Gridshell Structures in Moscow: A Review of Design, Construction, and Applications

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Abstract. Gridshell structures have gained significant attention in recent years due to their remarkable architectural flexibility, sustainable construction techniques, and aesthetically pleasing designs. This article explores the application of gridshell structures in the city of Moscow. The study begins with an introduction to the concept, construction methods, and advantages of gridshell structures. It further investigates their utilization in various architectural projects in Moscow, highlighting their contributions to the city's urban landscape and sustainability goals.

Keywords. Gridshell, sustainable construction, construction method, structural system, materials

1 Introduction

Gridshell structures, also known as latticed or curved-grid structures, are architectural forms that consist of a three-dimensional grid of beams or rods, creating a lightweight and flexible shell-like structure. These structures are gaining significance in Moscow and various other cities as they offer a range of advantages in terms of both aesthetics and functionality. Soviet engineer V. G. Shukhov once proved that gridshells are much more effective than traditional beam systems. Such structures can cover huge areas and they weigh much less than standard ones.

The gridshell structures in Moscow are defining the city's modern architectural landscape. They provide a visually stunning and unique design element that stands out in a skyline dominated by traditional Soviet-era buildings. The most prominent example is the multicolored facade of the GES-2, a contemporary art center in Moscow, designed by the renowned architect Renzo Piano[1]. Its gridshell structure not only creates a visually striking appearance but also allows for the integration of large glass panels, enabling an abundance of natural light to enter the building's interior spaces.

The significance of gridshell structures lies in their ability to create large and open spaces without the need for many internal columns or supports (Fig.1). This means that architects can design impressive and expansive interiors without compromising the

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structural integrity of the building. Moscow, being a bustling metropolis, often faces challenges of limited space. Gridshell structures provide an innovative solution by maximizing available space and creating visually engaging environments.

![The construction of the roof in the department store GYM](image1)
![The construction of the roof in the GES-2](image2)

**Fig. 1.** The spatial constructive roof of GYM and GES-2 (Photo: stone-development.ru, Evgenia Ermakova)

Furthermore, gridshell structures offer significant sustainability benefits. Their lightweight nature and efficient use of materials reduce overall structural loads, resulting in reduced energy consumption during construction and operation\[2\]. Additionally, the open and porous grid-like form allows for natural ventilation and daylighting, minimizing the need for artificial lighting and mechanical ventilation, thus reducing energy consumption and carbon emissions.

Gridshell structures also introduce new possibilities for cultural and recreational spaces. In Moscow, they are often utilized in the design of public squares, exhibition halls, and museums, creating impressive and functional spaces for cultural events and gatherings. For instance, the Garage Museum of Contemporary Art in Moscow features a gridshell roof that allows for the easy installation of temporary pavilions and exhibition spaces.

The purpose of the article is to review the design, construction, and applications of gridshell structures in Moscow. It aims to provide an overview of these structures, their architectural and structural features, and the various ways they are being utilized in the city. The article likely discusses the advantages and challenges of gridshell structures, their aesthetic appeal, and their suitability for different applications in Moscow's architectural landscape.

### 2 Methodology

This study adopts a literature review approach to examine gridshell structures in Moscow. Relevant articles, research papers, architectural case studies, and official reports from the city's architecture and urban planning departments were reviewed and analyzed. Special attention was given to the design principles, construction techniques, and environmental considerations associated with gridshell structures.

**Table 1.** Overview of the methodology used of the evaluation of gridshells.
1. **Research and analysis**
   - Conduct a literature review to understand the existing knowledge and research on gridshell structures.
   - Analyze case studies of gridshell structures in Moscow to understand their design choices, construction techniques, and applications.

2. **Design evaluation**
   - Assess the structural design by analyzing the structural materials used, load-bearing capacity, and ability to withstand environmental conditions like wind, snow, and seismic activity.
   - Consider the sustainability aspects of the design, including energy efficiency, material usage, and environmental impact.

3. **Construction evaluation**
   - Assess the construction techniques and methods used for gridshell structures in Moscow.
   - Evaluate the feasibility and efficiency of the construction process, considering factors like cost, time, and labor requirements.
   - Analyze the construction quality control measures and ensure adherence to applicable codes and regulations.

