

Vladimir Shukhov

A Critical Review on Digital Architecture

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This paper is a critical review on advantages and disadvantages of contemporary digital architecture, in retrospect to Vladimir Shukhov's design techniques, applied in the early 20th century. After investigating Shukhov's structural systems, this paper explores the relationship between performance and form, questioning the necessity of high-complexity structures. It will present unpublished archive material of his early work and stimulate a valuable discussion by comparing it with contemporary projects designed by renowned architects. The study on Shukhov focuses on his tessellation method of double-curved surfaces using simple standardized elements. The study of present digital approaches revolves around leading architects using computational tools (e.g. Foster and Partners, Buro Happold and Arup), who have materialized high complexity structures composed by irregular units. Our findings highlight advantages and disadvantages of contemporary computational approaches.

Keywords: *Fabrication, Material Studies, Architectural History, Design Concept, Performative Design*

INTRODUCTION

Technology, materials and construction are three interdependent components that change architecture. Contemporary architecture started with the Industrial Revolution, which brought new technologies and new construction materials: iron and steel. In recent decades, computation has become a next significant impetus for architectural development (Castle 2013). Computation redefined the practice of architecture. Instead of working on compositions, designers construct a parametric computational system, where the form can be generated simply by varying parameter values. On one hand, computational technologies make it possible to design a building of any

level of geometric complexity and optimize any design proposal. 'If you find a nice curve of surface somewhere with interesting properties you can incorporate it in your design' (Peters, Peters 2013). On the other hand, computational technologies create a gap between architects and the final product. Because of insufficient knowledge of algorithmic concepts (Peters, de Kestelier 2013), most practices come up with a building shape and a concept; then invite computational designers to optimize the project. Computational designers generate and explore architectural concepts by writing and modifying algorithms, but how efficient is this approach?

This paper is aiming to rethink and evaluate ad-

vantages and disadvantages of computational design techniques, by comparing contemporary performative design methods with Shukhov's pre-computational approach, the most efficient approach of the pre-computational era. In order to narrow down the research area, this investigation will focus on grid-shell structures, based on following main research questions:

- What were Vladimir Shukhov's design techniques?
- How do Shukhov's manufacturing and assembling processes differ from contemporary digital design techniques? How does their design logic differ?
- How can today's advanced performative design techniques benefit from Shukhov's design heritage?

ABOUT VLADIMIR SHUKHOV

Vladimir Shukhov was one of the most innovative engineers of the late 19th and early 20th century in Russia. Contemporaries used to call him the "Russian Edison" due to his extensive inventions in numerous science and engineering subfields. For Shukhov, design processes had always been associated with extensive analysis and research. In the design process Shukhov used to encourage his fellow workers to think '*symphonically*', (Kovelman 1958) which means 'complex thinking'. He perceived a construction as one organism consisting of hidden interconnections (Shukhova 2003) that he aimed to reveal during deep investigations.

Vladimir Shukhov realized the commercial nature of the construction industry and the power of optimization as aiding competitive advantage in the growing building industry. Thus, his design approach was based on two aspects, which, in Shukhov's opinion, fundamentally affected the total cost of a construction and its quality: material consumption and labor expenditure.

Due to the crucial interdependence between a structure and material consumption, Shukhov al-

ways started with mathematical models that he used to find the most efficient construction system. His mathematical approach was based on geometry as an analytical tool. In addition to calculations, Shukhov relied on physical models. He believed that even the smallest paper model was able to reveal hidden forces that could be missed during the analysis stage (Kovleman).

Shukhov successfully optimised structures as well as each step of the construction process. Trying to avoid different-type elements and keep clear of any details and elements that could complicate the structure, he aimed to standardize their size within the structure. Another important part of Shukhov's approach was preparing an elaborate plan for the assembling process. In an attempt to optimize the on-site building process and reduce faults, Shukhov limited the number of working drawings and tried to combine all the necessary information on a few sheets, developing detailed assembly process instructions for each specific task.

