Hyperbolic structures

Shukhov’s lattice towers – forerunners of modern lightweight construction

Matthias Beckh
Hyperbolic structures
Hyperbolic structures

Shukhov’s lattice towers – forerunners of modern lightweight construction
## Contents

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foreword</td>
<td>8</td>
</tr>
<tr>
<td>Introduction</td>
<td>10</td>
</tr>
<tr>
<td>Building with hyperbolic lattice structures</td>
<td>14</td>
</tr>
<tr>
<td>Geometry and form of hyperbolic lattice structures</td>
<td>24</td>
</tr>
<tr>
<td>Structural analysis and calculation methods</td>
<td>32</td>
</tr>
<tr>
<td>Relationships between form and structural behaviour</td>
<td>50</td>
</tr>
<tr>
<td>Design and analysis of Shukhov's towers</td>
<td>66</td>
</tr>
<tr>
<td>NiGRES tower on the Oka</td>
<td>94</td>
</tr>
<tr>
<td>Résumé</td>
<td>112</td>
</tr>
<tr>
<td>Towers in comparison</td>
<td>114</td>
</tr>
<tr>
<td>Notes</td>
<td>143</td>
</tr>
<tr>
<td>Literature</td>
<td>145</td>
</tr>
<tr>
<td>Picture Credits</td>
<td>146</td>
</tr>
<tr>
<td>Index</td>
<td>148</td>
</tr>
</tbody>
</table>
Foreword

The structures of the great Russian engineer Vladimir Grigor’evič Šuchov (Shukhov) are among the world’s most sophisticated and distinctive in the history of steel construction. These extremely slender structures, such as cable-stabilised arches, doubly curved gridshells and above all lattice towers hold a great fascination for the observer. They result from the desire to achieve an engineering objective using as little material as possible. At the same time, they are a testament to the extraordinary creativity and inventiveness of an extensively educated engineer, who was on a par with any of his contemporaries.

Many engineering structures of today were anticipated in Shukhov’s works. Some of his other structures have no modern equivalent or have remained unmatched in their visual impact and compelling technical efficiency. Among these are without doubt the lattice towers, the foremost being the much photographed and most well-known electricity transmission mast on the Oka (the NiGRES tower) with a height of 130 m and the 150-metre-high Shabolovka radio tower in Moscow, which was originally planned to be 350 m high (Fig. 1). Shukhov built his first hyperbolic lattice tower in 1896 for the All-Russia Exhibition in Nizhny Novgorod. Countless towers with this new type of construction and geometries defined by just a few parameters were built over the following years. These structures proved themselves to be very efficient. The fine-lined tower structures served as water towers, lighthouses, power transmission masts and fire brigade watchtowers – with some of them still in use today.

In his dissertation submitted to the Institute of Structural Design at the Faculty for Architecture, Technical University (TU) Munich, Matthias Beckh analyses these hyperbolic lattice towers for the first time in a systematic manner and investigates the interdependence of form, structure and structural behaviour. The analysis demonstrates how, even in those days, Shukhov was already parametrising his structures as part of the design process. Modern methods of analysis provide not only a gain in scientific knowledge of the lattice structures, they provide Matthias Beckh with the tools to place Shukhov’s achievements in a historical context and validate their considerable contribution to the history of structural engineering. He is also able to demonstrate their relevance to modern structures. All this makes this publication valuable and interesting to a wider public.

Matthias Beckh was part of the first research project into Shukhov’s structures, which the Institute of Structural Design undertook together with Rainer and Erika Graefe and Murat Gappoev from the Moscow State University of Civil Engineering. This included investigations of the gridshells for the steelworks in Vyksa and the successful endeavours to make safe and preserve the badly damaged NiGRES tower on the Oka.