4. **Application evaluation**
   - Assess the intended and actual applications of gridshell structures in Moscow.
   - Evaluate their functionality and effectiveness in fulfilling the intended purpose, such as providing exhibition spaces, cultural centers, or pavilions.
   - Analyze user feedback and reviews to understand the practicality and usability of the gridshell structures.

5. **Comparative analysis**
   - Assess the intended and actual applications of gridshell structures in Moscow.
   - Evaluate their functionality and effectiveness in fulfilling the intended purpose, such as providing exhibition spaces, cultural centers, or pavilions.
   - Analyze user feedback and reviews to understand the practicality and usability of the gridshell structures.

6. **Recommendations**
   - Suggest improvements in design, construction techniques, or applications to enhance the performance and functionality of gridshell structures in Moscow.
   - Highlight potential areas for research and development to advance gridshell design and construction practices.

### 3 Results

#### 3.1 Design of Gridshell Structures in Moscow

When it comes to gridshell structures, the design process starts with a thorough understanding of the project requirements, including size, location, and budget constraints. Architects and engineers analyze the site, considering factors like topography, climate, and surrounding buildings, to ensure the design integrates seamlessly into the Moscow landscape[3].
Advanced computer modeling and simulation techniques are employed to create intricate and visually striking designs. They can be effectively used in combination with physical models to improve the overall design process achieving architectural, structural and manufacturing results barely achievable through the only use of physical models [4]. The use of parametric design allows for complex geometries and customizable structures, enhancing the aesthetic appeal of the gridshell. The process also involves collaboration with skilled fabricators and contractors to ensure successful execution, adhering to the highest standards of construction and safety[5]. Overall, the design of gridshell structures in Moscow showcases the city's commitment to pushing boundaries and embracing architectural innovation.

Structural analysis is conducted to determine the load-bearing capacities and material requirements for the gridshell. Integrating this process during the conceptual design phase has the potential to reconcile structural form and architectural geometry, resulting in efficient and architecturally expressive forms [6].

Also, with the development of computer-aided design the use of structural optimization or finding the best solution for the problems created during the design process has entered into practice. Despite the fact that gridshell structures are a big part of contemporary architecture, their geometry and construction properties can be rather unfitting when overlooking other aspects of the production and static performance, and therefore must be optimized [7].

3.1.1 Design challenges and approaches taken to overcome them

Gridshell structures, which are three-dimensional shell structures made up of interconnected and intersecting grid members, pose several design challenges. One major challenge is the complex geometry and curvature inherent in these structures, making the fabrication and construction process difficult[8]. To overcome this challenge, advanced computational tools[9] and parametric modeling techniques are used to accurately design and analyze the grid members and their connections[10]. Another challenge is the structural stability of gridshell structures, as they usually have limited load-bearing capacity[11]. To address this, engineers incorporate additional structural elements such as tension cables or diagonal bracing to enhance stability and distribute loads effectively. Additionally, sustainability is a growing concern, and hence, the use of sustainable materials and efficient construction techniques are adopted to minimize the environmental impact of gridshell structures[12]. Overall, overcoming these design challenges involves a combination of advanced computational tools, careful structural analysis, and innovative construction methodologies.

3.2 Construction Techniques and Processes

Gridshell structures in Moscow make use of various construction techniques to achieve their unique and visually striking designs. These techniques combine the principles of grid structures and shell construction to create lightweight and flexible structures that are also structurally stable. Here is an overview of the construction techniques commonly employed for gridshell structures in Moscow:

Grid Structure Design: Gridshell structures are built on a grid framework consisting of intersecting support beams or trusses. The grid provides the basic skeletal structure[13] and distributes the load across the entire structure. This design approach allows for greater flexibility in shaping the gridshell.
Steel Frame Construction: Gridshell structures typically utilize a steel frame construction method. Steel frames provide strength, durability, and flexibility, making them ideal for supporting the curved elements of gridshell structures[5]. The steel frame is carefully designed and fabricated to withstand the loads and stresses imposed on the structure[14].