SHUKHOV'S LATTICE STRUCTURES

One of the most significant of Shukhov's inventions in the field of architecture was the thin metal lattice or grid shell structure. It was developed after detailed investigations searching for the most rational type of rafters that weighed and cost the least and could be quickly assembled. Shukhov suggested a proportion, which at first sight seemed senseless:

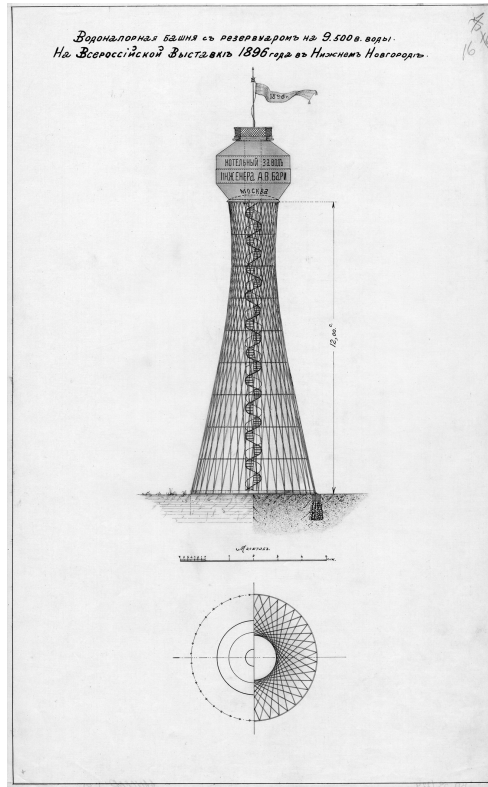
$$a = e = c$$

where a - length of panels, e - minimal distance between frames, and c - distance between two purlins, dependent on the actual situation (Shukhov 1897)

According to the formula, the minimal covering weight could be achieved only if the construction had no purlins, and the distance between trusses was equal to the distance between the missing purlins. The answer to this riddle was the spatial lattice structure, where trusses and purlins were the same, and the distances between trusses and purlins were equal. The new structures were first presented to the

general public at the All-Russian Industrial Art Exhibition in Nizhny Novgorod in 1896, where Shukhov designed a number of objects using three types of lattice structures: suspension, vaulted and rigid spatial shell. (Figure 1)

Figure 1
The first Shukhov hyperboloid water tower erected at the 1896 Nizhny Novgorod exhibition, Archive of the Russian Academy of Science, F.1508/Op.2/81(16)



Since engineers and architects have started using computer technologies, they rediscovered grid structures that do not dictate the shape of the building and allow forming more complex shapes. However, the shift to relying on algorithms for capturing and communicating designs in architecture has been slow, as many architects still do not have sufficient computer modelling skills. Additionally, since each grid structure is unique and no guides or design

and construction recommendations exist regarding these buildings, only large practices with the knowledge and research back-up available, for example, Buro Happold and Over Arup & Partners, have agreed to take part in such projects (Paoli 2007). This gap between the conceptual idea and the skill set needed to operate computational technologies contradicts the gist of the parametric approach and leads to a transformation from a method to a style. Striving to understand the current situation in more depth, in the next chapter we will compare the computer-generated grid structure design process with the most effective design and construction methods from the pre-computational era.

To assess the effectiveness of computational design process we have chosen four grid-shell structures with comparable parameters: 30 St Mary Axe and the Great Court of the British Museum designed by Foster+Partners, and the Radio Tower on Shabolovskaya St (1921) and Viksa Works (1897-98) by Shukhov. The comparison is focused on four main aspects: design process, grid-shell structure, fabrication and assembling.

SHABOLOVSKAYA TOWER AND 30 ST MARY AXE TOWER

Design process

The Radio Tower in Moscow (Figure 2) and The Swiss Re building, later rebranded 30 St Mary Axe, are two towers with the similar height (150 and 180 m) with the biggest diameter of 40.3 m and 56.15 m, respectively. The Radio Tower in Moscow is a grid-shell structure comprises of six hyperboloid blocks formed with angle rods and horizontal hoops. Its minimal surface and open lattice structure reduce the wind load, the main challenge for high-rise buildings. The dense intersections between elements and wide cross-sections granted the tower stability, while the multi-level construction system creates additional intersections in the tower's trunk, which reinforce the structure with minimal material consumption (Rainer, Perchi, Shukhov 1995). The logic of Shukhov's calculations that led him, to hyperboloid

