# ASSEMBLED WITHOUT SCAFFOLDING: THE CONSTRUCTION OF SCHUKHOV'S TIMBER LATTICE HYPERBOLOIDS


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**Keywords**

Schukhov, lattice hyperboloids, scaffolding, timber structures, tower



**Abstract**

The works of the Russian engineer Vladimir Schukhov (1853-1939) relate to the most cited examples of advanced engineering design from the turn of the 20th century. He developed and constructed new structural types such as hanging roofs, arched vaults and hyperbolic lattice structures. Schukhov`s lattice metal towers, patented in 1899, were built without scaffolding, which was feasible due to the special assembly sequence. On the eve of WWII, in a time of metal shortage, timber prototypes of lattice hyperbolic towers were developed: the cooling tower and the water tower for mass production. Researchers from IDB ETH Zürich found the only standing example of the former while the water tower exists in the form of detailed project documentation and a scaled experimental mockup of 1931. The paper focuses specifically on the assembly process of these two timber towers.


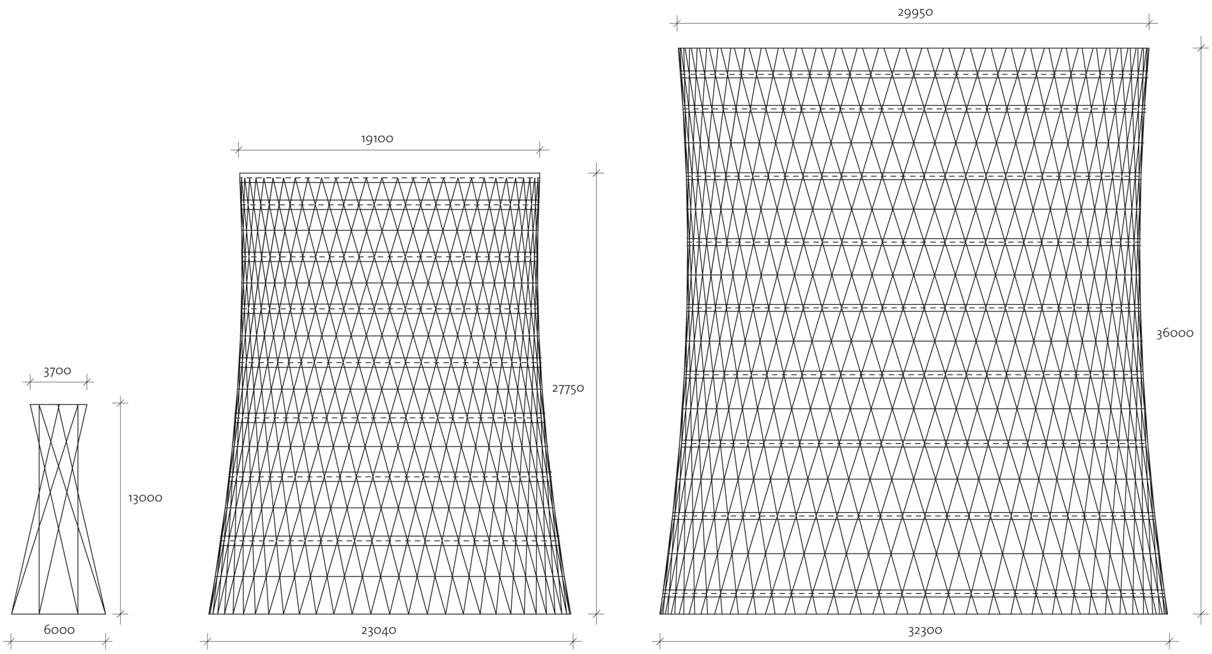


Figure 1: General parameters of designed timber lattice hyperboloids


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## LATTICE HYPERBOLIC TOWERS BY VLADIMIR SCHUCHOV

Russian engineer Vladimir Schuchov (1853-1939) is known for inventions and engineering challenges that were ahead of his time such as the construction of the first Russian oil-pipeline and the invention of oil-cracking. In the field of construction, he was the first to realize suspended roofs, lattice double-curved vaults and hyperbolic towers. Each of Schuchovs novel spatial structures is distinguished by a high level of prefabrication and a need for a detailed project of assembly. The latter included a clear sequence of steps, detailed schemes and a precise system of marking. In this article, we will focus on the assembly of timber hyperbolic towers. These structures are new for the discourse on Schuchov`s designs (Nozhova 2014). They resemble metal siblings, spatial structures built of similar straight elements, but at the same time have distinctive constructive features dictated by timber.