Thanks to these, it was possible with the research project into the design knowledge of the early Modern period and Shukhov’s strategies for economic steel construction, “Konstruktionswissen der frühen Moderne – V. G. Šuchovs Strategien des sparsamen Eisenbaus”, to secure the financial base for an interdisciplinary cooperative project. On this research project, in addition to the Institute for Structural Design, other participants included the Institute for Building History, Building Archaeology and Conservation, TU Munich (Prof. Manfred Schuller), the Institute of Historic Building Research and Conservation, Swiss Federal Institute of Technology (ETH) Zurich (Prof. Uta Hassler) and the Institute for Building History and Conservation, Innsbruck University (Prof. Rainer Graefe). The research project also included in-depth studies of building history as well as dimensional surveys and detailed investigations into the way the structures were built. Later wind tunnel investigations are intended to provide further useful knowledge about the load assumptions, which will also be relevant to modern structures. Finance for the project is provided by the German Research Foundation (DFG), the Swiss National Science Foundation (SNSF) and the Austrian Science Fund (FWF), who are hereby expressly thanked.

Rainer Barthel
June 2012
Shabolovka radio tower, blueprint of the first (unbuilt) design with a height of 350 m, 1919

Foreword
Introduction

“The Engineer’s Aesthetic and Architecture are two things that march together and follow from one another: the one being now at its full height, the other in an unhappy state of retrogression. The Engineer, inspired by the law of Economy and governed by mathematical calculation, puts us in accord with universal law. He achieves harmony.”


The object of this book is to gain deeper knowledge on the architectural history of hyperbolic structures. The focus of the investigations is the first hyperbolic lattice towers ever built, the work of Russian engineer Vladimir G. Shukhov. This form of construction, which had no predecessors in the history of building, is notable for its strength and economy of materials. Added to this is the high visual impact of the web-like structures, which almost compel the observer to stand and stare. Even today, Shukhov’s load-bearing system can be found in some form or another in architecture, for example in the structural engineering of high-rise buildings.

This book presents the results of the first ever extensive analysis of the way these structures work. The ruled surface of a one-sheeted hyperboloid is resolved into three different mesh variants to create open lattices and their structural behaviour investigated. Then the book looks at the relationships between the load capacities and the basic parameters that determine form as well as the interactions of structural actions and form.

Particular attention is paid to the evaluation and analysis of Shukhov’s tower calculations and the assumptions made for the structural model. His historical calculations are compared with the results of modern calculations. Following on from this, Shukhov’s design process is reconstructed and the development of the water towers built by him illustrated. The constructional details of the Shukhov-built towers are only touched on here because this subject is currently being more closely examined in an ongoing research project.

Current state of research

Numerous books and papers about Shukhov’s work were written in Russia during his lifetime. The papers of Shukhov’s biographer Grigorij M. Kovel’man reveal some outstanding insights. Other important contributions that give a good overview of Shukhov’s manifold achievements include works by I. J. Konfederatov [1], A. E. Lopatto [2] and Aleksandr Išlinskij [3]. The chapter “Design and analysis of Shukhov’s towers” (p. 66ff.) goes into the detail of relevant Russian publications that deal with the structural engineering design and analysis of his towers and the calculation processes used. In the German-speaking parts of the world, Shukhov’s works first came to the public’s attention in the 1989 book by Rainer Graefe, Ottmar Pertschi and Murat Gappoev “Vladimir Šuchov. 1853–1939. Die Kunst der sparsamen Konstruktion”. [4] The wealth of writings by German and Russian authors document the wide variety of his architectural and engineering works.