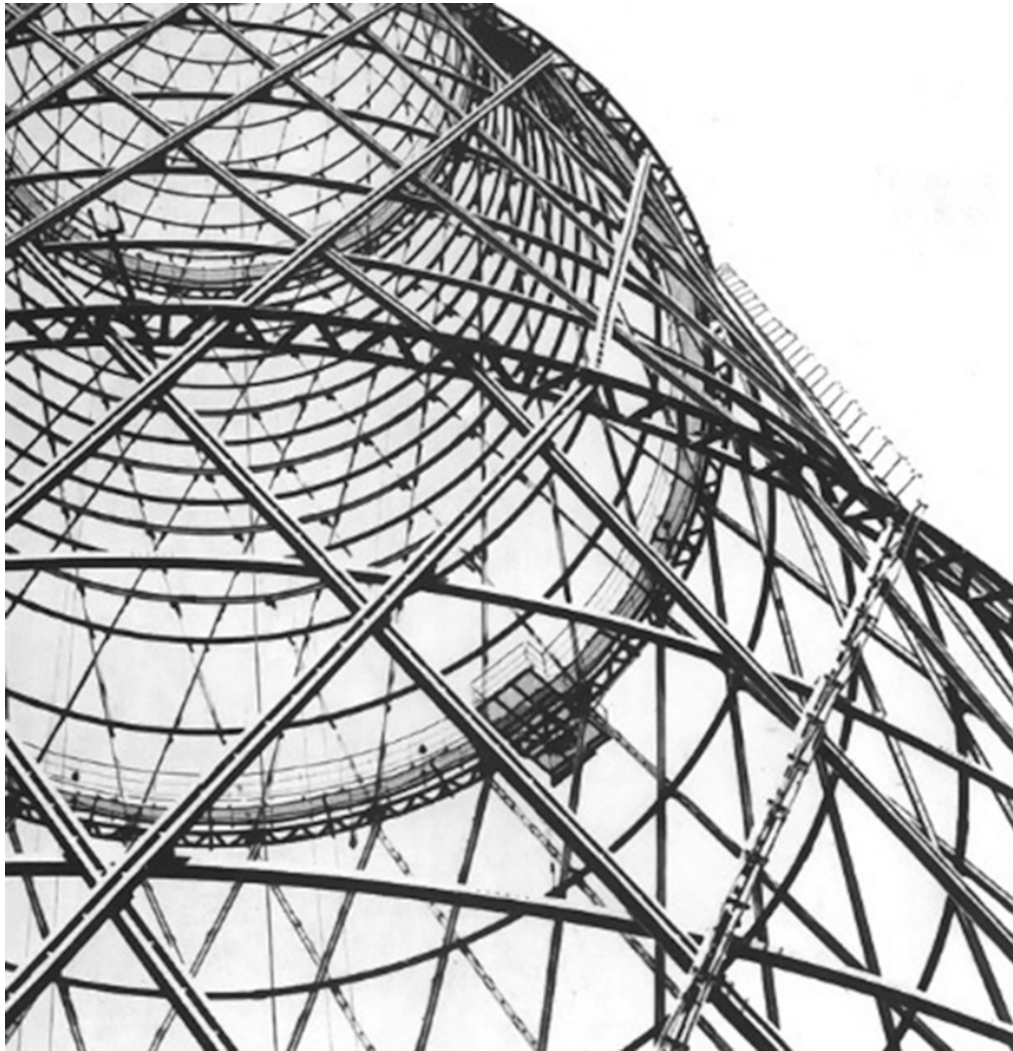


Figure 2
Radio Tower's lattice
structure, by author

spatial system, were based on exploring structural interdependences and embracing the most important parameters in generative formulas.

The elliptical shape of the Swiss Re building was designed also for reducing the wind load. By the time, Foster+Partners architects invited Mark Burry, a specialist from the Arup Group, to optimize the final shape according to aerodynamic requirements; they developed the initial tower concept using hundreds of card and plastic scale models (Burry 2011). The structure of Swiss Re's building consists of a central core and a perimeter steel grid-shell tightened to each other with rolled-steel radial beams. The grid's interlocking horizontal hoops turn the structure into a stiff triangulated shell with a lateral working load that resists wind force and makes the whole construction stable (Hart 2001).

