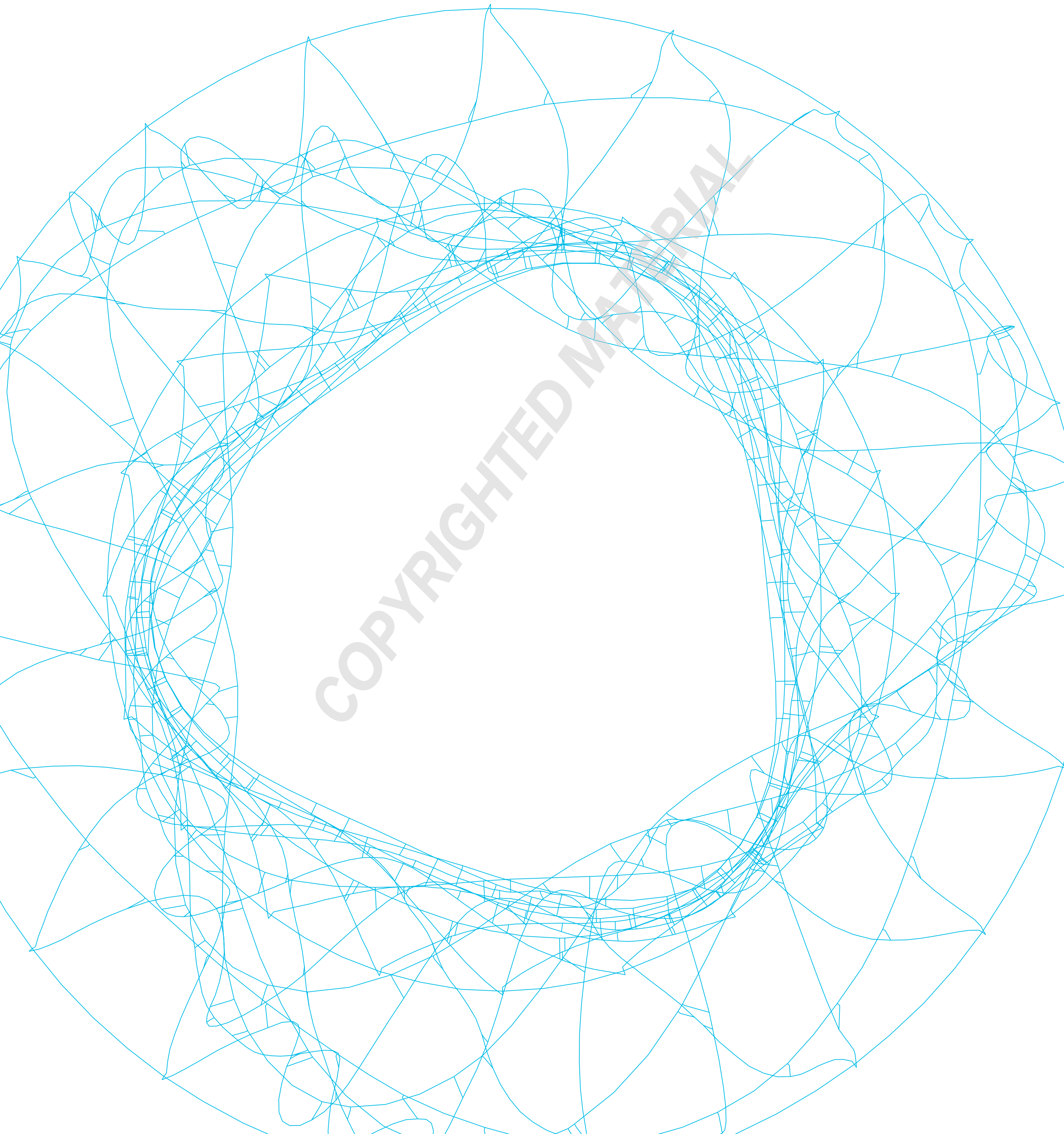


Building with hyperbolic lattice structures

Building with hyperbolic lattice structures began with the Russian engineer and polymath Vladimir Grigor'evič Shukhov (1835–1939). After a short summary of the earlier development of building with iron, this chapter will cover the history of this form of construction.

The development of building with iron in the 19th century

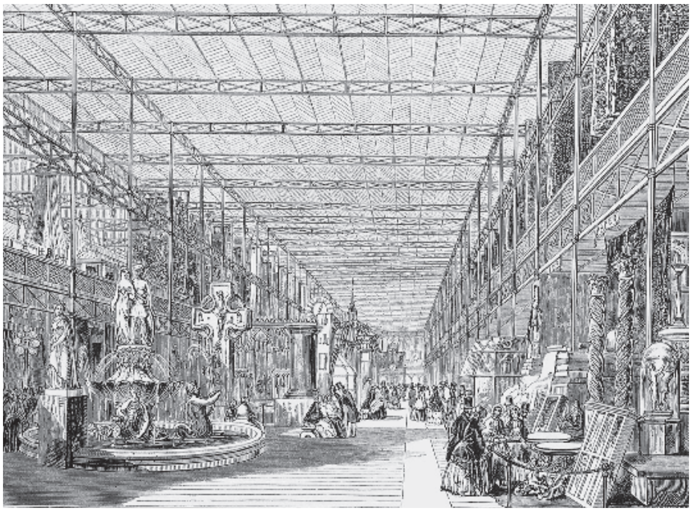
The threshold of the 19th century saw many new types of different load-bearing structures arising in western Europe. The conditions for this turn of events were created from the end of the 18th century by the rapid pace of industrialisation and the material being used to make new tools and machines – iron. New methods of production of this metal meant that ample quantities were also available for construction. After thousands of years of the predominance of stone and wood in buildings, architects and engineers were able to use iron not just as a means of making connections but also as a construction material in its own right. The characteristic properties of the new construction material, in particular its high strength, the toughness of wrought iron and, in contrast to the latter, the brittleness of cast iron demanded new types of construction and details. At the same time, the beginning of the 19th century presented architects and engineers with construction tasks quite unheard of before. Spacious railway stations, large exhibition halls for industrial expos and glazed arcades called for new structural solutions to bridge the often considerable spans. The new material's high strength gave designers the opportunity to realise relatively lightweight and delicately proportioned structures.