Schuchov built around fifty towers (Beckh 2012), with the geometry of each tower being unique and determined by function and context: the volume of the reservoir, the terrain, the pressure of underground water, the ground quality, all these parameters were considered in the design. There are some general characteristics of hyperbolic lattice towers that had to be taken into account by implementation. The accurate assembly of the strut base was decisive, as it determined the direction of the strut. The strut inclinations were controlled with the help of a plummet and gages. The projection points had to fit the control points; these were calculated and marked on a control template (Nozhova 2014). An important interdependence characterizes hyperboloids: the radial angle between the base points of the tower strut pairs at the horizontal projection is $2\alpha=(360°)/n$, where n is the number of pairs of struts. The points of the strut overlaps lie at the radial lines and the central angles formed by these lines are multiples of $\alpha$. This geometric interdependence could be promptly verified and thus eased precision control. Another bottleneck is the volumetric link between the struts. For the surface of profile to fit the point of overlapping with another profile, it had to be bent along the axis (Tomlow 1990). This was solvable due to metal's elasticity. For metal towers the assembly schemes are known. They demonstrate different patterns, depending on parameters such as height, radii of the top and bottom, angle of rotation and, crucially, the number of struts. The assembly of the high-rise towers of many segments (Schabolovskaya tower, 1919-1922 and NiGRES tower, 1927-1929) has its peculiarities (Hassler, Nozhova 2013), but its separate segments were built on the base of similar principles and schemes. All Schuchov`s towers, including the high-rise multisectional hyperboloids, were assembled without scaffolding. Historic photos reveal that light platforms were installed directly between the strut elements.

## LATTICE TOWERS BUILT OF TIMBER

During the time period between World Wars, timber was massively used for industrial structures (Seraphin 2003). The characteristic of lightness was for many years named as a prime quality of Schuchov`s towers; even the patent describes lattice hyperboloid tower as "a steady structure, strongly resistant to external forces at a reduced material consumption" (Patent No. 1896, 12 March 1899). The combination of lightness and steadiness was extremely advantageous as it coincided with the general motto of newly established construction research institutes to build safe at low cost. In light of the above, the recourse to Schukhovs designs and the reproduction of his construction principle in timber was logical.

By now two historic prototypes of timber hyperbolic structures are known: a 13-meter high water tower with 16 struts and a 27.75-meter high cooling tower with 120 struts (Fig 1). The water tower was published in the Atlas of Timber Engineering Structures (Karlsen, Zwingmam 1933), which was seen as an illustrative supplement to the previously edited Technical Norms and Conditions (of working with wood). This publication was a report of the State Research Institute of Structures on the development of standard designs that were easy to assemble, robust and structurally sound and could be reproduced throughout the country. It is highly likely that the second one, the cooling tower in Severouralsk, was designed by one of Schukhov's former colleagues who served a term in a prison camp in the Nizhny Tagil district. It was built by local, workers who were not necessarily qualified, possibly by concentration camp prisoners. Though based on the same geometrical prototype, these two structures are very different: one assumes a high level of precision by detailing and fabrication while the other tolerates inaccuracy. Both designs face a bottleneck in that the strut elements could not be bent and each overlapping had to be calculated and geometrically solved. Here we would like to elaborate on the assembly of these timber towers.

**Assembly of the cooling tower**

The cooling tower in Severouralsk had one predecessor – a cooling tower of similar construction in Kharkov. For a cooling tower in Kharkov, a special structure of portable scaffolding was elaborated (Fig.2). Fortunately it is a key theme of the only article about this structure (Mishustin 1938) so we can follow the engineers' logic. Special scaffolding consisted of a triangular element, fixed to the strut with the help of a belt and an ear-tag. The ear-tag left a hole after disassembly. The reason for having two different ways to fix the element might be explained by a wish to avoid unnecessary holes, which might weaken the strut. The platform planking was led between these triangular brackets. The system is light, rigid, easy to assemble and portable. It leaves a repetitive pattern of holes, and the sequence of assembly for the Kharkov tower can be explained with the scheme (Fig.3). Such a portable, light structure was considerably economical and was proudly regarded as "a separate engineering invention" by the author of the above-mentioned article.