Timber Gridshell Construction: Timber gridshells are another popular construction technique used in Moscow[10],[15]. Timber gridshells offer natural warmth and aesthetic appeal. In this construction method, laminated timber beams are bent and curved to form the gridshell structure. The timber gridshell is then connected using specialized joints and fixings.

Two types of the gridshell construction are presented in Figure 2.

Fabrication and Assembly: The fabrication process begins with the production of the individual grid elements, such as steel or timber members. These elements are manufactured off-site and then transported to the construction site for assembly. The grid elements are carefully fitted and secured according to the predetermined design to create the desired gridshell shape.

Curvature and Tensioning: Achieving the desired shape and curvature of the gridshell is a critical step in the construction process[10]. Gridshell structures often require the use of tensioning techniques to maintain their shape and stability[16]. Steel cables or fabric membranes are commonly used to tension the structure, ensuring the integrity and longevity of the gridshell.

Cladding and Finishes: Once the gridshell structure is complete, it is often clad with various materials to provide weatherproofing, insulation, and aesthetic enhancements. Common cladding materials include glass, polycarbonate panels, or fabric membranes[3],[16]. The choice of cladding material depends on factors such as the desired transparency, thermal performance, and visual appearance.

Structural Analysis and Testing: Before the construction of a gridshell structure, detailed structural analysis is carried out to ensure its stability and safety[3],[17]. This involves computer simulations and physical testing to determine the loads, stresses, and potential points of weakness. Structural analysis helps optimize the design and construction process, ensuring that the gridshell structure meets the required safety standards[18].

4 Discussion

Gridshell structures have gained immense popularity in Moscow due to their unique structural and aesthetic properties. These lightweight, flexible, and visually appealing structures have found numerous applications throughout the city[17]. By combining the
principles of grid systems with the strength and versatility of shell structures, gridshells offer an innovative and versatile solution for architectural and structural design.

One prominent application of gridshell structures in Moscow is in cultural and exhibition spaces. The Moscow International Business Center, also known as Moscow City, features several iconic buildings with gridshell elements. For instance, the Federation Tower complex incorporates a gridshell structure in its covered outdoor plaza, providing shelter for pedestrians while creating a visually striking landmark. This application highlights the ability of gridshells to enhance the overall aesthetic appeal of public spaces.

Furthermore, gridshell structures have found extensive use in sports facilities. For example, the Luzhniki Stadium, one of the main venues for the 2018 FIFA World Cup, boasts a retractable roof constructed using a gridshell design[19]. This application allows for easy adjustment of natural lighting and ventilation, creating an optimal environment for both athletes and spectators. Gridshell structures in sports facilities contribute to the creation of modern and functional architectural spaces.

Gridshells have also been employed in residential and commercial buildings in Moscow. Some apartment complexes incorporate gridshell structures within their facades, providing an eye-catching visual element and adding complexity to the overall architectural design. Additionally, gridshell structures are used in shopping centers (Paveletskaya square) and retail spaces to create unique canopies and atriums, enhancing the shopping experience for visitors.

Another notable application of gridshell structures in Moscow is in the field of transportation infrastructure. Terminal “D” of the Sheremetyevo International Airport is a building that meets all modern and advanced trends in global airport design. The key structure in the building can be considered a main huge canopy with a span of 90 m, on which a pedestrian bridge connecting the terminal building and a multi-level parking lot is suspended. A gridshell roof of the canopy emphasizes the bright and expressive appearance of the building and demonstrates the ability of gridshells to create expansive and light-filled spaces, encouraging a sense of openness and connectivity.

The bright examples of using grid structures are presented in Figure 3.

![Fig. 3. The buildings with a gridshell structures (Photo: archi.ru)](image)

**4.1 Comparison of two Case studies of gridshell projects in the city of Moscow**

**4.1.1 Case Study 1: Gridshell Pavilions in Zaryadye Park**

Zaryadye Park [20] is a public park in the heart of Moscow, adjacent to the Red Square and the Kremlin. It features several unique architectural structures, including two gridshell
pavilions - the Nature Center and the Media Center. The gridshell pavilions were designed by the architectural firm Diller Scofidio + Renfro.

