Differences between historical documentation and actual structure of the Shukhov tower in Moscow: 3D model-based analysis

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***Abstract*—The hyperboloid radio tower on Shabolovka Street built by V.G. Shukhov is one of the world known symbols of Moscow and of the USSR television broadcasting. The tower was laser scanned and 3D modeled in detail in 2011-2013 years. Virtual 3D modeling involved a thorough analysis of the existing historical documentation. This analysis revealed many discrepancies between the actual structure of the tower and existing historical documentation (including the design, working and survey documentation). In this paper we describe differences regarding the outline of the tower, structure of legs and connection joints, the height of the tower, and also discuss some assumptions on the change of mounting method during the building of the first two sections.**

***Keywords*—Shukhov hyperboloid tower in Shabolovka Street, historical documentation, actual dimensions, actual structure, method of mounting, 3D model-based analysis**

I. Introduction

Hyperboloid radio tower on Shabolovka Street in Moscow is a symbol of the Soviet radio- and television broadcasting and the world known monument of the Russian avant-garde architecture [1]. It is also called the Shukhov tower after the name of its constructor, Vladimir Shukhov (1853-1939), the famous Russian engineer and the honorous member of the Russian Academy of Sciences. The tower was built in 1919-1922 years, radio broadcasting started on March 19, 1922. In 1937-1967 years the tower was also used for the television broadcasting.

Currently the tower is a technical and architectural monument. Its technical condition is quite poor, and many projects of its restoration and reconstruction are developed.

In 2011 the laser scanning of the tower was performed [2, 3] to save the information about the tower in a digital form. Based on the results of the laser scanning, the tower was 3D modeled in details in 2011-2013 years. During the 3D modeling, an existing historical documentation was analyzed. This analysis has shown that the real structure of the tower differs significantly from the existing design, working and survey documentation [4-6].

The current paper describes main differences between historical documentation and actual structure of the tower. In particular, we describe differences regarding the outline of the tower, structure of legs and joints, the height of the tower, and also discuss some assumptions on the change of mounting method during the building of the first two sections.

II. Overview of the Tower Structure

The tower currently consists of six hyperboloid sections that are numbered in this article by the Arabic numerals (1-6) form bottom to top. In 1922-2015 the tower also had a superstructure. The original superstructure was reconstructed in 1937 and dismantled in 1991. A new superstructure for FM radio antennas was mounted in 1991 and dismantled in 2015.

Each hyperboloid section consists of straight legs which are located along generatric lines of the hyperboloid, and horizontal circular lattice girders which are located at the sections' junctions. Each circular lattice girder consists of two rings (outer and inner) and short straight beams between them which form a lattice. The legs of adjacent sections are skipped between the rings of the lattice girder and are attached to them and to each other through gussets. The structure of joints is unique for each pair of adjacent sections. In addition, there are intermediate rigidity rings in each section that are attached to the legs from the inside.

The four lower sections have 48 legs each, and the upper two sections have 24 legs each. In the lower two sections, each leg is made up of two channels mounted "back-to-back" through short spacers. In the four upper sections, each leg is made up of the equal angle (different sizes are used in different sections). Each leg is twisted around its axis.

A capital repair of the tower was never made during its existence. In 1937, 1947, 1971-1973, 1991 the tower was reconstructed, and a number of additional elements were installed on it: technological platforms at different levels, additional intermediate rigidity rings, an electric elevator, cellular antennas, etc. In 2015, many additional elements were dismantled and a massive supporting structure was installed inside the tower.

III. Overview of the Existing Documentation

There are three types of existing historical documentation: design documentation, working documentation and survey documentation.

The design and working documentation is almost completely lost. The surviving design documentation includes the calculations in the workbook of V.G. Shukhov (January-February 1919) [7, L. 25-30] and two drawings of 1919 [8, 9] that are stored in the Archive of the Russian Academy of Sciences (RAS). The surviving working documentation includes two drawings of 1921 [10, 11] that are stored in the Russian State Archive of Scientific and Technical Documentation (RGANTD).