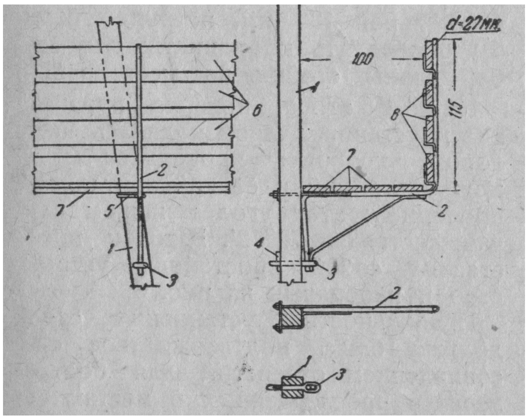


Figure 2: Portable scaffolding elaborated for the construction of the cooling tower in Kharkov

We assume that the tower in Severouralsk was assembled without scaffolding, but, like the prototype in Kharkov, with the use of similar portable triangular elements fixed directly on the struts. During the examination of the structure, we revealed a repetitive pattern of holes, which resembles the pattern described for the Kharkov tower. The pattern of holes should be "read" together with the pattern of the struts prolongations. While being prolonged, the struts needed to be sequentially rotated to fit the angle of the hyperboloid's surface. Here it was done with the help of specially cut cover planks, which form the guiding surface for the separate elements of the strut. It is possible to deduce from the general geometry of the tower that at each joint the next element should deviate from the previous one by approximately 3.5 degrees. Close examination of the details revealed considerable deviation from this deduced ideal angle. When we summarize the artifacts revealed on the structure, its details, and the sequence of steps described for the prototype in Kharkov, we come to a possible assembly sequence.

