The design of the overall stability of the Shukhov radio tower taking into account the local damage

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Abstract. The construction of the radio tower engineer V. Shukhov. For almost one hundred years the structures and components of the radio tower are heavily corroded which resulted in local damage. The danger of accumulation and increase of local damage is that they lead to the collapse of the tower. In 2016 anti-damage support structure was made to exclude the sudden avalanche-like collapse of the structure of the radio tower engineer V. Shukhov (Fig. 1). But there is a risk of formation and distribution of local damage. The checking calculation of the Shukhov radio tower was performed to identify the impact of the anti-damage support structure, taking into account the local damage. The calculation was made at the software complex "Lira-CAD". Normative loads, their application, reliability coefficients for loads and combination coefficients are adopted in accordance with Building Act 20.13330.2016 "Loads and impacts". The compatibility of the Shukhov radio tower and the anti-damage support structure is provided by pre-tension in the suspensions units of the radio tower attached to the support structure consoles. The tension force was determined by the calculation based on the experimental results of 2015.

The results of the combined geometrically nonlinear analysis of the Shukhov radio tower and the support structures showed the increased overall stability of the radio tower; the maximum movement of the unit stands and support rings was reduced by 20-30%, the maximum stands stress were reduced by 10-15% due to the load redistribution among the stands, but the maximum stress slightly exceed the allowed value. The complex of checking calculations of the Shukhov radio tower and the supporting structures showed that the existing anti-damage construction eliminates a sudden avalanche-like collapse of the structure. There is a risk of formation and distribution of local damage with the irreversible deformations of the stands and support rings of the radio tower with the increase of defects and damages of the structure of the radio tower which are still in a damage state. For a more uniform distribution of loads and increase the overall stability of the structure, it is necessary to increase the number of consoles of anti-damage support structure to 24 at each level of the support structure. Full-scale restoration works of the Shukhov radio tower structures are required to prevent the formation and distribution of local damages.
1. The description of emergency support structures of the radio tower engineer V. Shukhov

It will be 100 years since the construction of the radio tower V. Shukhov in 2022 [1, 2, 3]. For almost one hundred years the structures and components of the radio tower are heavily corroded which resulted in local damage. The danger of accumulation and increase of local damage is that they lead to the collapse of the tower [1, 4, 5].

The main cause of the formation of local damage is the corrosion damage of the structural sections and units of the radio tower V. Shukhov: the continuous surface corrosion of elements, significant crevice corrosion of the units of the connection elements. Non-corrosive defects caused by the project deviation during the tower construction, the damage caused during the installation, operation or strengthening the radio tower are the secondary causes of local damage [4, 5].

In 2016 anti-damage support structure was made to exclude the sudden avalanche-like collapse of the structure of the radio tower engineer V. Shukhov (Fig. 1). But there is a risk of formation and distribution of local damage. The construction of the radio tower engineer V. Shukhov taking into account the multiple defects and damages which are still in the damage state [5, 7].

Figure 1. The diagram of the radio tower V. Shukhov with the ant-damage support structure

The anti-damage support structure is a lattice hexagonal truncated pyramid of 4 sections. The support tower stands are made of metal pipe shapes (the diameter – 1020 mm for the two lower
sections, 720 mm – for the two upper sections). The metal hexagons consisting of a flat horizontal trusses with channel belts №.30P are built into the levels of sections connection. The lower stands of the tower are based on the free-standing monolithic reinforced grillage uniting the bored piles (9 piles under each grillage). The stands of the lower section are made vertical to reduce the impact on the existing foundation of the radio tower [5, 6].

The stability of the support structure is provided by the bedding-in of rigid stands in the grilles and by the flexible cross ties made in each section of the support tower.

The dead load of the radio tower is transferred by "hanging out" the radio tower units on the consoles of the anti-damage support tower (Fig. 2) in six units of four lower sections. The dead load of the radio tower are transferred along the axis of its elements through specially designed units for connecting the traverse to the rod elements of the Shukhov radio tower, preventing the bending (Fig. 1). The component of the vertical load (P), from the traverse (1) is transferred through the stops (2) to the inserts (3) pressed to the tower channels by the clamps (4). Due to the friction and compressed channel irregularities, the P1 the distributed load is transferred to the inclined stand of the radio tower. The link of the second component (P2) of the load P and excluding the corresponding deformation of the rods is the traverse and the clamps that attach it (5). To prevent the transfer of horizontal loads, "hanging out" is made with the flexible metal cables. The stands sections of the Shukhov radio tower are reinforced at the suspension units. The dead load of the sections of the Shukhov radio tower is distributed at four height levels on the console of the anti-damage support structure. Thus stands and support rings of the lower sections of the radio tower are unloaded. However, the continued formation of local damage deforms the stands and support rings of the radio tower V. Shukhov. Then it will be impossible to restore the original geometry of the radio tower shape [6].