But designing in iron was destined to have a long developmental phase. Until the middle of the 19th century, engineers cautiously felt their way forward with new types of structures and methods of construction, which led the first iron roof trusses to look very much like their wooden predecessors. However, the creation of iron structures required a complete rethinking of design and construction planning: The necessary prefabrication of the structural members and their details in factories was shifting the focus of the building process from the construction site to the workshop; factory assembly was replacing the flow of conventional skilled craftsmen's operations on site. The expense and effort required to make casting moulds and fabricate connections forced designers to repeat elements as many times as possible. Early consideration of how members could be joined to one another efficiently and erected quickly was increasingly influential in the design and led to new forms of construction, systems and details: "Repetitive elements and standardized connections characterize a system approach to design that implies organizing component hierarchies rather than composing forms," writes Tom F. Peters in "Building the Nineteenth Century". [1] Modular building systems like the one used for the Crystal Palace, built to house the Great Exhibition of 1851, in London epitomise this development (Fig. 1). The details in these structures became more and more sophisticated, not only successfully contributing to the continuity of form and load transfer but also fulfilling a wide range of other requirements, such as the ability to accommodate temperature fluctuations and fit in with the sequence of operations on site. [2]

Among the many progressive building projects completed by the middle of the century were the cupola of the corn exchange (Halle au blé) by François-Joseph Bélanger and François Brunet in Paris (1811), the casting shop at the Sayn ironworks in Bendorf by Carl Ludwig Althans (1830) and the Palm House in Kew Gardens in London by Richard Turner (1848), all of which have primary load-bearing elements made from cast iron. Developments in bridge-building also had an impact on buildings, for example cast-iron arches, which are usually composed of several segments. New systems appeared, such as the Wiegmann-Polonceau girder, which can be seen in countless railway stations and market halls, and its further development, the sickle girder, which was first used by Richard Turner in Lime Street Station in Liverpool (1849). [3]

"The 1840s marked the end for the first epoch of iron construction, which had been very largely cast iron based," remarks Werner Lorenz in his book "Konstruktion als Kunstwerk". [4] Following the invention of the Bessemer (1856) and the Siemens-Martin smelting processes

Hyperbolic structures: Shukhov's lattice towers – forerunners of modern lightweight construction, First Edition. Matthias Beckh.



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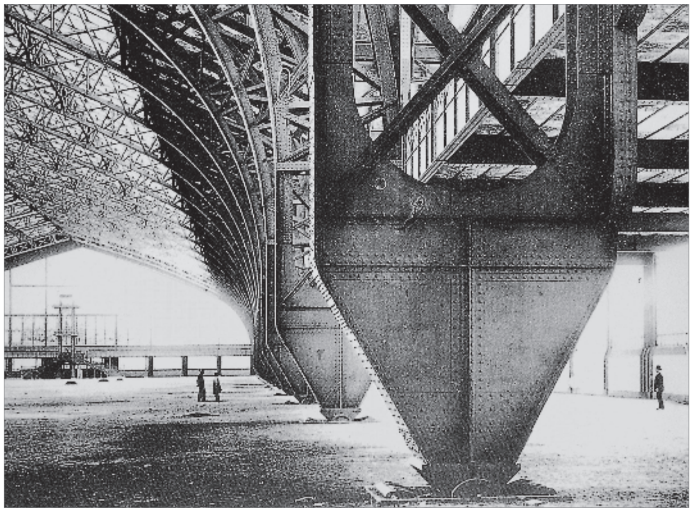