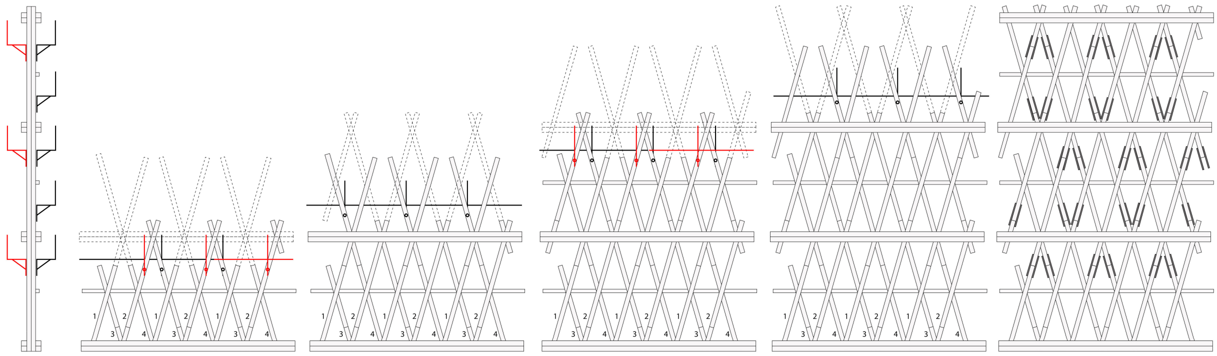

Figure 3: Assembly scheme for  the cooling tower in Kharkov

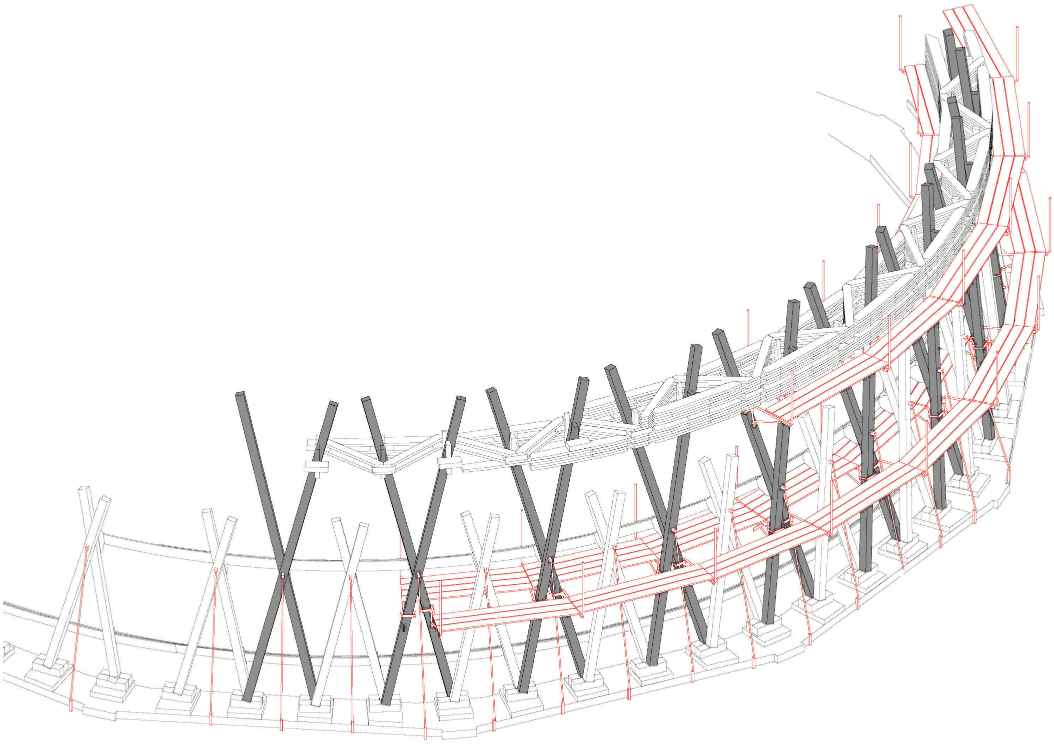

Figure 4: Assembly sequense for  the cooling tower in Severouralsk

First, the short pieces of the struts were installed and presumably fixed to the concrete ring with the help of clamps. The short struts have dimensions 150 x 150 mm on around 3,5 m, which gives a weight of each element around 52 kg. Two secondary rings helped to stabilize the structure and provided a third supporting point for the longer strut pieces (Fig. 4). On these longer struts, triangular elements were fixed on the two different heights. From these two platforms, the short struts could be prolonged (assembly from both levels, from the top downward and from the bottom upwards) and the first main ring could be built, which provided the whole structure with stability, so that the fixing clamps could be removed. Thus, the prolongation of the shorter struts was tightly fixed by the ring and the ring served as a platform to install a new level of brackets C (Fig.5). Level C and the first ring served to prolong both types of struts (again from the top downward and from the bottom upwards) and to construct the second ring. A new level of brackets D was assembled at the top of the higher struts, and then the process repeated: struts were prolonged and the new ring was constructed. This sequence repeats up to the top of the tower. Behind the seeming repetitiveness a considerable variety remains, necessitated by constructive logic, work safety and ease of assembly.

