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Assessment of the concrete part of the contact system supports in the field

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Abstract. This article describes the issues of historical tour to the development of the supporting facilities fleet on the electrified railways of Russia; it considers the causal relationships of defect formation in reinforced concrete supports of the contact line. For the given operating conditions, a 3D model of the interior bracket-type reinforced concrete support was created in the SolidWorks software package. Using the SolidWorks Simulation module, the engineering review of the reinforced concrete support tension was made using the developed computation algorithm. 3D images of the support model were visualized from operating loads under design conditions and the values of the strain in the support height subject to the exposure to additional factors.

1 Introduction

Russia has one of the largest railway networks in the world. The operational length of the public railway system is 86,000 km, of which 43,400 km are electrified (3 kV DC for 19,000 km, 25 kV 50 Hz AC for 24,400 km). In terms of length of electrified roads, Russia ranks second in the world being inferior to China only.

As of January 1, 2019, the fleet of contact system supports in Russia is 1.79 million pieces (39.9% - on DC sections, 60.1% - on AC sections), of which 1.58 million are of reinforced concrete and 0.21 million are metal supports [1].

2 The history of the issue, problem state

For the years of electrification within the former USSR, various types of supports were designed and installed on railways. Reinforced concrete I-shaped supports of types SD, SDU, PD, ZhBD, round centrifuged of types SKZhB, SK, GC, SKC, SKU, So of 44-98 kN•m in capacity and 9.3-15.6 m long. In the 2000's, the annual average demand rate for reinforced concrete system supports for the Russian railways amounted to about 13,000 pieces and they used to be delivered by the reinforced concrete plants: Tolmachevsky, Overyatsky, Ryazansky, Beslansky, Meleuzsky, Uyarsky plants, etc. Then, the maintenance and repairs of bearing and supporting structures of the contact system was performed in line

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with the following regulatory documents as approved by the Department of electrification and power supply of the Ministry of Railways of the Russian Federation: "Instructions for the maintenance and technical repair of reinforced concrete structures of the contact system", Russian State Standard GOST 19330 "Reinforced concrete supports for the contact system of railways", "Instructions on anti-corrosion protection of reinforced concrete underground structures by the earth current" (CE 3557), standard plans of institutes. In compliance with these documents, incoming quality control and sampling inspection of supporting structures to be installed were performed. However, the incoming control was formally done on the range of roads, from time to time, indeed. The sampling inspection revealed the following deviations from standards in terms of production and installation of supports: non-compliance with the concrete wall thickness, contact between the embedded parts and the supports fittings, low resistance of supports, support deflection above the norm, cracks, chips, no insulation of embedded parts, etc.

Besides, deviations from the requirements of Russian State Standard GOST-19330 during the support storage and transportation resulted in their defects even before they are mounted. The bearing and supporting structures on roads were replaced and repaired as per the results of their assessment.

In 1992, the rate of support replacement decreased to the level of 1988, which caused the speedup in support aging. Consequently, the demand in support replacement increased even more and by 1995, 11.5 thousand pieces required replacement, and 14.5 thousand pieces by 2000. Additional mechanisms, supports, foundations, workforce, "windows", and finance were required to cover the support replacement of that volume.

Meanwhile, the railways management did not evaluate the replaced (defective) supports, they were not classified, the service life of supports that remained in operation was not predicted. In the 2000's and subsequently, the maintenance personnel were required to ensure the resource use of supports to the highest extent, predict and extend their service life, timely identify defective supports followed by their repair or replacement. For these purposes, specialized structural units of linear shops were established at power supply divisions, responsible persons were assigned who kept records on the state of supports and foundations, and fulfilled the basic operating requirements for anti-corrosion protection of supports and foundations. However, despite the measures taken, the problem of assessing the residual bearing capacity of supports were not solved and the ways to increase the service life of reinforced concrete supports were not found in full.

The Department of electrification and power supply of the Ministry of Railways of the Russian Federation jointly with the state corporation of the Ministry of Transport Construction were involved in the development of new design solutions for the contact system supports. The new reinforced concrete contact system supports developed by Gipropromtranstroy (State Institute for the Design of Industrial-Transport Construction Enterprises) based on CO-type supports, of non-stressed and stressed reinforcement. They were tested to show that such supports had the three-fold load margin and 1.8-fold margin for the fracture opening. In the 2000's, the Tolmachevsky plant of reinforced concrete products utilized the technology of serial production thereof.

The centrifuged supports of the contact system in the form of hollow conical pipes prevailed (mainly in section of roads electrified after 1960). They were produced with non-stressed and pre-stressed rebar. To reinforce the pre-stressed supports, high-tensile wire reinforcements were used.

For the first years of mass electrification, the supports with non-stressed rebar of the ZhBK type (conical) were manufactured as per projects designed by the Gipropromtransstroy in 1955 and 1957. Production of supports of two types were planned in both projects: separate and non-separable. Separate supports were mounted on block concrete foundations. The supports were fastened to the foundation with bolts. The design thickness of the walls of supports with non-stressed reinforcement was 50 mm. The supports were planned to be made of concrete of Grade 400. The design thickness of the protective layer in front of the rod on the outside was 17-19 mm, and 18-22 mm from inside. The position of the reinforcement cage in the formwork was planned to be fixed with gaskets. Cages and spiral winding were assembled on the special master plate. Mounting rings were placed with 750 mm increment. They were intended to be made of 4x16 mm strip or round steel of 6 mm in diameter. The spiral rebar was wound at a pitch of 125 mm. The diameter of the longitudinal reinforcement, number of rods and the steel grade were determined depending on the required capacity of supports.