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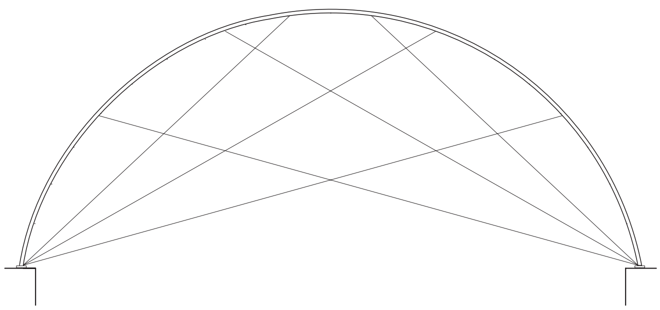
(1864), wrought iron and eventually steel became cheap and available in sufficient quantities. From 1845, it was possible to produce rolled ⌶-sections, which quickly became very popular. In addition to these technical and industrial advances, the use of the new materials was accelerated further thanks to the development of structural mechanics, which was increasingly seen as a separate engineering discipline. Largely responsible for the recognition of this new discipline was Claude Louis Navier, through his outstanding paper on the elastic behaviours of structures (originally published in French in 1826 [5]), which was available in most European languages from the middle of the century, alongside publications on the theory of trussed frameworks by Johann Wilhelm Schwedler and Carl Culmann (1851) [6], with Culmann also being responsible for developing the technique of graphic statics (1862). These technical and scientific innovations encouraged the development between 1850 and 1880 of many new load-bearing systems whose dimensions were no longer determined empirically or intuitively as before but by calculation. At the heart of the development were the countless new truss systems that came to the fore at this time. "If the fifties were the decade of cautious exploration of new systems, then the sixties began the classic era of trusses in buildings." [7] The railway station halls of this time in metropolises, such as London (e.g. St. Pancras and Victoria stations) and Paris, bear clear witness to the advances in spanning capability and efficient use of materials. Further new load-bearing systems that became very popular because they are statically determinate and therefore simple to design included suspended span girders (also known as Gerber beams) and three-pinned arches, which were used in buildings for the first time by Schwedler in 1865 and set against a splendid backdrop in Charles Louis Ferdinand Dutert and Victor Contamin's Galerie des Machines (Fig. 2), built for the Paris International Exhibition in 1889 [8]. In 1863, Schwedler's success with his "Schwedler domes" was the breakthrough for three-dimensional reticulated shells.

In the last quarter of the 19th century, the pace of innovation in iron and steel construction in western Europe hit a plateau. While new records for girder spans and building heights continued to be set, the development of a canon of new types of structures was more or less at an end, their design mastered. The eyes of engineers in western Europe were now focused mainly on a new material developing at a tremendous pace at this time: reinforced concrete.
The important stimulus to architecture and its revival that the new style of engineering structures of the 19th century and their aesthetics gave is underlined by a quotation from Henry van de Velde, the Belgian architect and designer who was involved in the Bauhaus movement. Writing on the role of the engineer in 1899, he said "there is a class of people from whom the title artist can no longer be withheld. These artists, these creators of the new architecture, are the engineers. The extraordinary beauty inherent to these works of engineers, is based on an unawareness of their artistic possibilities – as it is with the creators of the beauty of our cathedrals, who were also unaware of the magnificence of their works." [9]

The work of Vladimir G. Shukhov, pioneer of lightweight construction
The last quarter of the 19th century was a period of advancing influence for the Russian engineer and inventor Vladimir G. Shukhov, one of the most important pioneers of lightweight construction and modern building with iron and steel. Shukhov was as significant to the development of lightweight structures as outstanding engineers such as Robert Maillart or Pier Luigi Nervi were to the advancement of modern reinforced-concrete construction. However, it is Shukhov's extraordinary versatility which allows him to stand comparison with similar universally proficient engineers at the end of the 19th century such as Alexander Graham Bell or Gustave Eiffel.
A wealth of design principles, which are still applied in structural steelwork today, find their roots in Shukhov's works. He was responsible for the first doubly curved gridshell, built the first suspended roofs and developed extremely slender arched girders, which were

1 Crystal Palace, London (GB) 1851, Joseph Paxton, interior view from "The Crystal Palace Exhibition Illustrated Catalogue", London 1851
2 Galerie de Machines, Paris (F) 1889, Charles Louis Ferdinand Dutert, Victor Contamin

3 Schematic section (a) and interior photograph (b) of the arcade roofs of the GUM department store, Moscow (RUS) design from 1890
4 Gridshell mesh roof over a pump station, Grozny (RUS) ca. 1890
5 3D visualisation of the doubly curved gridshell, Vyksa (RUS) 1897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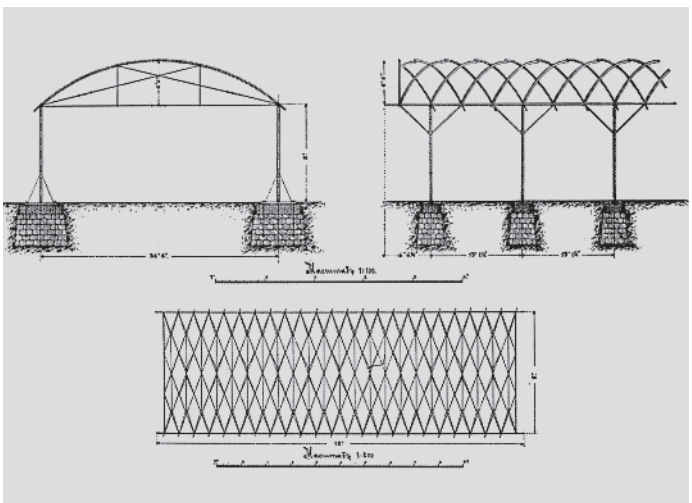
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stiffened by thin tensile members. But it is not this technical finesse alone which makes his structures so fascinating. The delicate, almost dematerialised, structures have a high degree of aesthetic attraction from which it is difficult to disengage. In his homeland, Shukhov was decorated with the highest national awards and is still spoken of today in modern Russian society. However, outside Russia his diverse and extraordinary works remain for the most part unknown. It was not until the publication in 1989 of "Vladimir G. Šuchov. 1853–1939 Die Kunst der sparsamen Konstruktion" [10] by Rainer Graefe, Murat Gappoev and Ottmar Pertschi that the interest of the broader professional public was awoken in western Europe.