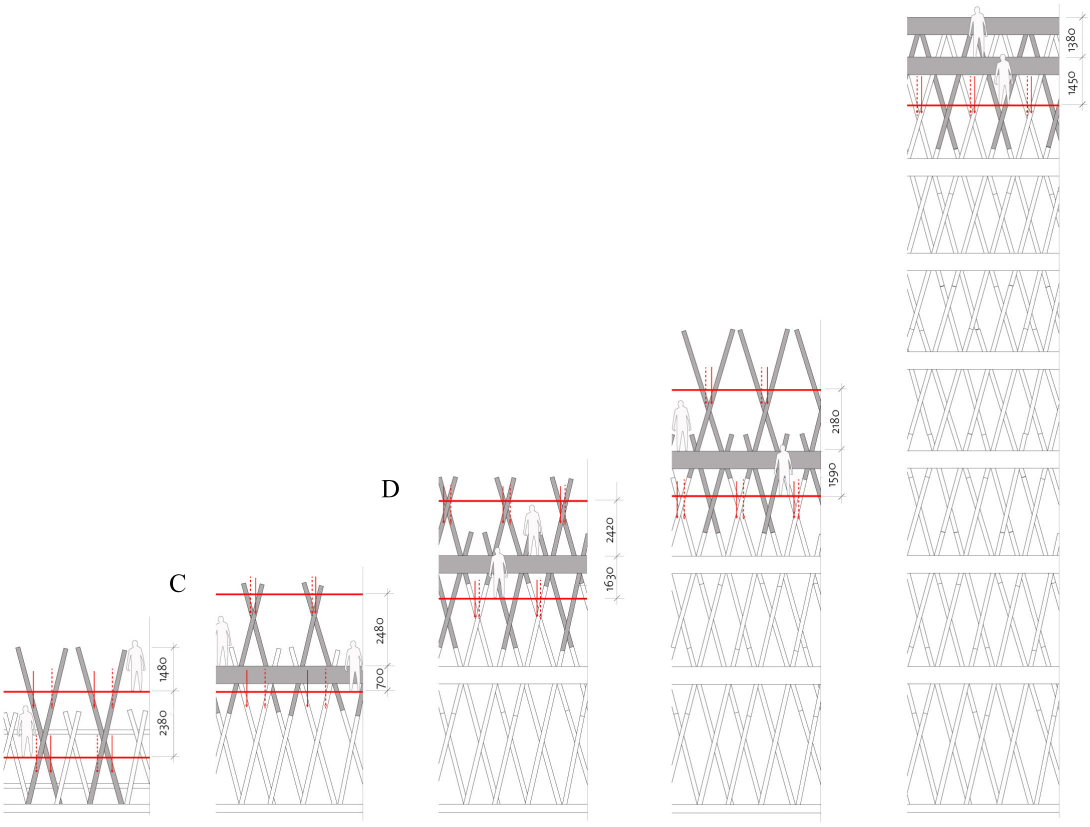

Figure 5: Assembly scheme for  the cooling tower in Severouralsk

The distance between the rings is different for every segment and the angle of the strut inclination also varies depending on the height of the section, such that the pattern of prolonged struts is different at each new step (Fig. 5, Fig. 6). Nevertheless, the platforms are installed at the heights appropriate for the safe assembly: the top of the 600-mm high ring is at a height of 1300-1700 mm from the lower platform, which matches the condition of convenient assembly. The height between the ring and the upper platform (1900-2400) always fits the safe passage. To foresee and coordinate these varying distances, together with a statically persuasive position of the bracing on the strut and with a pattern of prolongations dictated by the available size of timber,