A complete survey of the tower was performed in 1947, after the first 25 years of operation. The results of this survey are stored in the Archive of the Melnikov Central Research and Design Institute of Steel Structures (TsNIIPSK im. Mel'nikova) [12] and include detailed measurements and drawings of the tower and its individual parts and joints. Several projects of the tower reconstruction were developed

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later (in 1969 [13], 1971 [14], 1991 [15] years); general diagrams of the tower and its individual joints in these projects are based on the survey of 1947. Until the 2011 the survey of 1947 stayed the most complete set of the tower documentation.

It should be noted that the survey documentation was created with the aim of calculating the bearing capacity of the structure and does not reflect a number of details and elements of the original structure that do not influence on its bearing capacity (but could be important for the historical and technical analysis). In particular, it does not indicate the location of the joints of the individual parts of the legs and rings, mounting marks and holes, stamps on the metal. In addition, the available survey documentation as well as the tower reconstruction projects created on its basis [12-15] do not reflect a number of elements installed on the tower during its reconstruction in 1971-1973 and later. Among them are: reinforcing pads in the lower part of the 5th section and in some places of sampling; additional rings of rigidity and a vertical circular lattice girder in the upper part of the 5th section; technological platforms at the levels of 50, 75, 100, 138 m.

Thus we have a very poor set of the historical documents that can be used for the analysis of the tower design and mounting process as well as for analysis of its further changes. The most information is concluded in the tower itself. The under-documentation of the tower and its poor technical condition were the main reasons for starting the project of its digital 3D modeling based on laser scanning.

IV. Laser Scanning and 3D Modeling of the Tower

In 2011-2013 an initiative project on laser scanning and 3D-modeling of the tower was performed in the S. I. Vavilov Institute for the History of Science and Technology of the RAS [2-4]. The project was aimed to preserving information on the geometry and design of the tower in digital form and providing access to this information for specialists and the general public. All the results of the project, including the full 3D point cloud of the laser scanning, solid and meshed 3D models and interactive stereo 3D application for their analysis, were transferred to the RGANTD and are available for independent verification [16].

The tower was modeled with high geometric accuracy and high level of details. All legs and rings were modeled using a steel profile (angle or channel) of the corresponding cross section, taking into account their individual deformations. The accuracy of modeling the legs and rings of the tower was about 1 cm in the local coordinate system. This local coordinate system was tied to the reference geodetic network of Moscow.

Also, the model shows all the joints between the legs of different sections, between the legs and intermediate rigidity rings, between the joints of parts of the legs of different profiles. The historical survey documentation of 1947 was used to model the joints (courtesy of the Melnikov Central Research and Design Institute of Steel Structures) [12]. The general view of the 3D model is shown in Fig. 1.

Also in 2011 another project of the laser scanning of the tower was performed at the request of the owner of the tower, the “Moscow Regional Center” – a branch of the Federal State Unitary Enterprise “Russian television and broadcasting network (RTRS)” [17].