![Figure 2. The photo of suspension units of the radio tower V. Shukhov at the console of the anti-damage support structure](image)

The checking calculation of the Shukhov radio tower was performed to identify the impact of the anti-damage support structure, taking into account the local damage [5, 7, 8]. The design of the load-bearing capacity of the radio tower structures engineer V. Shukhov was made in accordance with current standards. It was chosen the (increased) level of importance of the structure in accordance with State Standards R 54257-2010. The reliability coefficient of the importance of the calculation of load-bearing structures and bases was chosen as 1.2. The calculation was made at the software complex "Lira-CAD".

The spatial geometric rod diagram of the radio tower was obtained with an inserted digital rod model in the * .dfx format, designed on the basis of laser scanning data; it shows the actual place of
units and elements of the radio tower. The final design scheme was made after load application, describing the conditions of supporting stands of the radio tower and connection of the individual elements, their rigidity with adjustments based on the results of data analysis of preliminary calculations, measurement and survey work [1, 5, 9, 10].

The design takes into account the following loads – the dead load of tower metal structures, the load of the existing lift, ice load, wind load and temperature effect. The dynamic impact design take into account the pulsation component of the wind load. Normative loads, their application, reliability coefficients for loads and combination coefficients are adopted in accordance with Building Act 20.13330.2016 "Loads and impacts". The backbone units are concreted, the design scheme of the units of intersection stands of the radio tower are clamped in the top of the concrete. To strengthen the elements of the rod finite-element model of the Shukhov radio tower and the anti-damage support structure, the actual cross-section of the elements are used according to the measurements results.

2. The results of checking calculations of the radio tower V. Shukhov and existing reinforcement structures
Initially a static calculation was made for working out the design scheme and overall assessment of the stress-strain state of the radio tower, analysis of the calculated load combinations. According to the results of the static calculation without taking into account the local damage, longitudinal forces in the stands cross-sections and rings element are distributed uniformly. The results of the static calculation taking into account the local damage show the load redistribution in the damage areas: load redistribution in stands mainly takes place in two stands placed near the damage area. There is stresses increase in the cross-section of the radio tower structures that exceeds the allowed value. Then a dynamic calculation was made [11].

The dynamic calculation is made to determine the internal load in the primary load-bearing parts and units of the radio tower, taking into account the pulsating impact of the wind load and to determine the inertial forces. Besides, the forms and their corresponding eigenfrequencies are obtained. After a dynamic load, the load of the structure weight was formed from a load with a given dead weight of the structure. During the dynamic calculation, ten forms of natural vibrations were studied. The rod finite-element model of static calculation is used as a basis but to provide the correct calculations all rod elements (except the connecting and fixing elements) are divided into four finite elements [12, 13].

Ten vibration forms and their characteristics were obtained after the dynamic calculation. The calculation and analysis of the designed combination of loads were made. The vibrations forms having the significant impact on the design scheme were analyzed; the maximum forces in the characteristic groups of finite elements modeling the principal metal structures of the radio tower were selected on the basis of the calculated load combinations. The modeling of the local damage for each section were selected. In different wind directions, the radio tower mainly vibrates in the direction of the lift.

The calculation taking into account the geometric nonlinearity was made to obtain more accurate results of checking calculations and correct redistribution of loads during the local damage. The calculation with the geometric nonlinearity is made according to the scheme and the actual places of the units. The dead load, ice load, wind load as the sum of the average and pulsating components, temperature effects are used in these calculations [11, 14, 15]. The pulsation component is obtained by converting the results of the dynamic calculation into inertial forces. The rod finite-element model of dynamic calculation is used as a basis; all types of finite elements type 10 are replaced with type 309.