Grid-shell structure

The most significant difference between Shukhov's and computational approaches reveals in the logic of the grid shell structure. The main idiosyncrasy of Shukhov's lattice towers was that he never used equal rings and regular intersections: the intersection points between straight lines in the upper and lower parts are not symmetrical (Khan-Magomedov 2010). Rod connections were also shifted from one to another, trying to create as much small-scale intercrossing as possible, like in a knitted garment; whereas, The Swiss Re's diagrid system represents a polyhedron compiled with diagonal columns and nodes.

The lattice mesh of the hyperboloid pylons in the Shabolovskaya Tower is made of two layers of diagonal double 140 mm U-section rods aligned between two rings. These rings have a truss structure comprising of two L-section rods, which simplifies pylons' connections and makes it possible to fix rods securely. Intermediate U-section rolled metal holding rings fix the rods between the main structural rings. In the process of connecting the diagonal rods to the rings, they were slightly twisted along the whole length, which was done quite easily due to high ma-

terial flexibility and because the rod section was relatively small. That granted additional structural stiffness to the construction. In order to stabilize the construction, the number of the rods reduced from the lower pylon to the top.

The Swiss Re's diagrid system comprises of a series of steel two-story A-frames. Each frame consists of two tubular diagonal columns bolted with a two-meter-height node. Nodes connect the diagrid shell to the radial beams of the central core and govern the curvature of the building that makes them crucial in the overall structure of the construction. Due to the building's elliptical shape the geometry of each node is different, so the Arup team designed each node in detail during the computer modelling stage (Powell 2006). Additionally, in order to stabilize the tower, Arup designed two column types: bigger and heavier for bottom levels and lighter for upper floors.

Fabrication and assembly

The fabrication and assembly of the Radio Tower was quite simple due to the identical elements throughout the building and highly original 'telescopic' assembly method implemented by Shukhov. All sections were assembled and lifted in large blocks inside the structure with five basic wooden cranes and pulleys (Khan-Magomedov 2010). The only issue was bending horizontal U-section rings according to the structure's diameter because it was an expensive process at the time (Shukhova 2003). The simplicity of the design and the assembling method made it possible to build a complex structure using primitive equipment and relying on low-skilled workers. Besides, the 'telescope' assembly method was highly accurate. In another famous hyperboloid tower with similar structural features to the Radio Tower the leeway from the dead center was only 24 mm (Kovelman 1961).

The main issue in assembling the grid-shell structure for 30 St Mary Axe was that it depended on accurate fabrication (Powell 2006). *'With a triangular grid, there's nothing you can do if all goes wrong'* (Peterson 2002). Building such a structure was possible only

with the aid of advanced 3D-modelling and modern computational fabrication technologies that enable accurate calculation and construction element production with minimum defects and errors. There was the most difficult step of construction, when all 18 nodes were in place around the circumference forming a horizontal hoop, and tie-sections were added to link the nodes. To close the bolt holes, all the tie-sections would have to line up; the process demanded high precision.

THE GREAT COURT OF THE BRITISH MUSEUM AND VIKSA WORKS

Design process and grid-shell structure

The covering for the Viksa Works (Figure 03) represents the first time in the world's building practice when double-curved spatial vaults were created with single-type rod elements (Khan-Magomedov 2010). Overall, the roof is divided by three-pinned arches into five segments covered with symmetrical double-curvature shells. The single-curvature system was transformed to a double-curved surface simply by bending the longitudinal beams. From the cross to the long sections, the curcular-cut dome edges have a bend size equal to 1/6 of the span. The symmetric shape of the double-curved domes made it possible to form them with identically bent rods (Rainer, G, Otmar, P and Shukhov, 1995). 68° was considered the most optimal angle of rods' intersections. One professor, Shukhov's contemporary, describing his structures, proposed the angle of 90° instead, which, as a result, led to a 31% increase in the structure's weight during the calculations (Shukhova 2003).

The character of the Great Court covering structure is more complicated. The covering works as a lattice-glazed canopy stretched between the dome's drum of the Reading Room and four sides of the Museum's quadrangle. Its design was generated in two stages. At first, engineers from Buro Happold calculated its geometry using standard static, or linear, computer programming. Then, Chris Williams, a pioneer of design computation, was invited to study the deformation of the roof structure. Us-

ing computer software, he designed a 3D simulation model and optimized the mesh of the grid-shell. The grid size was determined by the maximum glass panel size available, so the structure consists of 3,312 unique double-glazed panels. The total weight of the canopy without glazing is 478 tons.