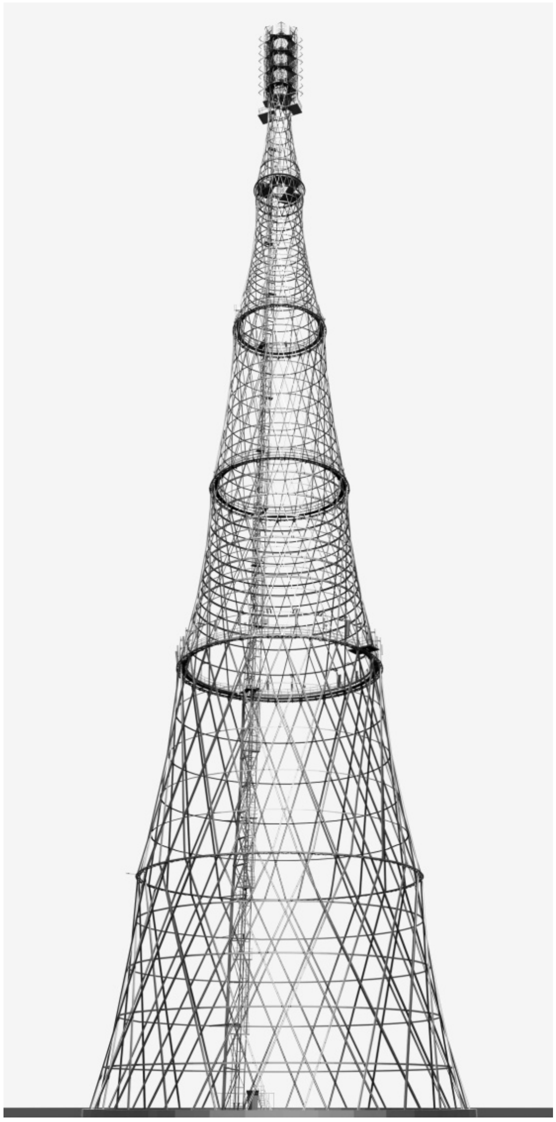

Fig. 1. 3D model of the Shukhov radio tower on Shabolovka.

This project was aimed to developing design documentation for the reconstruction of the tower [18]. Although the point cloud of this laser scanning is not available for analysis, we managed to compare two 3D models [19] and confirm their general geometric correspondence.

V. Outline of the Tower and Radii of the Support Rings

The first calculation of the mass of the tower with a height of 250 m was made in the workbook of V.G. Shukhov on January 27, 2019 [7, L. 25]. On February 01, 1919 the calculation of the mass of the tower with a height of 320 m was performed made of nine sections (two sections with a height of 20 m and seven sections with a height of 40 m) [7, L. 26]. On the same day, a detailed calculation of the mass and structure of a tower of arbitrary height begins made of sections with a height of 25 m [7, L. 26-28]. Sections are numbered from top to bottom in Roman numerals. The calculation was interrupted in the XV section, thus a tower with a height of 350 m (14 sections of 25 m each) was completely calculated. All legs are supposed to be made of a pair of channels (from No. 10 for section I to No. 18 for section XIV). The diameter of the support rings (i.e. circular lattice grids at the joints of adjacent sections) grows linearly: from 5 m for section I to 70 m for section XIV. On February 12, 1919 the calculation of the 350 m tower made of 14 sections continues: the number of legs, their design and total weight are indicated for each section [7, L. 28-29]. Brief calculations of the mass of the towers with a height of 75 m, 100 m, and 150 m were performed [7, L. 29].