Outline biography

Shukhov was born in 1853 in the small town of Grajvoron near the Ukrainian border and his youth coincided with a time of great social and economic upheaval in Russia. Alexander II implemented numerous reforms in the backward tsardom. Among other measures, he abolished serfdom in 1861 and reformed the universities. The monopolistic, state-controlled policies produced an upturn in the mining and heavy industries and a gain in the pace of industrialisation in Russia, which had been rather late in starting. In this time of rapid change, the 18-year-old Shukhov enrolled at the polytechnic in Moscow, which had emerged from the earlier state craftsmanship schools and offered a very advanced curriculum. In addition to a thorough study of mathematics and physics, his education also gave him a practical grounding in the polytechnic's own workshops. In 1878, two years after his graduation as a "Mechanic Engineer", Shukhov began his professional life at the engineering company Alexander V. Bari in Moscow, which he had come across at the International Exhibition in Philadelphia and would be associated with for much of his life. Soon after his appointment, Shukhov rose to become chief engineer and was named company manager in 1918 following nationalisation. [11]
His first assignment with Bari took him to the Russian colony of Azerbaijan, where he quickly made a crucial contribution to the expansion of the Russian oil industry: he developed an industrial plant for the thermal cracking of crude oil, designed the first Russian pipeline and constructed the world's first pipeline for preheated mazut, a viscous liquid residue from petroleum distillation. At the same time, he designed and built the first cylindrical crude oil tanks, the same principle being still in use today. On his return to Moscow, he continued to work with the same intensity. In 1879, Shukhov patented a nozzle for burning mazut, and in 1885 he designed the first Russian tanker ships. A few years later, he filed patents for horizontal and vertical boilers for which he would receive numerous awards.
The abundance of his engineering innovations and inventions seems almost limitless, as do his fields of activity. From 1890, Shukhov turned his attention increasingly towards buildings. The following sections cover his most pioneering innovations in the field of construction engineering. [12]

Arched girders

In 1890, Shukhov started work on the design of the barrel-shaped roofs for arcades in the GUM department store, situated directly adjacent to Red Square in the centre of Moscow (Fig. 3). Their semicircular arched elements bridge the 15 m spans and have a sophisticated stiffening system: Shukhov attached three slender ties to each impost, which were then fanned out and connected to the arch.
To understand the way this completely new method of construction worked requires some familiarity with the deformed shape of an arch. Arched girders are particularly efficient when supporting uniformly distributed loads, but asymmetric loads, such as wind or a one-sided snow load, cause the arch to deform out of line; only the flexural stiffness of the arch then resists the deformation. This necessarily higher stiffness can only be achieved by having a larger cross section, which makes the structure relatively heavy.
The radial arrangement of ties is designed specifically to prevent this deformation. As a result, the cross sections can be kept small. Shukhov designed almost all his arched girders according to this principle. After this method of construction had been long forgotten, several structural engineers in the 1990s rediscovered and further developed his design approach. Examples include the station roof in Chur by Peter Rice and the radially stiffened arch elements frequently used by Jörg Schlaich for his reticulated shells.

Lattice gridshells

1890 was also the year Shukhov built the first lattice gridshells. While the reticulated shells of Berlin engineer Johann Wilhelm Schwedler, which were known as "Schwedler domes", had members of different sizes to suit their loads, Shukhov's lattice shells were made up of elements of the same size. For the roof of a pump station in Grozny, he used two layers of circular arc segments made from steel profiles that ran from edge beam to edge beam to create a shape in plan composed of rhomboid meshes (Fig. 4). The beams, fabricated out of Z-profiles, are riveted together at the intersection points, the shear forces are carried by horizontal circular rods. The radial stiffening system of the arched girder mentioned above is used again here to stabilise the singly curved surface. [13]
The contract for the temporary exhibition hall for the All-Russia Exhibition in Nizhny Novgorod helped this form of construction to make its final breakthrough. Bari constructed four large halls with more than 16 000 m^2 of exhibition space using gridshells. The popularly named "roofs without trusses" [14] achieved spans of up to 32 m. Bari's drawings demonstrate that a great many warehouses and factory buildings with a variety of spans, rises and numbers of ties were built in Russia using this basic design.
The hall designed by Shukhov in 1897 in the metal production city of Vyksa reached a whole new level of quality. The construction principle of the barrel-shaped gridshell roof developed for Grozny is led along a parabolic – the first doubly curved gridshell in the world. Analysis of the structure and the historic calculations shows that the double curvature of the gridshell was chosen for practical construction reasons and not on structural engineering grounds. [15] Today, after lying unused for 20 years, the much neglected hall is in urgent need of refurbishment. It has been extensively investigated and recorded in recent years. [16] Plans for refurbishment and new use concepts are already being discussed. The unusually light construction has lost none of its elegance, even 110 years since its erection, as the visualisation of the internal space shows (Fig. 5, p. 16). [17]

6 Doubly curved glass roof of the British Museum, an example of a modern reticulated shell, London (GB) 2000, Foster and Partners
7 Cross section through the suspended roof on the rotunda at the All-Russia Exhibition in Nizhny Novgorod (RUS) 1896
8 Drawing from Shukhov's patent application No. 1896


