The First Doubly Curved Gridshell Structure - Shukhovs Building for the Plate Rolling Workshop in Vyksa

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ABSTRACT: In the year 1897, the renowned Russian engineer-polymath Vladimir Shukhov built a production hall in the town of Vyksa, a steel mill 150km southwest of Nizhny Novgorod. This building entails the first doubly curved gridshell structure. The paper explicates the construction of the building, its details, as well as the interdependence of its key elements. Different ways to conceive the geometry of the gridshell are discussed. A comparison between the original design method and the actual structural behaviour of the gridshell is presented in the last part of the paper.

INTRODUCTION

Vladimir G. Shukhov (1853 - 1939) was one of the most distinguished and versatile engineers of his time. As the Chief Engineer of the engineering company Bari in Moscow, he devised a multitude of technical innovations and patents that ranged from shipbuilding to petroleum engineering. Shukhovs contribution to structural design revolutionized building construction. The systems he conceived – most notably his doubly-curved structural forms - were of unprecedented lightness and clarity (Graefe 1990, p. 7-19).

Shukhov had started to build barrel vaulted gridshells in 1890, when he covered two pump stations in Grozny. The cross section of the roofs followed the segment of a circle, with a span of approximately 9m. In plan view, the structure had the form of a diamond-shaped net, which was created by two layers of inversely running members. The elliptically shaped Z-sections were connected at the “intersection points” with rivets; the horizontal shear was balanced by tie rods. (Compare Figs. 4a) He patented his system for single curved gridshells in 1895 and implemented this type at various locations, most notably for the All-Russian exhibition in Nizhny Novgorod in 1896. Here, he used this system for a variety of exhibition pavilions, covering an area of about 20000 m², with spans ranging from 12.8m to 32m. The vaults were stiffened by tension elements that originated from the springs and connected the quarter-points – a method that he had already employed at various occasions before, most notably for the bracing of the arches that roof the passages of the Upper Trading Rows (GUM) in Moscow (Gappoev 1990, p. 58). The new system, often referred to as “roof without framework”, received much international acclaim. The British journal “The Engineer” praised its advantages and innovation in the same year:

The arched roofs have horizontal and diagonal tie rods. The strains in every part of the roof are equally distributed on the material, and a considerable reduction of weight per square yard is effected, as compared with a roof truss... The iron being of the same section throughout, can be all prepared and drilled to template on an interchangeable system...This is one of the few instances of original thought and design in the engineering exhibits. (The Engineer 1897, p. 293)

In the same year, Shukhov constructed a production hall with a covered area of 70 x 24m for the Bari boiler factory in Moscow. This building consisted of five barrel vaulted gridshells, spanning 14m between evenly spaced three-hinged trussed frames. The straight top chord of these frames is inclined against the horizontal
plane, with the crown hinge being approximately 4.60m higher than the eaves. Due to the kink of the top chord at the ridging, the barrel vaults are discontinuous and separated above the crown hinge by a gap.

One year later, in 1897, Shukhov designed and built a production hall for a steelwork company in the town of Vyksa. This building bears remarkably resemblance to the one in Moscow – but it also offers striking alterations. Unlike in the prior building, Shukhov formed the top chord of the frames after a parabola, thus allowing a continuous gridshell system and avoiding the interruption at the ridge. By moving a curved generator line along a parabolic curve, Shukhov built the very first doubly curved gridshell structure.

Figure 1: Production hall in Vyksa, Lithography around 1900; (Graefe 1990, p.48)

Figure 2: Production hall in Vyksa, Construction documents; (Archive of R. Graefe)
SUPERSTRUCTURE

Overview
The location of the building is Vyksa, a small town about 150km southwest of Nizhny Novgorod. The production hall is on the vast premises of the Vyksa Steel Works, a manufacturer of metallurgical products, founded in 1757. The building was designed in 1897 and construction could be completed a year later. The building was in use until the 1980ies. Abandoned and neglected for more than two decades, the building is today in a disastrous state of repair (See Figs. 3). The construction with a footprint of 73.00m x 38.40m consists of five 14.60m wide bays, which are separated by four trussed arches. In the longitudinal direction, the building is braced by six vertical cantilevers, which are integrated into the front facades, and connected to the arches with tie rods. The polygonal top chord of the frames provides the base for the grid shell. In the following, the construction of the arches and the front façade structure will be explicated.

Trussed Arches
The building is divided into five bays by four trussed three-hinged arches with a span of 38.40m. A spot-check of the arches geometry with a tachymeter (carried out by A. Kutnyi) revealed that the built construction is in line with the existent construction documents. The polygonal top chord of the truss is formed after a parabola. Based on the historic construction drawings, the function of this parabola can be approximated as:

\[ y = 6.27 - 0.01706x^2 \]

Each half of the trussed girder is divided horizontally into six 3.2m wide bays, separated by posts made of two L-shapes. At these locations, the top and bottom chord change their inclination to follow the curvature of the parabola. The bays are further subdivided by half with posts that support the straight top chord above (See cross section at the left bottom on Figs. 2). All members of the trussed arch are composed of steel angles and steel plates; all connections are carried out with rivets. The top chord of the arch is made of 600mm wide steel plates and L-shapes of varying thickness, the lower chord consist of two C shapes, set 420mm apart. At the base, the hinges are executed with a cast iron key and slot connection. The hinge at the apex is carried out with a 75mm diameter bolt. The arches are braced horizontally by fourteen tie rods (26mm diameter). Two rods are located at the sharp bent of the lower chord. Twelve rods are attached to the top chord of the trusses, at mid bay position, slightly off the intermediate post.