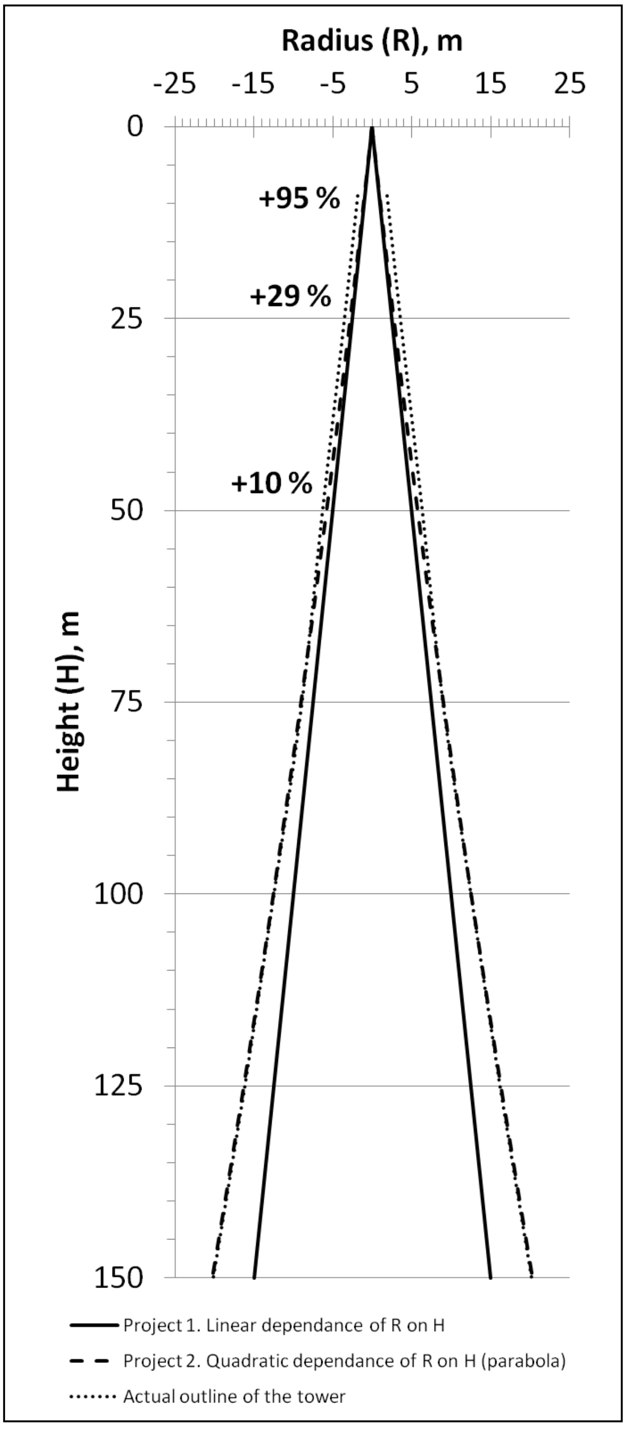

Fig. 2. Comparison of the projected and actual forms of the tower.

On February 28, 1919 V.G. Shukhov performed in his workbook a calculation of a 150 m tower made of six sections 25 m each. For each section he indicated the radius of the support ring, the number and design of the legs [7, L. 30]. On a back side of the leaf 30, a method for calculating the radius of the support rings is explained in details. The method includes both linear and quadratic dependence on the section number:

"Outline of the tower. Basic dimension. Cone with variable r that accumulates constant increment; in our case r, 2r, 3r, 4r ... or generally r, r + f, r + 2f, r + 3f, etc.; and variable increment with a continuous increase of slope from the vertical line α. The slope increment is expressed by the formula α × n × (n-1) / 2, where n is the number of the tower section starting from the top. Thus, the following series is obtained: 1) f, 2) 2f + α, 3) 3f + 3α, 4) 4f + 6α, 5) 5f + 10α, 6) 6f + 15α, 7) 7f + 21α, 8) 8f + 28 α etc. where the sizes r, f and α are set. In this case, r = 2.75 m, f = 2.75 m = r, α = 0.25 m and thus the radii get 2.75, 5.75, 9, 12.5, 16.25, 20, 25 (slopes 3 → 3.25 → 3.5 → 3.75 → 4)" [7, L. 30].

If a section height is 25 m, the distance from the top of the tower to the support ring of the n-th section is expressed by the formula H = 25×n. The radius of the support ring of the n-th section, according to the calculation method proposed above, is expressed by the formula R = 2.75×n + 0.25×n×(n-1)/2. If we express n through H in the first formula and substitute it in the second formula, we obtain the dependence of R on H: R = H×H/5000 + H×21/200. Thus, the outline of the 150-meter tower proposed in the workbook of V.G. Shukhov on February 28, 1919 is a parabola.

The actual radii of the support rings of the Shukhov radio tower on Shabolovka coincide with the calculations in the workbook [7, L. 30] for the four lower sections. In the upper part of the tower, the outline of the tower diverges from the calculated one. The actual radius of the ring at 100 m level is 10% more than the calculated one, at 125 m - 29% more, at 141 m - 95% more, Fig. 2. In the 1919 drawing [8] the outline of the tower visually coincides with the actual one.