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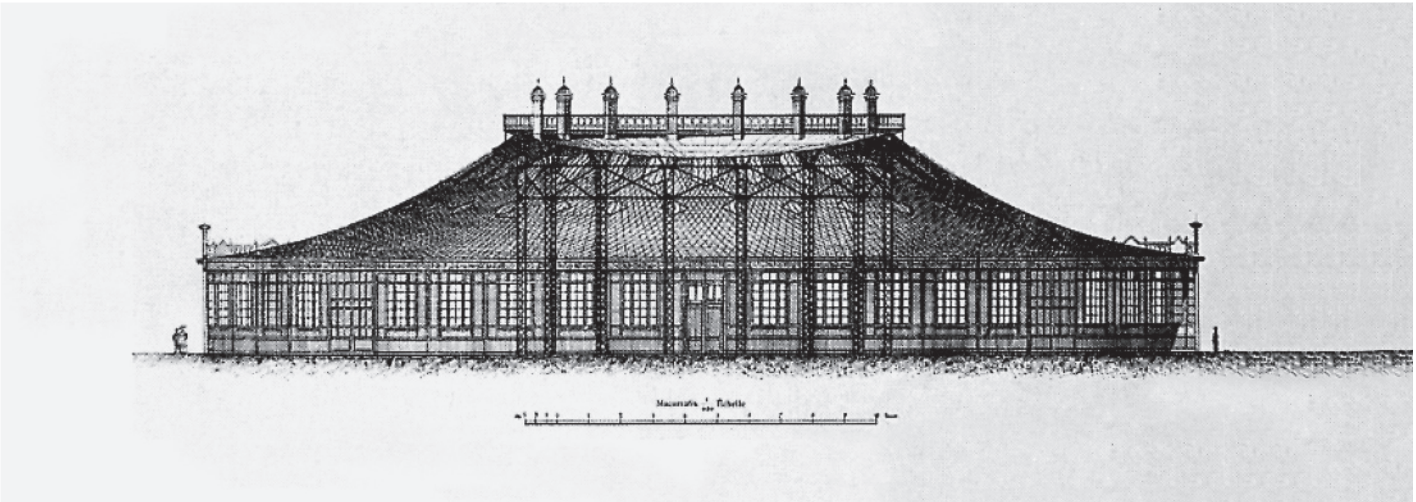
Suspended roofs

In 1895, Shukhov registered a patent for a suspended mesh roof in which he transformed his compression-loaded gridshell system into a tensile structure: he suspended two layers of steel flats, skewed in opposite directions to one another, between a tensile top and a bottom compression ring. In plan, the meshes were the characteristic diamond shape. He created the world's first steel anticlastically curved tensile structure. Just as he did with the gridshells, Shukhov used this new form of construction to span more than 10000 m^2 at the All-Russia Exhibition, this time with four suspended roofs. The most spectacular example is the rotunda with a diameter of 68 m, which is a combination of two suspended roofs (Fig. 7). Between a higher ring supported by 16 lattice columns and a compression ring on the outside are two families of steel flats, which create a fine mesh and span the 21.5 m between the two rings. The dimensions of the 640 steel strip sections are only 50 ≈ 5 mm. The interior of the rotunda is also covered by a tensile structure. Though here, the load-bearing structure is not a mesh, but a thin membrane. A suspended calotte of riveted sheets, a mere 1.6 mm thick, hangs over the 25 m diameter inner circle. This building therefore used two tensile structures whose horizontal support forces to some extent cancelled one another out. [18]

In spite of their low self-weight, no more suspended grid roofs were built in the years after the All-Russia Exhibition. This form of construction seemed to have been forgotten until almost 60 years later when the Polish-American architect Matthew Nowicki designed the famous suspended cable net for the Dorton Arena in Raleigh in 1953, which prepared the way for Frei Otto and his cable net structures.

The hyperbolic lattice towers of Vladimir G. Shukhov

In 1896, Shukhov developed a new type of structure which had no predecessors in building history: the hyperbolic lattice tower. The doubly curved surface of a one-sheeted hyperboloid can be created by rotating a skewed line about a vertical axis. Shukhov put this principle to use and created a mesh of two counter-running families of straight members on this surface.



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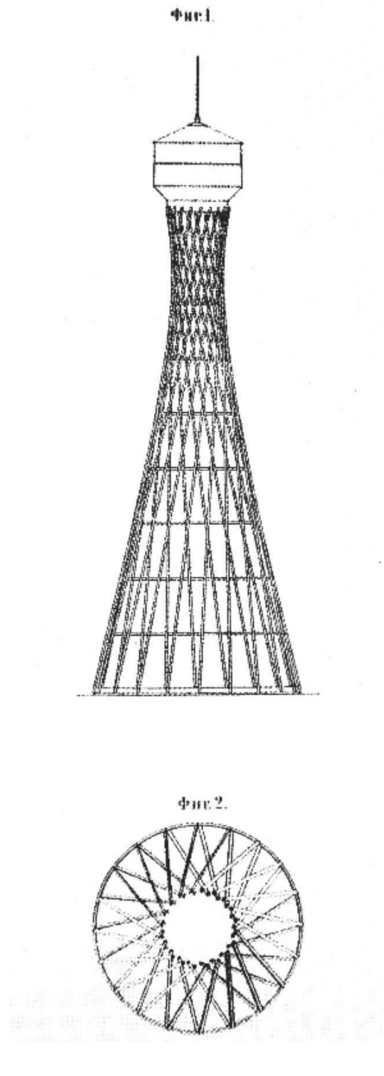
The resulting structure is relatively light and exceedingly efficient; it is also simple and quick to erect. For these reasons, but also for its characteristic shape, it was used extensively in Russia and her colonies – mainly for the countless water towers built according to this principle. The method of construction was also used for shot towers (used for the production of lead shot) and lighthouses as well as radio and electricity transmission masts. The structures were also used as lookout masts on ships of the Russian and United States navies. [19]