Front façade
The structure of the façade on the front and rear side of the building consists of six vertical cantilevered trusses and an intermediate orthogonal grid of cross beams. The cantilevered trusses and intermediate vertical members carry the L-shaped ridge beam, which follows the same parabolic curve as the trussed arches. The arrangement of the cantilevered trusses in the front façade does not follow the spacing of the vertical posts in
the trussed arches. Nor does it comply with the spacing of the longitudinal running tie-rods that balance the shear of the gridshells. Only the outer vertical cantilevers align with the rods that brace the inner corners of the trussed arches. The spacing of the vertical cantilevers decreases from the center towards the sides, refuting the assumption that the spacing might reflect equal contributory façade areas. Most likely, the layout of the cantilevers was determined by functional requirements, like the widths of the portal doors at the front facade or others.

**GRIDSHELL**

**Geometry and generation of the gridshell**

There is no historic evidence on how Shukhov generated the form of the gridshell in Vyksa. Neither are written documents available, nor do the existent construction drawings yield any precise information about the geometric principles that determine the surface. (See also Kovelman 1961, p. 105)

The curved members of the gridshell run diagonally, meaning that start and end point are offset by four bays (See Figs. 3). The exact shape of these members could not be measured accurately enough to discern whether the curve stems from a circle, a parabola, an ellipse or some other curve of higher order. (Parabolas and segments of circles with small rise-to-span ratios differ only slightly). The historic drawings only indicate that the clear rise of the shell is 1.98m, measured perpendicular to the parabolic curve of the top chord. Different ways are possible to conceive the geometry of the gridshell, three of which will be pointed out briefly in the following paragraphs:

**First assumption - elliptic paraboloid**

The geometry of the shell is generated by the translation of a first parabola along a second one. Hereby, an elliptic paraboloid is created, a surface of second-order. If surfaces of second order are intersected with a plane, the generated curves have the form of conic sections: i.e. parabolas, hyperbolas, or ellipses. If the cutting plane is parallel to the normal vector at the apex of the paraboloid, then all resulting curves are parabolas as well. The geometry of these resulting parabolas can be computed comparatively easily. (See Figs. 4b) However, as the gradient of the parabola increases with distance from the apex and the resulting intersected curves are always oriented vertically, the rise of the gridshell would not be constant in elevation. This method would imply that the height of the shell is highest at the apex and decreases towards the sides – an outcome that is not in line with the appearance of the roof structure. The “apex line” of the shell appears to run parallel to the top chords of the trussed arches. The rejection of this approach leads to the next assumption.

**Second assumption - freely defined translation surface**

The surface of the shell could have been generated by moving a segment of a circle along the parabola of the top chord in such a way that the segment is always oriented perpendicular to the parabola (See Figs. 4c). The resulting geometry is a freely defined translation surface. The geometry of the individual members can be found by intersecting the surface with a plane. This cutting plane is defined by the connecting line between start and end point and the normal vector of the surface which is perpendicular to this line and divides it in halves. Depending on the position of the cutting plane, the resulting geometry is a curve of 3rd or 4th order and its calculation extremely cumbersome. Although it is known that Shukhov was very skilled in mathematics, this approach doesn’t seem likely due to its inadequate practicality.

**Solution - translation surface with solely identical elements**

Most likely the geometry was generated by moving an obliquely oriented segment of a circle along the parabolic top chord of the truss, as shown in figs. 4d. The segments were all identical, with the same fixed radius and chord length. With the clear span of the shell between the top chords of the trusses (14.00m), the horizontal distance between start and end point of the member at the apex (i.e. two times the bay width of the truss; 6.40m), the chord length can be approximated with 15.39m. The vertical distance between start and end point and the apex of the parabola and the rise of the shell according to the construction documents (1.98m) the arch rise of the circular segments can be obtained (h = 2.16m). With the chord length and the arch rise, the approximate radius of the circular segments can finally be gained as 14.80m.

The resulting surface is again a freely defined translation surface. This approach seems to be the most practical, as all the members are identical and can be manufactured using the same template. However, the usage of only identical elements has implications on the arrangement of the members. As the gradient of the parabola varies and gets higher towards the endings, the arc lengths of the equally divided parabola increases likewise. Thus, the start and end points of the members don’t line up with the spacing of the truss any more as one moves outwards. This effect can be witnessed at the springs of the trussed arches, an observation that affirms that the supposition of identical elements of the same lengths is correct. (See Figs. 5)
Figure 4 a b c d: Different types of translation surfaces
The grid shell is composed of two sets of inversely running Z-shaped (h = 80mm, b = 50mm, t = 7mm) steel sections. The support for the grid shell is provided by 8mm thick gusset plates, which are bolted to the top chord of the arch and bent upwards. 25 connections are mounted to each side of the top chord. On each of these plates two Z-shaped members start, attached to either side of the plate. This support condition sets the two layers of the shell 8mm apart. At each intersection of the diamond formed mesh, the members are connected with 8mm thick shim plates. These shim plates have the form of equilateral triangles with an edge length of about 120mm. They connect the lower and upper grid shell members with three bolts, thereby providing a soft moment connection.