The drawing of the 350-meter tower [9] contains only 9 sections and does not correspond to the calculations in the workbook both in the number and height of the sections. The dependence of the radius of the support ring on the height here is not linear that also does not correspond to the calculations in the workbook. The outline of the tower in this drawing visually corresponds to the quadratic dependence, which was proposed in the workbook for a 150-meter tower only.

VI. Structure of the Tower Sections

The actual design of the tower sections (the number and design of the legs) differs significantly from the calculations in the workbook [7, L. 30], see Table 1. The project assumed a uniform design of the legs of all sections (double channels). In reality, double channels were used only for the two lower sections, while the legs of the four upper sections are made from angles.

It is difficult to determine the number and design of the legs in the drawing [8]. We can only say that the legs in all sections are shown by double lines, which corresponds to the design in the workbook. The number of intermediate rigidity rings in the drawing [8] in the four upper sections differs from the actual one, see Table 1.

TABLE I. STRUCTURE OF THE SECTIONS: DESIGNED AND ACTUAL

№ of the section	Ele-ment	Structure		
		Workbook (1919)	*Drawing (1919)*	*Actual (1922)*
6 (I from the top)	legs	12 double channels No.10	double lines	24 angles 9/8 cm (lower/upper part)
	rings[a]	not specified	8 rings	9 rings
5 (II from the top)	legs	16 double channels No.12	double lines	24 angles 9 cm
	rings[a]	not specified	8 rings	9 rings
4 (III from the top)	legs	24 double channels No.12	double lines	48 angles 9 cm
	rings[a]	not specified	6 rings	9 rings
3 (IV from the top)	legs	24 double channels No.14	double lines	48 angles 12/10 cm (lower/upper part)
	rings[a]	not specified	8 rings	7 rings
2 (V from the top)	legs	30 double channels No.14 or 36 double channels No.12	double lines	48 double channels No. 14
	rings[a]	not specified	4 rings	4 rings
1 (VI from the top)	legs	36 double channels No.14	double lines	48 double channels No. 14
	rings[a]	not specified	4 rings	4 rings

a. Intermediate rigidity rings

VII. STRUCTURE OF THE JOINTS

The project presented in the workbook of V. G. Shukhov assumed a uniform design of the legs of all sections (i.e. double channels of different sizes). Apparently, a uniform design of the joints of the legs of adjacent sections was also assumed, which was reflected in the drawing [8]. In reality, the structure of the joint of the adjacent sections' legs is individual for each pair of sections.

The diagrams of the joints of the legs shown in the drawing of 1919 [8] do not correspond to the actual design. In particular:

- Both diagrams show the joint of the legs made from the double channel No. 10 (in reality there are no such legs on the tower);
- On the diagram "Connection of the legs of two sections", the gusset is located in the radial plane (whereas in reality all gussets at the joints of the legs are perpendicular to the radial plane and have a different shape); and the actual way of attaching the legs and gusset to the circular lattice girder is different from that shown in the diagrams;
- The diagram "Upper ring of the II section" roughly resembles the actual structure of the joint of the legs of the 1st and 2nd sections, but the shape and size of the gussets and the location of the rivets in this diagram are noticeably different from the actual ones.

Thus, the actual structure of joints of different sections has practically nothing to do with the diagrams in the drawing [8]. Unfortunately, in many publications devoted to the Shukhov radio tower on Shabolovka, the diagram "Connection of the legs of two sections" (1919) is given as a diagram of the actual structure. In particular, it is given in the 1961 book of G. M. Kovel'man, the student and the biographer of V.G. Shukhov [20, p. 157] and in the 1995 book [1, pp. 92, 94], without any reservations that the real structure of joints is completely different.