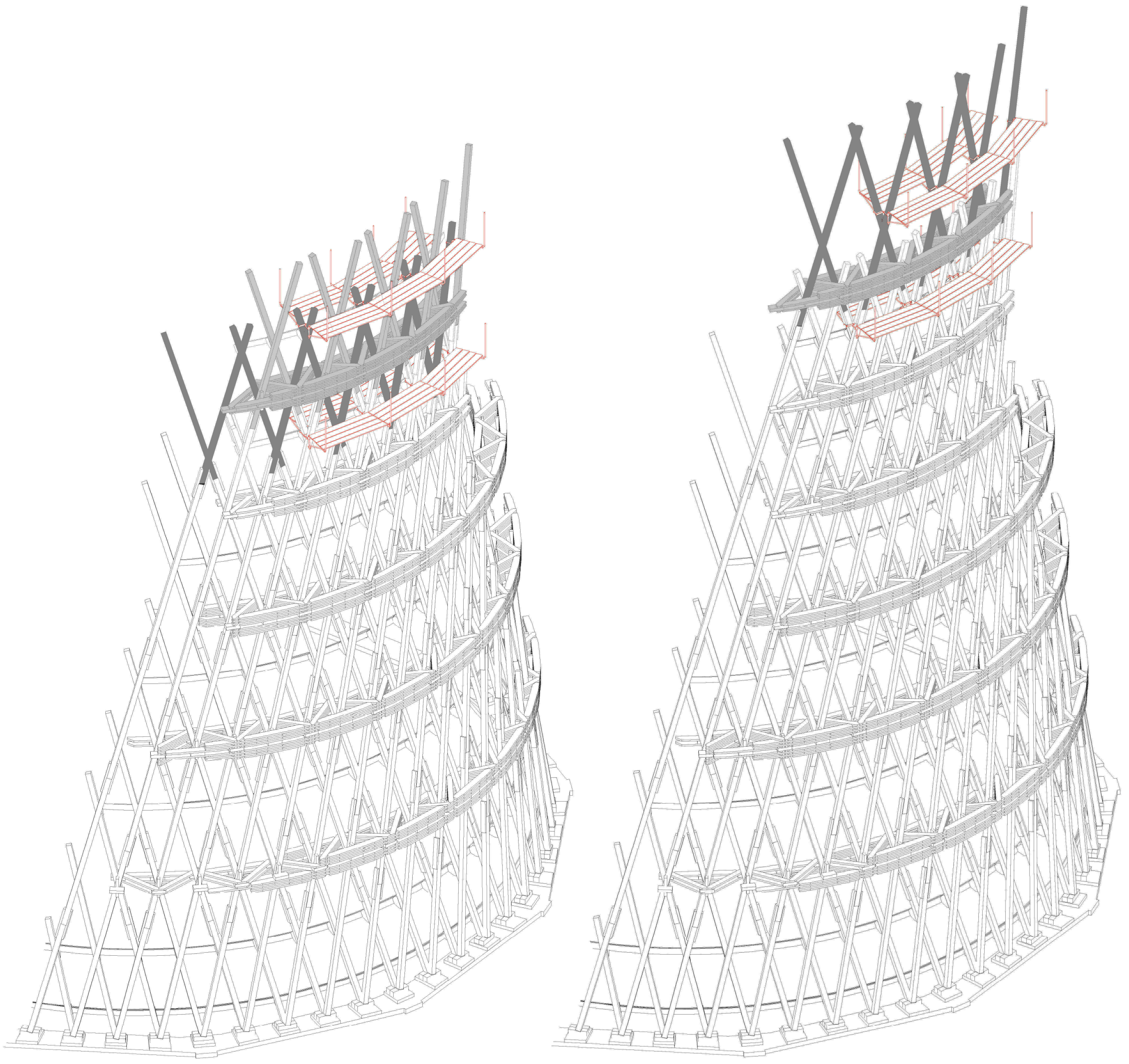

Figure 6: Assembly sequence for the cooling tower in Severouralsk: fifth and sixth rings

was a feat of engineering. Further, the construction manager could not rely on the availability of professional workers, which means every step had to be foreseen in detail, documented in a perceivable form and clearly communicated on site. It is worth mentioning, that despite the high precision of the structure in general, its detailing tolerated a degree of inaccuracy unavoidable when employing unskilled labour. Unfortunately, no trace of any working documentation concerning the cooling tower in Severouralsk was found.

### Assembly of the water tower

The documentation of the water tower impresses by a collection of complex three-dimensional joints; each strut has five overlappings with the struts of the opposite direction (fifth overlap is implicit and lies within the upper ring) that had to be precisely calculated and laid out. The necessity of the strut bending is compensated by the tower geometry: the tower is an octahedron in plan, which can be represented as a system of two crosses rotated at 45°. The structure of the first and upper ring repeats the same logic of two superimposed rectangular systems, rotated at 45°. Thus the struts and the elements of ring they are linked to are perpendicular in plan. Only by using 8 x 2 =16 struts is the problem of the strut bending eliminated; any other geometry leads to very complex and less reliable joints. This geometric characteristic was presumably used for the tower's assembly, and here we will present a possible succession.