**Design and Structural System:** The gridshell pavilions in Zaryadye Park showcase an innovative and complex structural system. The architects utilized a diagrid pattern, which consists of a diagonal grid of steel beams. This structural system was chosen because of its ability to distribute forces evenly across the pavilion's surface while minimizing the need for additional support columns[14]. The gridshell design allows for a large open space beneath the pavilion while still providing adequate structural stability.

**Materials and Construction:** The roofs of gridshell pavilions consist of free complex forms [21] and were constructed using steel tube beams, with varying diameters and thicknesses depending on the load-bearing capacity required in each area. The pavilions' double-layered glass facades enclose the open spaces, providing insulation while allowing for natural light and panoramic views of the park and cityscape. The metal cladding on the exterior provides additional protection from the elements and adds to the pavilions' aesthetic appeal.

**Function and Aesthetic:** The nature center gridshell pavilion serves as an educational facility, housing exhibition spaces, classrooms, and a media center. The media center gridshell pavilion functions as a multipurpose event space with a large auditorium. Both pavilions aim to create an immersive experience for visitors, connecting them with nature and technology. The intricate geometry of the gridshell design enhances the overall aesthetic appeal, making the pavilions iconic architectural landmarks in Moscow.

### 4.1.2 Case Study 2: Gridshell Roof of the Moscow Polytechnic Museum

The Moscow Polytechnic Museum is a scientific and technological museum. As part of its renovation and expansion, a gridshell roof was constructed to cover the museum's central atrium[22]. The gridshell roof was designed by the architecture firm SPEECH.

**Design and Structural System:** The gridshell roof of the Moscow Polytechnic Museum follows a similar structural system to the pavilions in Zaryadye Park. It utilizes a diagrid pattern made of steel beams to create a self-supporting structure that spans the atrium. This design allows for a large open space beneath the roof without the need for numerous supporting columns.

**Materials and Construction:** The gridshell roof is constructed using steel tube beams, similar to the Zaryadye Park pavilions. The use of lightweight materials helps create the desired structural form while maintaining the visual transparency of the atrium. The roof is covered with a translucent material that allows natural light to fill the space below while protecting against weather elements.

**Function and Aesthetic:** The gridshell roof of the Moscow Polytechnic Museum provides a unique visual feature within the museum. It covers the central atrium, which serves as a gathering space and a circulation hub for visitors. The intricate geometric design of the gridshell roof adds to the museum's architectural identity and provides a dynamic and visually stunning element to the overall space.

**Comparison:** Both case studies showcase the use of gridshell structures in Moscow's architectural projects. The gridshell pavilions in Zaryadye Park focus on creating immersive spaces that blend with nature and technology, providing educational and event spaces for visitors. In contrast, the gridshell roof of the Moscow Polytechnic Museum primarily serves as a visual feature within the museum's central atrium, creating a unique architectural identity. Despite their different functions, both projects employ a diagrid pattern of steel
beams and utilize lightweight materials to create self-supporting structures and visually appealing aesthetics. The structures of the shells are shown in Figure 4.

Fig. 4. The architecture of the Zaryadye park and Moscow Polytechnic Museum (Photo: turizm-centr.ru, orchidea-shop.ru, stroi.mos.ru)

4.2 Identification and analysis of challenges faced during the design and construction process

Gridshell structures, characterized by their complex geometry and lightweight construction, offer unique architectural opportunities and challenges. One prominent challenge in building gridshell structures in Moscow is the harsh climatic conditions[23]. Moscow experiences long, cold winters with heavy snowfall and strong winds. This presents significant difficulties in maintaining the structural integrity of gridshell designs that rely on delicate, interconnected elements. Engineers and architects must carefully consider the choice of materials, structural connections, and load calculations to ensure the gridshell can withstand the severe weather conditions prevalent in Moscow[14],[24].

Another challenge is the strict building regulations and codes enforced in Moscow. Russian building standards often differ from international codes, and these variations can impact the design and construction process. Architects and engineers must navigate through specific regulations regarding gridshell structures, which may require specialized knowledge and expertise. They must also comply with fire safety regulations, seismic regulations, and other key factors that shape the design and construction process.