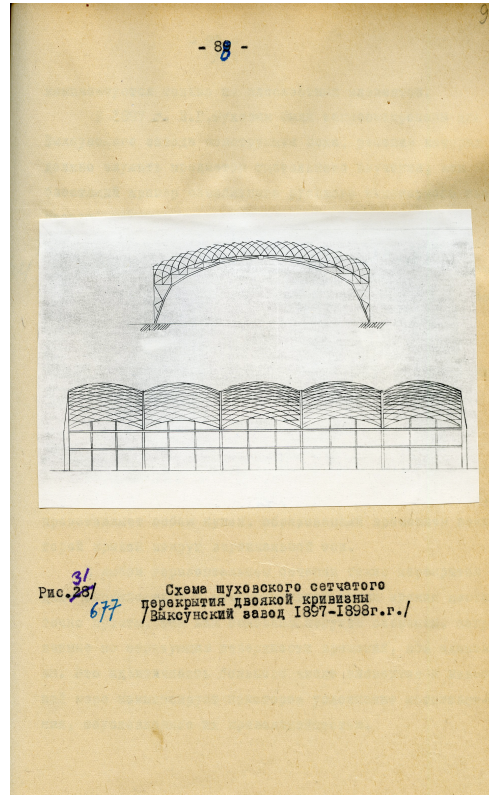


Figure 3
The Viksa Works
covering, Archive of
the Russian
Academy of
Science,
F.1508/Op.2/37(91)

Fabrication and assembling

Chris Williams designed the highly complicated shape consisting of thousands unique elements relatively easily. Yet although the grid-shell details were successfully prefabricated following 3D models, the process of assembling such a non-standardized structure was expensive and difficult. The final grid

construction was formed of radial hollow steel sections (box beams), which were welded to 1,826 structural nodes, each node having a unique design (Anderson 2000). The engineers were highly concerned about the reliability of the structure; therefore, Hap-pold, instead of using lower grade steel that might contain impurities, chose Grade D steel material, which is usually used in marine and offshore applications (Hart 2001).

In contrast to the canopy of the Great Court, the construction system of the roof for the Viksa Works, while highly original, was relatively simple and used no extended scaffolds, which are necessary in the assembling of complicated spatial shell structures. This construction system was 40% lighter than other roof structures. Kovelman (1961) writes that initially builders even refused to climb on the roof because they could not believe that such a light lattice structure could sustain their weight.

DISCUSSION AND CONCLUSION

By looking at the two grid-shell structures presented, it becomes clear that they were built following fundamentally different principles. Shukhov's design logic, based on crossed rods, minimal asymmetry and displaced detail interconnections is similar to the logic of a wicker basket structure. Thin fragile elements joint together form a strong elastic spatial construction. In contrast, Foster's computational structure is composed by polyhedrons made of beams. It is easy to trace this back to computer modelling, where the most straight-forward way to design and calculate a smooth form is by using a polygon mesh. This discrepancy poses a question: do we use computer technology as a supporting tool, or has it started dictating the design process? Computational technologies make it possible to generate shapes of any level of complexity, but Lynn stresses another issue:

The computer is not a brain. Machine intelligence might best be described as that of mindless connections. When connecting multiple variables, the computer simply connects them, it does not think critically about how it connects... Even in the most scientific ap-

lications of computer simulations it is argued that first an intuition must be developed in order to recognize the nonlinear behaviour of computer simulations.' (Lynn 1997).

Nowadays, architects and engineers design forms using the most convenient ways of computation that lead to structures that are difficult to build. The presented comparison demonstrates that, despite new opportunities given by new technologies, the design logic did not go much further than post and lintel system. If the architecture generated by computational logic is called 'smartgeometry,' perhaps engineers and architects should strive for 'wisegeometry,' geometry based not as much on calculations as on optimal construction logic in the physical world, such as that of Shukhov's structures? Perhaps 'wisegeometry' would start addressing Chris Williams's contemplation in *Smartgeometry: 'Computers are no longer a new technology, but their implications for the ways in which people will work are still unclear'* (Peters and Peters 2013).

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