The polygonal construction of the trusses top chord leads to a geometric problem – the gusset plates for the shell members that are located midway between two bends sit 42mm below the intended parabola curve. The solution to this predicament is both simple and skilful: By moving the bent gusset plate further away from the edge, differences of level can be balanced easily (See Figs. 6). As the Z-sections are attached tangentially
to the parabola formed arches, the members are slightly twisted. This explains the application of more twistable Z sections. The gridshell is stiffened by bifurcated bracing elements, a method that Shukhov had already employed before to stabilize his single-curved gridshells and arched roofs. The bracings are made of 4mm thick steel wires that originate at the gusset plates and are attached to the intersection points of the shell at three-fourths of the span.

Small steel angles (L 35x35x3mm) are mounted upside down to the upper layer of the Z-sections (See Figs. 7). These angles run in the cross direction of the building and are spaced about 120mm on center. The roofing is made of thin galvanized iron sheets that are arranged in an overlapping order and wired to the lattice below – a standard practice in Russia at that time.

**Structural behavior**

As Shukhov's structural calculations haven't been found so far, his design assumptions remain unknown. However, the calculations for the gridshells and façade members for the buildings of the All-Russian exhibition in Nizhny Novgorod survived and offer a good insight into his design approach. The members of barrel-vaulted gridshells with slanted tie-rods were designed the following way: The maximum moment was found by applying a vertical unilateral load upon half the distance between spring and the three-quarter points (the endpoint of the bracing elements) of the arched members. A surface load of 1.80KN/m² was used for the unilaterally applied load, divided by the spacing of the members and by the number of layers (two). A uniformly distributed load of 3.60KN/m² was used to compute the shear of the barrel-vaults and to design the horizontal tie-rods. An allowable tensile and bending stress of 7.00KN/cm² was used to compute the required section moduli (around the strong axis) and steel areas (Suchov 1990, p. 181). If one applies this design method (and the same load assumptions) to the situation in Vyksa, the required section modulus of the employed Z-sections is 28.4cm³. The section modulus S_y of the used 80mm deep Z-sections is 29.6cm³. Apparently, Shukhov just transferred his hitherto used design method for barrel-vaulted gridshells and did not take the structural advantageous double curvature of the gridshell into consideration.

A comparative FE calculation based on Shukhov load assumptions, the ideal geometry without the consideration of imperfections, and S 235 steel (f_y = 240 N/mm²) shows that the resulting stresses are in the range of an allowable stress level, even if one deactivates the bifurcated bracing elements. The positive impact of the doubly-curved shell can be observed in a stability analysis. The resulting buckling mode shapes were significantly higher than those of single-curved barrel-vaulted gridshells. The stiffening effect of the curvature in cross
direction is most pronounced at the apex of the gridshell and decreases towards the sides, as the curvature of the parabola diminishes with increasing distance to the center. The weight of the gridshell alone is 13.50\(\text{kg/m}^2\), the weight of the complete superstructure including the trussed arches is 52.20 \(\text{kg/m}^2\) (both without roof cladding and the battens). According to Shukhov's biographer G. M. Kovelman the employment of the gridshell structure allowed weight savings of 40 percent as compared to more conventional roofing systems. Another advantage he states is that the construction of the gridshell is possible without the erection of scaffolding (Kovelman 1961, p. 107).

**CONCLUSIONS**

Although the double curvature of the shell in Vyksa is structurally advantageous compared to the earlier built barrel-vaulted gridshells, it seems that the positive impact of the curvature in cross-direction was neglected. The members of the shell appear to have been designed with the same method that had been used before for the barrel-vaulted system. This observation leads to the assumption that the double curvature was introduced not so much for structural reasons, but for the sake of constructional simplicity. Thus could the detrimental break at the ridge (Bari boiler factory) be avoided and the roof sheeting led continuously over each bay. Shukhov's doubly-curved gridshell is constructed with solely identical elements – this is the real technical innovation as compared to earlier shell structures made of steel. The net-like structure is not only efficient but also economic, as the identical elements allow rapid manufacture and assembly. A rendering of the extremely light and delicate structure unveils the timeless elegance of the building, which seems already to evoke modern high-tech architecture (See Figs. 7). Today, the ailing and roofless building persists times and weather. An international team of professionals is striving to rescue the building and convert it into a museum dedicated to Shukhov's oeuvre. Only little time is left to save this artful engineering masterpiece.

**REFERENCES**


All figures are from the authors unless otherwise noted.

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