome provides the best aerodynamic compared to other structures: domed houses are stable during destructive hurricanes and tornadoes;
− the symmetry of the sphere allows to freely orient the dome on the land;
− the internal layout of the supporting walls can be free;
− solar panels and solar modules can be most effectively oriented in space.

Grid shell domes in individual housing
Individual housing with grid shell domes fully comply with the requirements of minimizing resources and energy consumption for the construction and upkeep building, as well as the principles of bio positivity:
− to use only low-rise high-density buildings with buildings no higher than trees (2-3 floors);
− to place workshops, shops, cafes on the first floor and residential premises – on the second;
− to use green roof on the house top or place solar collectors, solar batteries there;
− to use space framework, which forms are closest to natural;
− to choose the shape of construction, which is more suitable for utilization of solar and wind energy and energy saving;
− to use areas where it is impossible to place multi-storey buildings;
− to provide measures for the greening of horizontal and vertical surfaces of the house;

Many authors believe that traditional national dwellings, as well as possible, satisfy the principles of bio positive construction [5, 6]. Discussing the grid shell, it is worth recalling about the traditional dwelling of nomads - yurt (Figure 2). It is a portable, round tent covered with skins or felt which can be disassembled in the shortest time, compactly packed, transported, and reassembled at a new place.

Figure 2. A yurt (traditional dwelling of nomads in the steppes of Central Asia)

It should be noted that the domestic construction industry in terms of the materials use for the construction of buildings, until recently, remained a fairly conservative industry. Traditionally in housing construction the materials checked by time are widely applied - a tree, a brick and concrete. At the same time, the practice of industrially developed countries shows that metal has a lot of advantages such as durability, strength and high-performance characteristics. However, aesthetic factor is also important and today steel allows the creation of the most unusual building forms, facades and interiors.
An equal importance is simplicity and ease of manufacture, maintenance and repair. Such houses have ecological and fire safety properties due to a combination of proven qualities of traditional building and modern finishing materials, the high quality of which is confirmed by the corresponding certificates.

Today it is possible to assert with confidence that metal in residential construction is becoming no less demanded material than wood, brick and reinforced concrete. Practice shows that the performance characteristics of houses from metal structures are absolutely not inferior, and even surpass the similar parameters of buildings made of traditional materials in a number of indicators.

Results
To date, we have created and patented fundamentally new constructions of steel frame modules [7–9]. The basis of such buildings’ frame is formed by the steel angle equal legs. In contrast to the currently used steel frames, consisting of many elements, the proposed design consists of the minimum possible number of sizes of rods. Moreover, the frame form itself is optimized taking into account the following factors:

− maximum strength and seismic stability of the frame;
− the minimum possible number of frame sizes of rods;
− simple foundation design (spread footing foundation, pile foundation);
− the maximum possible internal volume with a minimum area of external walls;
− optimal cutting of standard 12 meters of rolled steel profile;
− the use of effective modern thermal insulation materials enclosure, wall maintainability.

Frame module (Figure 3), consist of rolled steel profile. The framework is formed by grid shell of steel angles equal legs 100x7 and parallel flange channels № 20, steel shaped tube 150×4, connected by bolts M18 (quality grade 5.8).

![Frame module of individual housing construction](image_url)
The minimum labor for the installation of the frame module is of particular note. All of the frame elements are factorial, connected by bolts in construction site, using heavy equipment only once to place elements in design position. The rod connection (racks with the edge of the dome, Figure 3) of frame module has the ability to rotate the racks to simplify installation (Figure 4).

The proposed modules can be used as exhibition pavilions, shops, cafes with the height of the room up to 6 m, and residential cottages with a total area up to 170 - 200 m² and the rooms height up to 3 m.

Mass production of grid shell domes became possible with the advent of computer-aided design, allowing to perform the calculation and design of a three-dimensional model of the structure. To create a framework model, the SCAD Office software was used (Figure 5). As a result of the calculation, the values of displacements of the construction nodes from the impact of the own weight of the supporting and surrounding structures, wind, snow loads, as well as seismic impacts [10] were obtained, the values of the calculated internal forces were determined, and the cross sections of the frame elements were selected.

Summary
Technological capabilities of design, the use of new materials and structures, the use of new methods of installation have expanded many times over the past years, including the use of the creating physical objects layer-by-layer method using a digital 3D model. In the core structural elements manufacture, connecting nodes, the cutting of fencing materials, high accuracy is required, which is available using modern high-precision equipment [11].
Figure 5. The frame module 3D CAD model using SCAD Office

High aerodynamic and structural properties, seismic stability, quick and easy installation, the possibility of delivery to remote areas of all components in a compact packed, the possibility of the structure dismantling and transporting to a new location, the possibility of complete or partial reconstruction, low load on the foundation allow to apply similar designs with high efficiency.

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