Patent No. 1896

On 11th January 1896, Shukhov submitted a patent application in Moscow for his new type of tower structure, which was granted on 12th March 1899 (Fig. 8). He described the content of the patent in the following words: “A lattice-form tower characterised in that its load-bearing structure consists of straight wooden beams, iron tubes or angle profiles which cross over one another and lie on the directrix of a solid of revolution and that takes the form of a tower. They are riveted to one another at the crossing points and also connected by horizontal rings.”
Shukhov described the advantages of this method of construction thus: “The tower built in this way is a stable structure which resists extreme forces and uses very little material. The main application of these structures could be as water towers or lighthouses.” [21]
How Shukhov arrived at his invention cannot be precisely reconstructed from the available records. Grigorij M. Kovel’man wrote on the subject: “I thought a long time about the hyperboloid. Then something evidently took place in my subconscious but did not spring directly from it.” [22] As well as the theory that a small wicker basket in the form of a hyperboloid, which Shukhov used in his office as a waste paper bin, could have served as the inspiration, it may also have been simply the sound teaching during his studies that provided the basis for the idea. Shukhov recalled “in the lectures on analytical geometry, it was said that hyperboloids were good training for the intellect, but had no practical uses.” [23]
Another supposition is that an important source of inspiration for



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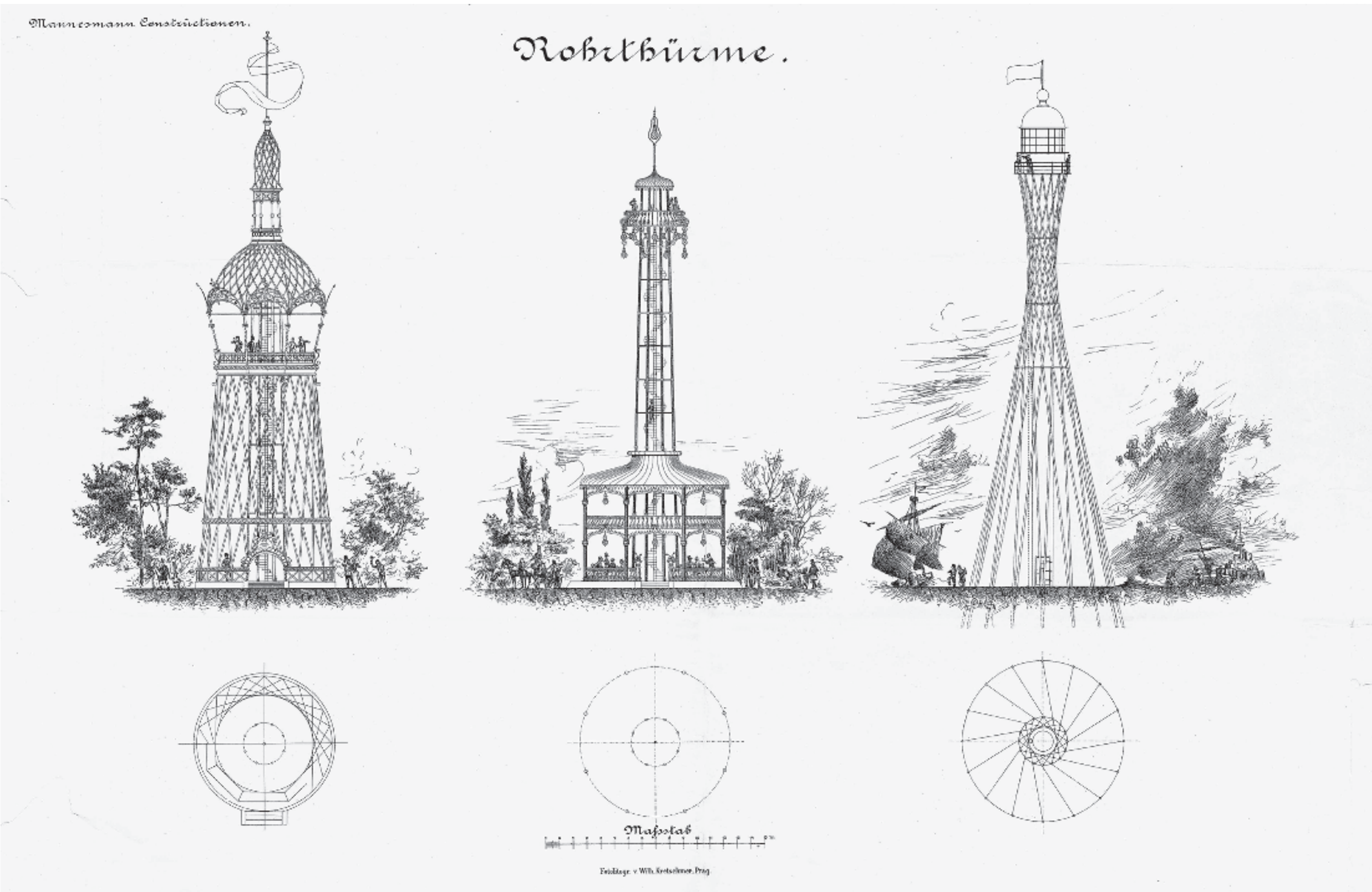

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9 Mannesmann tube towers, undated
10 First hyperbolic lattice tower by Shukhov at the exhibition in Nizhny Novgorod (RUS) 1896 (a) and at its present location in Polibino, southern Russia (b)
11 Water towers in Kolomna (RUS) 1902 (a), Mykolaiv (UA) 1907 (b), Kharkiv (UA) 1912 (c) and Džebel (TM) 1912 (d)

Shukhov was the non-Euclidian geometry developed by the Russian mathematician Nikolai Lobatschewski in 1829. [24] This theory, which has no further substantiation, would be very difficult to verify in any case.
The most probable assumption is that he had the idea of the hyperbolic tower after extensive consideration of the suspended roofs he developed earlier: if the curved steel strips of his rotunda roof are replaced by straight members, it results in the new form of structure.