The 1921 working diagram of the joint of the legs of sections 2 and 3 section [11] looks similar to the actual structure, however, a number of discrepancies are found in the analysis. The angles of the inner and outer rings in the diagram are shown with the roots up (and the channel bars lays above them with the flanges directed upward); in fact, the angles of the inner and outer rings are set with the roots down (and the channel bars are riveted to them from below, with the flanges directed downward). The inner ring shown in the diagram is made from an equal angle 100x100x10 mm; in fact it is made from an unequal angle 150x100x10 mm. The outer ring shown in the diagram is made from an angle 100x100x16 mm, in fact it is made from an angle 100x100x12 mm. The length of short pieces of channel No. 14 between the gusset and the rings is 356 mm on the diagram but 240 mm in fact; their flanges are directed downwards on the diagram but upwards in fact.

Note that the joint between sections 2 and 3 was mounted twice. On June 29, 1921, when the fourth section was lifted, an accident occurred - the third section (already mounted by that time) had broken, the fourth one fell and damaged the second and third sections. After the resumption of work, the first two sections were repaired, and the third one was completely disassembled and then reassembled. The second lifting and installation of the third section was carried out at the end of October 1921. The diagram [11] is dated August 9, 1921 - just ten days after July 30, when V.G. Shukhov made a famous entry in his diary: "Verdict to Shukhov – conditional shooting up" [21]. It is not known whether this diagram reflects the actual structure of the joint of sections 2 and 3 in the first embodiment, or is it a project for re-assembling the joint – anyway, the actual structure has significant differences.

VIII. THE HEIGHT OF THE TOWER

As noted above, the calculation of the 150-meter tower made from 25-meter sections [7, L. 30] is closest to the actual design. However, in reality, the upper section of the tower has a lower height than the other sections, and a superstructure (antenna section) is installed on its upper ring. This option is also depicted in the design drawing of 1919 [8]. In the diary of V. G. Shukhov, there is a record for May 13, 1921: "Sixth section: 16 legs, channel No.10, height 20 m, number of rings 5" [22]. In reality, in the sixth section there are 24 legs made from the angles 90 mm (in the lower part of the legs) and 80 mm (in the upper part of the legs), and 9 intermediate rigidity rings, see Table 1.

The survey documentation of 1947 indicates the level of the upper ring of the sixth section: 144.16 m, and the level of the lower supporting ring of the first section: 0.5 m [12]. Thus, the total height of the six hyperboloid sections according to the 1947 documentation is 143.66 m. The same figures are given in the 1971 survey documentation [14].

In 1991, the historical superstructure (antenna section) of the tower was replaced with a new one. During the installation of the new antenna section, a new ring was installed on the sixth section at a height of 0.3 ... 0.36 m below the upper ring [15], after which all structures above this new ring were cut and dismantled. Thus, based on the information contained in the archival documentation, the height of the six hyperboloid sections of the tower presently should be 143.3 ... 143.36 m.

The current height of the six hyperboloid sections is 144.61 m according to our 2011 laser scanning [2, 3] and 144.40 m according to the 2011 design documentation [18, L.2]. It is not possible to find out the reason for the discrepancy of [18] with our data, because the point cloud of laser scanning used for developing of design documentation [18] is not available for verification and comparison.

The results of modern tower surveys using laser scanning technology show that the tower height was measured in 1947 with an error of more than 1 meter. According to our data, the true height of the six hyperboloid sections of the tower in 1922-1991 was 144.91 ... 144.97 m. This figure is close to the "round" value of 145 m. As noted above, V.G. Shukhov used the “round” section heights (20, 25, 40 m) in his design calculations, and it is logical to assume that a “round” design value of 20 m was also used for the shortened upper section of the radio tower on Shabolovka. This is also confirmed by the record in the diary of V.G. Shukhov [22].

IX. Fastening of the Intermediate Rigidity Rings to the Legs of the 1st and 2nd Sections

Each of the two lower sections of the tower consists of 48 legs: 24 internal (tilted clockwise when viewed from above) and 24 external (tilted counterclockwise when viewed from above). At each intersection, the outer and inner legs are connected to each other by four rivets.

Each leg is made from two parallel channels No. 14 positioned “back-to-back” and spaced 60 mm apart. Approximately every 0.5 m, these channels are riveted to each other. The shank of each rivet passes inside a piece of metal pipe installed between the channels.