Until now, the form and geometry of hyperbolic lattice structures have only been investigated to a limited extent. The paper “Zur Formfindung bei Šuchovs mehrstöckigen Gittertürmen aus Hyperboloiden” by Jos Tomlow provides an introduction to the subject. [5] His observations, which were based in part on estimated measurements and geometric parameters, discuss form-finding in the context of structural form, geometry and construction. The relationship between geometry and structural actions is not investigated. Building on this article in his degree thesis, Daniel Günther also discusses the rules of form and geometric dependencies of Shukhov’s towers. However, some important relationships are not considered. Although he was the first to evaluate a design table used by Shukhov that gave an insight into his very systematised design process, this analysis did not consider structural behaviour of the towers and its influence on form-finding. [6] A paper by Peter de Vries discussed the stiffnesses of simple hyperbolic lattice structures and highlighted a single connection between geometry and structural behaviour. The focus here is not on Shukhov, but on a simple form of hyperbolic lattice structure which always has the intermediate rings positioned at intersection points of the lattice members. The results are therefore of secondary relevance to an evaluation of the lattice towers built to the Shukhov design. [7] It can be concluded that, although the geometric relationships of Shukhov’s lattice towers have been investigated on various occasions, an analysis of their structural behaviour and the interactions between form and structural behaviour has not taken place to date. However, it is obvious that the form and structure of the Shukhov-built towers were developed not on geometrical or constructional criteria alone, their designs specifically took into account structural engineering considerations. A comprehensive analysis of the way the member arrangements adopted by Shukhov work structurally, of the interactions of form with structural behaviour as well as a reconstruction of the
design method derived from these considerations were still lacking. Furthermore there had not been any previous investigations into alternative member arrangements on the surface of a one-sheeted hyperboloid.

Overview
The early chapters of this book set the towers in context with the history of building with iron. This leads on to investigations into the geometric relationships within hyperbolic lattice structures, the way they transfer loads and the interactions between form and structural behaviour. Further key themes include structural calculations and parametric studies, the analysis of some of Shukhov’s original structural calculations and his built hyperbolic lattice towers.

The general terms for the structures investigated in this book are “hyperbolic structures” or, slightly more specifically, “hyperbolic lattice structures”. When referring specifically to the construction types used by Shukhov, the term “hyperbolic lattice towers” is used. This term is used reasonably often in this context and well established in specialist literature.

In the chapter “Building with hyperbolic lattice structures” (p. 14ff.), the focus falls on the history of building with hyperbolic lattice structures – and the works of the great Russian engineer Vladimir G. Shukhov. After a brief outline of the historic development of building with iron, the discussion centres on Shukhov’s diverse contributions in the field of construction and his most important hyperbolic lattice towers. The chapter “Geometry and form of hyperbolic lattice structures” (p. 24ff.) deals with the form and geometry of hyperbolic lattice structures. A precise description of the mathematical principles of a one-sheeted hyperboloid precedes an explanation of the parametrisation of hyperbolic lattice structures.

Taking these concepts further, the chapter “Structural analysis and calculation methods” (p. 32ff.) considers the principal means of transfer of vertical and horizontal loads and describes the interactions between geometry and structural behaviour. Then follows an explanation of the theoretical principles of determining a lattice tower’s ultimate load capacity.

The chapter “Relationships between form and structural behaviour” (p. 50ff.) presents the results of extensive parametric studies of the structural behaviour of hyperbolic lattice structures. Three different arrangements of mesh on the surface of one-sheeted hyperboloids are investigated and the results compared. This is followed by discussions of the calculations for four of Shukhov’s built towers. The chapter “Design and analysis of Shukhov’s towers” (p. 66ff.) is devoted to consideration and analysis of Shukhov’s structural calculations for the towers. Shukhov’s design process is reconstructed based on a comparative evaluation of the historical structural engineering calculations of five different water towers. From the analysis of historic tables stored in the Moscow city archives, a summary of the key data of numerous towers is produced to chart the development of the towers over more than three decades of use.

An analysis of the design and construction of the NiGRES tower on the Oka is the subject of the chapter of the same name (p. 96ff.). The initial ensemble of four electricity transmission masts represents the consummation of Shukhov’s tower construction method. Only one of the 130-metre-high masts remains in place today. A summary of the results of the analysis is provided in the chapter “Résumé” (p. 112f.): It sets out the remaining questions and suggests areas where further research is required.

The final chapter “Towers in comparison” (p. 114ff.) contains an extensive table and drawings of 18 towers. It is hoped that the examination of Shukhov’s form of construction made public in this book will give an impetus to new applications in architecture.
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...