The tubular towers of Mannesmann

In 1885, brothers Reinhard and Max Mannesmann invented the process of skew rolling to manufacture seamless pipes. This very quickly transformed the small Remscheid file-making factory into a major company with subsidiaries and business dealings all around the world. In the unpublished documents of Reinhard Mannesmann, which can be found in the archives of the German Museum in Munich, there is a drawing of lookout towers made from tubular profiles, two of which are in the form of a hyperboloid (Fig. 9). According to the information in the archive, the drawing, which is not dated, must have been prepared between 1890 and 1895 and had already been published in the papers of Ruthild Brandt-Mannesmann and Berthold Burkhardt. [25] The extent to which the drawing had been been in circulation at the time can no longer be determined.

Considering the enormous importance seamless tubes would have been in particular to machine making – in comparison with the welded alternatives, they are more reliable and can withstand higher pressures – and the fact that Mannesmann supplied the pipes for the first pipeline from Balachna to Cherny Gorod – with Bari as the main contractor for Nobel Brothers – there would seem to be a great deal of overlap between Shukhov's spheres of activity. [26] Possibly Shukhov knew of the designs for the Mannesmann tubular towers, but there is no evidence for this. The Mannesmann tubular towers themselves were never built; the preliminary design was more likely a demonstration of the diverse fields of application of the new product. What cannot be disputed in any case is that Shukhov was the first to build hyperbolic lattice towers.

Water towers

Soon after the submission of patent application No. 1896, Shukhov built his first tower using his new principle. He erected a water tower with a height of 25.6 m and a shaft with 80 straight members made out of angle profiles for the All-Russia Exhibition in Nizhny Novgorod (Fig. 10 a, p. 21). The tower, which was used by Bari as a showpiece, caused great excitement among the visitors and in the international specialist press. A particular attraction was the Moiré effect, which appears to make the structure move. [27] After the exhibition, the tower was translocated to a new site in Polibino in southern Russia, where it stands today (Fig. 10 b, p. 21).
The construction of this prototype signalled the start of a real boom in the following years. According to some sources, over more than 200 towers of this new design were erected in all parts of Russia;


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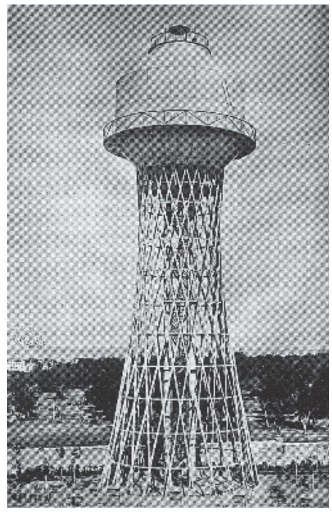
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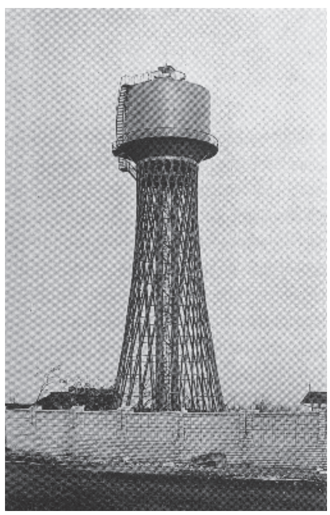
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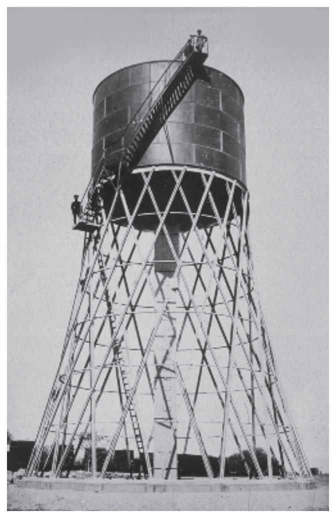
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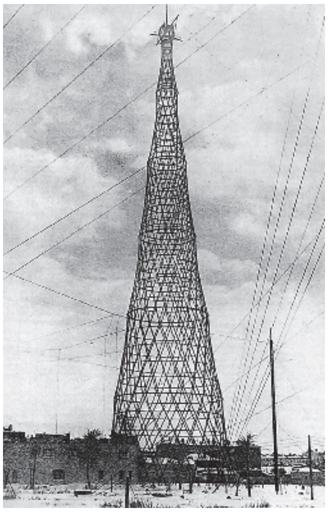
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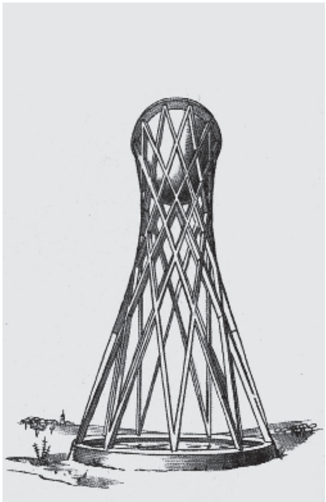
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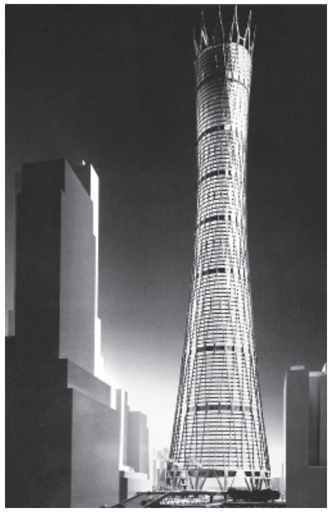
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the precise number can no longer be identified. There are two crucial reasons for this: firstly the economically efficient construction of the towers, which very often considerably undercut the competing systems, as was demonstrated by the water tower in Mykolaiv, for which Bari tendered and won the contract. Secondly the high architectural quality of the towers was crucial for this success: "The search for new engineering solutions was fuelled by prosperous cities in the 19th century using these utility structures as architectural attractions. In the mainly one- or two-storey Russian cities, these high water towers, masts and lighthouses must have provided an element urban beauty." [28] The water tower built in a prominent position near the church in Kolomna (Fig. 11 a, p. 21) underlines this statement. Perhaps the historic photograph also shows a somewhat less prejudiced and more open attitude existed in Russia towards the new types of engineering structures than that prevalent at that time in Western countries, where the erection of a modern utility building in the historic centre of a historically significant city would certainly have met with resistance.