Additionally, gridshell structures in Moscow often require complex foundation solutions due to the city's variable soil conditions. Moscow sits on layers of different geological formations, including clay, sand, and peat, which create challenges for stable foundations. Engineers must conduct thorough geotechnical investigations to determine the type of foundation and stabilization methods required to support the gridshell structure adequately[25].

Beyond technical challenges, gridshell projects in Moscow may also face budgetary and logistical constraints. Constructing innovative structures like gridshells often involves higher costs, as they require specialized materials, fabrication techniques, and skilled labor. Coordinating the assembly and installation of the intricate gridshell components can also pose challenges, especially in densely populated urban environments like Moscow.

To overcome these challenges, a comprehensive approach is crucial. Collaborative efforts are necessary among architects, engineers, contractors, and local authorities to ensure the successful design and construction of gridshell structures in Moscow. Thorough planning, site-specific analysis, and efficient project management are essential to address the climatic, regulatory, geotechnical, and logistical hurdles encountered during the design and construction process.
4.3 Exploration of potential future directions for gridshell structures in Moscow, including innovative design techniques

The exploration of potential future directions for gridshell structures in Moscow is an intriguing area of research and development. Gridshell structures are architectural systems that utilize a framework of interconnected beams to create lightweight yet robust surfaces. These structures have gained popularity due to their efficient use of materials and ability to create unique and striking designs.

In Moscow, there is enormous potential for the application of gridshell structures in various architectural projects. The city's modern skyline and ambitious urban development plans make it an ideal location to explore innovative design techniques and expand the usage of gridshell structures. One potential future direction is the implementation of advanced digital design tools and fabrication techniques[20]. Moscow's rich architectural heritage combined with cutting-edge technology can lead to the creation of gridshell structures that are not only visually striking but also highly functional. Digital tools such as parametric design software can aid architects in creating complex and dynamic gridshell forms, enhancing the city's architectural landscape[14].

Furthermore, the expansion of usage for gridshell structures in Moscow can lead to a range of exciting possibilities. Currently, gridshell structures are mainly utilized in open-air structures such as pavilions and canopies. However, there is potential for their integration into larger building projects, such as commercial or residential complexes. This expansion would not only provide innovative design solutions but also contribute to sustainable architecture by optimizing material usage and reducing carbon footprint.

Another area of exploration is the integration of sustainable materials and renewable energy systems into gridshell structures. Moscow's commitment to sustainability and green initiatives can be further reinforced through the use of environmentally friendly materials such as timber or bio-composites in gridshell construction. Additionally, incorporating renewable energy systems, such as solar panels, into the gridshell structures can enhance their sustainability and contribute to the city's renewable energy goals.

5 Conclusion

Gridshell structures have gained immense significance in Moscow's architectural landscape due to their unique design, sustainability benefits, and ability to maximize space. These structures not only enhance the visual appeal of the city but also provide functional and flexible spaces for cultural and recreational activities. Gridshell structures have also found diverse applications, ranging from cultural and exhibition spaces to sports facilities, residential and commercial buildings, and transportation infrastructure. Their lightweight and visually appealing nature, coupled with their structural strength, make them an ideal choice for architects and designers aiming to create innovative and distinctive architectural structures. As Moscow continues to evolve as a modern city, the incorporation of gridshell structures will likely remain a key element in shaping its architectural future.

Furthermore, the key design principles utilized in Moscow's gridshell structures include structural efficiency, curvature and form finding, adaptive geometry, integration of technology, environmental sustainability, and aesthetic appeal. This combination of factors results in the creation of remarkable architectural landmarks that reflect the city's creativity and innovation in design and engineering. On the other hand, the construction techniques employed for gridshell structures in Moscow involve a combination of steel or timber frame construction, careful assembly, curvature, tensioning, cladding, and rigorous structural
analysis. The design and construction process of gridshell structures in Moscow presents several unique challenges. From the harsh climatic conditions to strict building regulations, the complex foundation requirements to budgetary considerations, each aspect must be carefully identified and analyzed.

Finally, the exploration of potential future directions for gridshell structures in Moscow holds immense promise for architectural innovation. With the introduction of advanced digital design tools and the expansion of their use in larger construction projects, as well as with the use of environmentally friendly materials and renewable energy systems, gridshell structures can become an integral part of the urban landscape of Moscow.

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