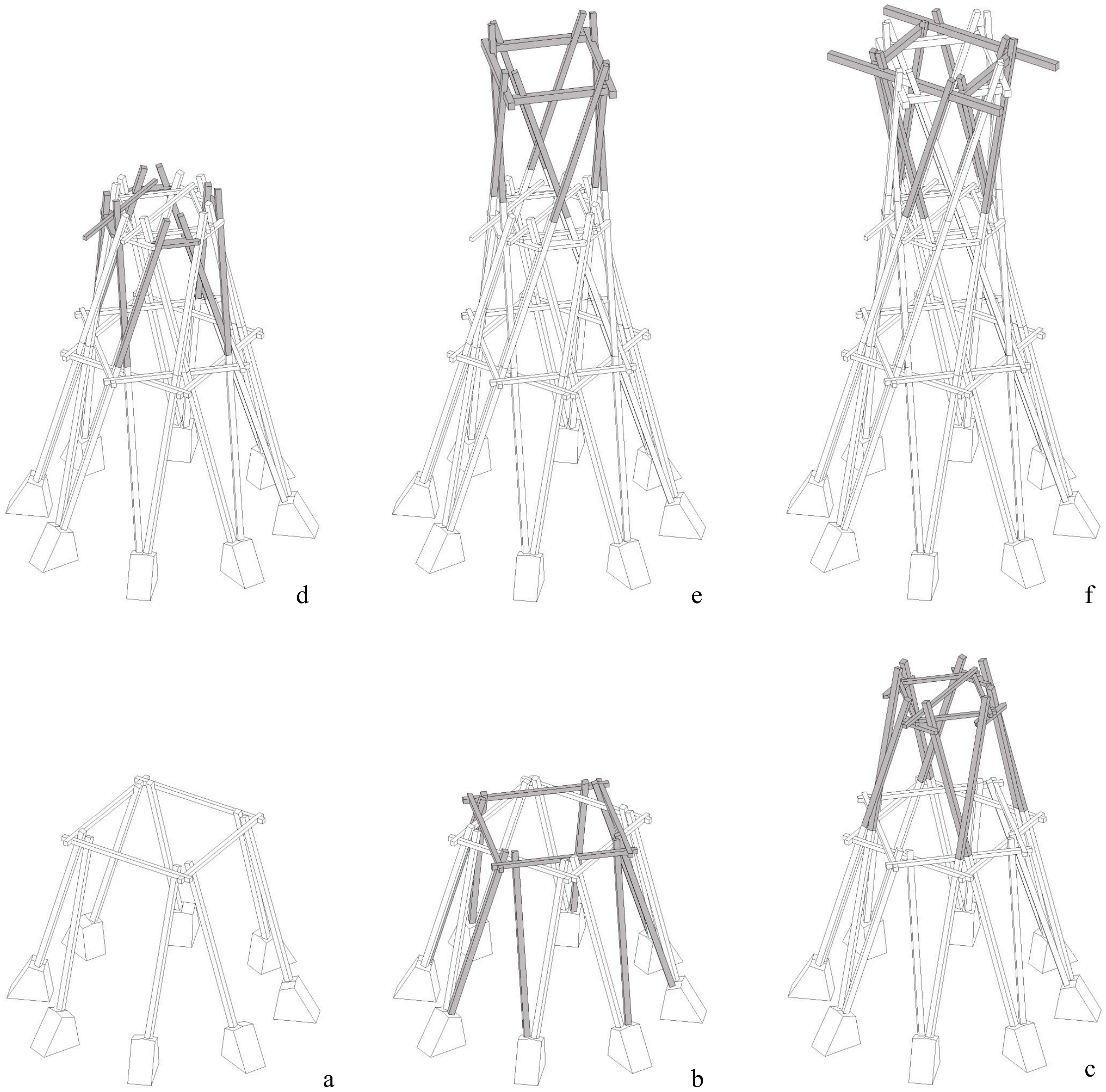


Figure 7: Assembly sequence for the water tower

The first stable structure could have been performed by lifting and fixing four flat frames together (Fig. 7a), before adding a similar system, rotated at 45° (Fig. 7b). Its assembly was easier, as it used the initial structure for support. Then half of the struts were prolonged; the elements of the second ring form a flat vertical stable structure together with the two struts. These were fixed in a right position by the square ring element with diagonal beam(Fig. 7c). This could have been done from the level of the temporary platform, installed on the beams of the first ring. Next, eight other struts were added, each strut overlapping with the struts of the opposite direction (Fig. 7d). Then the platform was installed at the second ring of the tower, and another eight struts were prolonged (Fig. 7e). Again, it is a system of flat, vertical frames, fixed together with the first square of the upper ring. The second square of the upper ring is rotated at 45°, and the last eight struts are fixed to its beams; the elements of the structure are again vertical and flat (Fig. 7f). Here we once more observe a bright example of engineering inventiveness: a system of two superimposed rectangular grids, which eases the joints between the elements, allows a sequential assembly separated into uniform simplified steps and leads in the end to the complex double-curved structure. In comparison to the cooling tower analyzed above, this design was intended for mechanized factory prefabrication, and the exactness of all joint cuts, distances and dimensions was extremely high.

## CONCLUSIONS

Behind each of the two structures is a unique and elaborated project of its realization, which is in fact an inherent part of the design, but because of its ephemeral character, it can be studied and analyzed as a postscript, on the basis of in-site findings, archival drawings, photographs and different types of written documentation. The outcome of this research recreates an important block of constructive information, essential for a deeper insight into engineering design process.

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