According to the results of a geometrically nonlinear calculation without local damages, the longitudinal forces in the stands sections and ring elements are distributed uniformly, with a small stress excess in the stands in the area where the lift are placed. The results of a geometrically nonlinear calculation taking into account the local damage showed the load redistribution in the damage areas: uniform load redistribution in the stands takes place on six adjacent stands with an increase stress exceeding the allowed value.
Figure 3 shows the deformed design diagram of the Shukhov radio tower and the anti-damage support structure for geometrically nonlinear calculation. Figure 3 shows the most deformed areas of the structure at the junction of the first and second sections of the stands and at the junction of the fourth and fifth sections of the radio tower.

![Image of deformed design diagram](image)

**Figure 3.** The deformed model of radio tower structures designed by V. Shukhov for geometrically nonlinear calculation of the local damage.

The loads of the rod finite elements of the radio tower and the direction of units moving towards the local damage were determined as the result of calculation with the geometric nonlinearity. The calculation and analysis of the load combinations was performed; the most unfavorable load combination was determined. The stress and the percentage of the load-bearing capacity depletion of the structural elements of the radio tower during the formation of local damages were determined according to the maximum load. Maximum stress and ununiform load redistribution take place in the attachment area of the lift taking into account the local damage.

Then the compatibility of a geometrically nonlinear calculation of the Shukhov radio tower and the anti-damage support structure was made taking into account the local damages.

The compatibility of the Shukhov radio tower and the anti-damage support structure is provided by pre-tension in the suspensions units of the radio tower attached to the support structure consoles. The tension force was determined by the calculation based on the experimental results of 2015.

The results of the combined geometrically nonlinear analysis of the Shukhov radio tower and the support structures showed the increased overall stability of the radio tower; the maximum movement of the unit stands and support rings was reduced by 20-30%, the maximum stands stress were reduced by 10-15% due to the load redistribution among the stands, but the maximum stress slightly exceed the allowed value.

The maximum movement and load in the elements of the Shukhov radio tower without the influence of support structures are shown in figures 4-6. Figure 7 shows a forces pattern of the elements of the Shukhov radio tower.
Figure 4. The maximum movement of radio tower units along the horizontal axis X-332mm;

Figure 5. The maximum movement of radio tower units along the horizontal axis Y-51mm;

Figure 6. The maximum movement of radio tower units along the horizontal axis Z-102mm;

Figure 7. Loads N in the elements of the radio tower of the calculation taking into account the geometric nonlinearity.
3. The results of checking calculations of the Shukhov radio tower and additional reinforcement structures

A combined calculations of the Shukhov radio tower with an anti-damage support structure and an increased value of consoles for the suspension of the radio tower units was made to increase the redistribution of loads between the radio tower stands during the of local damages. The number of suspension consoles was increased to 24 at each level of the support structure. The support structures behind the radio tower contour were added to the design scheme to increase the rigidity of anti-damage support structures (Fig. 8).

Figure 8. Additional anti-damage support structure

The results of the combined calculations of the Shukhov radio tower with additional support structures showed: the load while the local damage is distributed uniformly among the stands of the tower due to the co-operation of radio tower construction and the support structures; the maximum tension in the most loaded stands of 1 and 2 sections is reduced by 30-40%, so the part of the load is redistributed to the suspension support structure.

4. The key findings of the study

Analysis of the calculation results showed that the identified defects and damages have little effect on the overall stress-strain state of the structure, but significantly increase the load in the selected elements. The formation of local damage did not exclude the loss of stability of the Shukhov radio tower. Anti-damage support structures were installed in 2016 to prevent an avalanche-like collapse of the structure.

The complex of checking calculations of the Shukhov radio tower and the supporting structures showed that the stress in selected elements made from the redistribution of loads during the formation of local damage exceed the allowed value; but there is no loss of the overall stability of the structure. The most damaged elements of the Shukhov radio tower were selected when calculating the elements;
the load was selected by recalculating the overall scheme with the strong wind direction, thus the worst variant of loading the damaged section was selected.

The existing anti-damage construction eliminates a sudden avalanche-like collapse of the structure. There is a risk of formation and distribution of local damage with the irreversible deformations of the stands and support rings of the radio tower with the increase of defects and damages of the structure of the radio tower which are still in a damage state.

There is an irreversible deformations of stands and support rings of the radio tower as a result of ununiform distribution of loads from a small number of suspension units. For a more uniform distribution of loads and increase the overall stability of the structure, it is necessary to increase the number of consoles of anti-damage support structure to 24 at each level of the support structure.

Full-scale restoration works of the Shukhov radio tower structures are required to prevent the formation and distribution of local damages.

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