In spite of the large number of towers built and the highly systemised design process, hardly any two towers are exactly the same. Geometry and structural members are determined specifically for each project. The chapters "Relationships between form and structural behaviour" (p. 50ff.) and "Design and analysis of Shukhov's towers" (p. 66ff.) deal exclusively with the construction, structural analysis and the design of water towers and their development.

Multistorey towers

As well as single-storey towers, there were also towers constructed from more than one hyperboloid segment placed one on top of the other. The multistorey construction technique was used for the first time on the water tower erected in 1911 in Yaroslavl. A suspended-bottom tank is installed at the top of each of the two segments, which each consist of 30 vertical members. The tower has a total height of 39.1 m at the top ring. A handwritten fragment of the calculations for this tower is discussed in the chapter "Structural calculations for the two-storey water tower in Yaroslavl" (p. 79f.).

Shabolovka radio tower

In 1919, shortly after the revolution, the demand for lattice towers took on another order of magnitude: Shukhov designed a radio transmission tower for the Comintern radio station Shabolovka in the centre of Moscow, which was to provide the radio broadcasting link from the capitol to the provinces. The first design was for a 350-m-high tower made from nine hyperboloid segments (Fig. 1, p. 9). In contrast to the other multistorey towers, the number of vertical members reduces continuously from 72 in the first segment to 12 in the ninth. [29] The even decrease in the number of vertical members creates eccentricities at the transitions between the individual sections. This structural problem had to be solved by installing spreaders under each main ring to bridge across the ends of the vertical members. A shortage of structural steel prevented this bold design from being built to its original ambitious dimensions. Eventually a 150-metre-high version was completed in 1922 (Fig. 12). It has 48 vertical members in the lower four segments, halving to 24 in the upper two. The type and size of the steel profiles in each segment are designed to suit the actual load. The structure was erected using the telescopic method in which the next hyperboloid segment is assembled at ground level inside the shaft and then hoisted upwards using small timber industry cranes to rest on top of the last section.

The completion of the structure, at that time the tallest in Russia, was celebrated as the "Trumpet of the radio revolution" [30] and was mentioned in contemporary works of literature and the performing arts. The tower remained the tallest structure in Moscow for many decades. Even today, its signature silhouette characterises this city.

NiGRES towers on the Oka

Perhaps the most beautiful of Shukhov's tower structures are the NiGRES towers erected as an ensemble of pairs of high-voltage electricity transmission masts in 1927 southwest of Nizhny Novgorod on the Oka. The mast pairs were stepped in height and reached 130 m at the river bank to allow the conductors to span almost 1000 m across the water. Nothing before had matched this late

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work of Shukhov for its timeless structural elegance and the natural simplicity of its detailing. The design and load-bearing structure of this tower are discussed extensively in the chapter “NiGRES tower on the Oka” (p. 96ff.).

Hyperbolic structures after Shukhov

Hyperbolic lattice structures were very seldom built after Shukhov’s death in 1939. A few structures have been designed or built in the intervening 70 years that made reference – at least in terms of form – to Shukhov’s invention. The most famous are the water tower feasibility study by the Spanish engineer Eduardo Torroja (Fig. 13) and the unbuilt skyscraper for mid-town Manhattan designed in 1954 by Ieoh Ming Pei (Fig. 14). In addition, several high-rises have emerged with load-bearing systems based on hyperbolic lattice structures. Modern examples in Ghuangzhou – the highest television tower in the world at 610 m (Fig. 16) – and in Doha (Fig. 17) show the endless fascination of these structures.

17

12 Shabolovka radio tower, Moscow (RUS) 1922
13 Preliminary design of a water tower, 1935, Eduardo Torroja
14 Unbuilt high-rise, 1954, I. M. Pei
15 Mae West sculpture, Munich (D) 2011, Rita McBride
16 Ghuangzhou TV Tower (CN) 2010, IBA Information Based Architecture
17 Tornado Tower, Doha (Q) 2008, SIAT – Architeckten und Ingenieure; CICO Consulting Architects Engineers