Four intermediate rigidity rings are attached to the legs of each section from the inside. Each such ring is directly adjacent to the internal legs and is located at a distance of 140 mm from the external legs. Thus, each intermediate ring must be somehow attached to the external legs in 24 places.

The 1919 design documentation assumed the attachment of intermediate rings to the external legs through a U-shaped bracket installed in one of the nodes for attaching the leg’s channels to each other [8]. In reality, the first section uses two different methods of attaching intermediate rings to the external legs: through a bracket and through a short piece of channel No. 14. The bracket is used for all joints of the first intermediate ring and for 15 joints of the second intermediate ring of the first section, Fig. 3. Pieces of channel are used in almost all other joints of the first and second sections. Also there is no fastening in at least two places.

Fig. 3. Fastening of the 1st intermediate ring of the 1st section to a leg through a U-shaped bracket.

The bracket is attached to the intermediate ring with one rivet, the short piece of channel – by two rivets. In many places on the rings of the first section, there is an unused hole between the two rivets that fasten the piece of channel, Fig. 4. In some places there is an unused hole next to the rivet of the bracket, Fig. 5. All photos were taken by the author in the summer of 2014.

We can assume that the method of attaching the rings to the legs was changed (simplified) directly during the installation of the second intermediate ring of the first section, and the unused holes that remained on the rings were prepared for rivets for attaching brackets.

Mounting through a bracket is more difficult to implement than the mounting through a piece of channel. In case of using the bracket, one of the attachment nodes of the leg’s channels must be combined with the node of attachment of the legs to the ring. It means that you must either mount the ring simultaneously with the assembly of the legs, or accurately calculate the height of the brackets and the corresponding brackets holes on the rings. The mismatch of the actual bracket rivets with the prepared holes in some places allows to suppose that the exact calculation of the mounting locations of the brackets and counter holes in practice turned out to be quite complicated. Fastening through a piece of channel is much easier to install. In such a case, the assembling of the leg and attaching the intermediate ring to this leg can be performed independently.

Fig. 4. Unused holes in the 3rd intermediate ring of the 1st section.

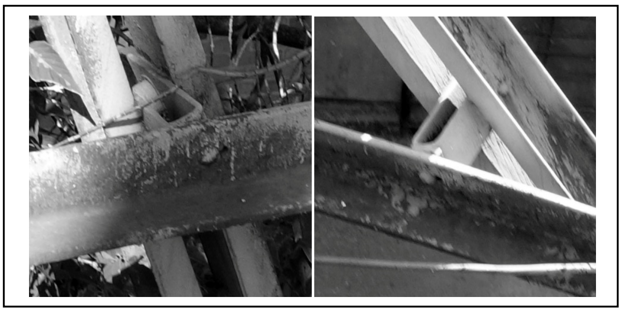

Fig. 5. Unused holes in the 2nd intermediate ring of the 1st section.

X. CONCLUSIONS

In the paper we analyzed a structure of the Shukhov radio tower on Shabolovka and compared it to the existing historical documentation. In particular, we investigated such questions as the outline of the tower, the design of the tower sections and joints, the height of the tower. We also clarified the method of mounting of the intermediate rings in two lower sections.

The 3D-model based analysis helped us to identify a number of differences between the design, working and survey documentation and the actual structure of the tower. In particular, it was found that:

1) The actual structure of the Shukhov Tower on Shabolovka (outline, construction of legs and joints) has significant differences from the existing design and working drawings of 1919-1921, as well as the calculations in the workbook of V.G. Shukhov.

2) The information on the height of the tower given in the archival documents is more than a meter different from the true value. According to our data, the original height of the six hyperboloid sections without superstructure was approximately 145 m.

3) The method of mounting of the intermediate rings was simplified directly during the installation process.

The laser scanning and 3D-modeling of the tower allowed us to efficiently detect and analyze the discrepancy between the historical documentation and the actual structure, identify mistakes in the description of the technical monument and raise new questions for further research.

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