Not all rebar embedded in the supports were as long as the supports. Due to the fact that the moment of flexure is small at the end sections, some part of rebar was "cut" in sections which did not required them by design. As per the project of 1955, only half of the total number of rebar in the supports was laid to the end sections. In the upper part of supports manufactured as per the project of 1957, all the rebar, except two, were pulled upward, if they fell in holes provided for the console anchor tie. In the butt part of the supports of 44-79 kN•m in capacity, every third rebar was cut off, and in the supports of 98 kN•m - every 4th rebar at the length of 650 mm from the bottom line. The length of supports as per the previous project is 10 m, and 9.35; 11.,5; 12.7; 13.5 m - as per the late ones. In spite of disadvantages of ZhBK supports (spontaneous girth cracking, etc.) on total, this type of support was one of the most successful as evidenced by the further experience of use.

Supports of types UZhBK, GC were made by projects developed in 1956 and 1960, with the pre-stressed rebar. This is how they differ mainly from the supports of type ZhBK. The peculiarity of these projects was that the reinforcement was pre-strained using special machines, and then was embedded in the concrete. The reinforcement preserved the tension until the concrete sets. As the tensile strength was removed from the reinforcement, it compressed the concrete in the attempt to reduce its length. Further on, when the support was already stressed, tensile stresses in the concrete were observed.

As per the project of 1960, the consoles were supposed to be fastened using the embedded parts, in contrast to the previously used fasteners on clamps. The wall thickness of the supports with the capacity of 44-59 kN•m was assumed to be 50 mm, and 55 mm - with the capacity of 79-98 kN•m. To prevent the contraction of the reinforcing frame, wound with spiral reinforcement, mounting rings were installed inside at a pitch of 2-3 m. At the ends of supports, at the top and bottom, plugs were provided.

In 1957, the project of supports of SZhBK type was developed. Supports were made of two versions: separate, of 10.1 and 11.6 m long and non-separable - of 12.6 m long. In terms of overall dimensions, mounting conditions for consoles and brackets, the supports were not significantly different from supports of UZhBK type. They mainly differed in the reinforcement cage made as the package of loops of high-strain wire. Spiral armature of 2 mm in diameter was wound on the top of the rebar package at a pitch of 125 mm. In separate type supports, the ring fittings of 5 mm in diameter and at a pitch of 50 mm were used in the anchorage cone (4 m long), and mounting rings made of hot-rolled smooth wire with the diameter of 6 mm were installed every 3 m along the length of the stand. To avoid the excess compression of concrete by the force of pre-stressed reinforcement, it was projected to take the part of rods out of service at the length of 2 m from the top of support by coating with bitumen.

Supports of the SK type were longer than the previous ones. The diameter of the spiral reinforcement was increased. For AC roads, the ground conductor was embedded in the support, which later resulted in such a negative phenomenon as the reduction in the support resistance below the norm (as per requirements of sustainable operation track circuits). In 1966, the project for SK type supports was redesigned in terms of reduction of the susceptibility of supports to longitudinal crack formation: high-strength deformed section wire was used, reinforcing rings (3 pieces) made of wire of 6 mm diameter were used to at the top, the pitch of the spiral reinforcement decreased from 125 to 75 mm, and the wall thickness of supports tend to depend on their specified torque. Rubber tubes were used to insulate the parts.

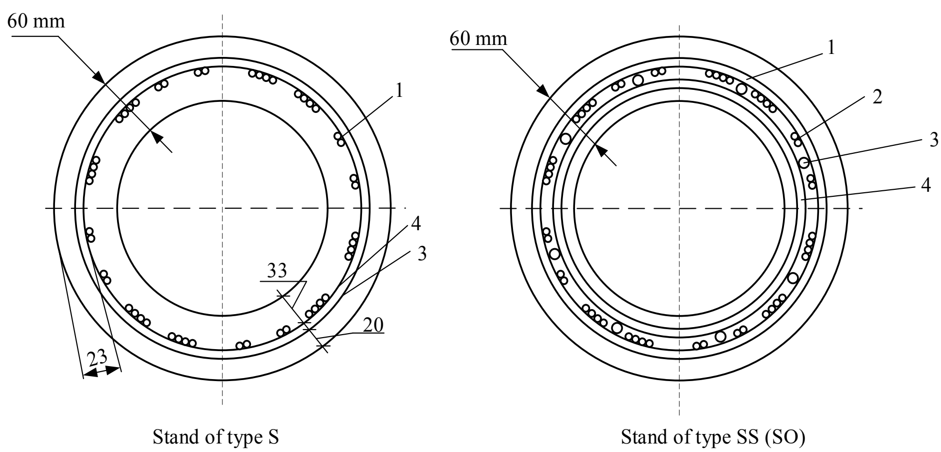
In 1970, the project for the existing SK type supports was re-adjusted, and new supports of the SKU type appeared. Their length (for separate type supports) was reduced from 11.2 to 10.8 m, and the wall thickness was increased to 60 mm. Rubber gaskets were used to isolate the embedded parts from the surface of supports.

In 1976, further improvements were made to the project for SKU type supports. SKC type supports appeared differing from the SKU supports in eight vents above the level of the embedding. Along with rubber tubes, the project allowed the installation of insulating sleeves of polyethylene.

Since 1983, the Russian State Standard GOST 19330-81 "Reinforced concrete pillars for the reinforced contact system supports. Specification" has been put into effect which regulates the types of produced supports. As per this standard, the term "support" takes the meaning of the structure on whole (along with embedded parts, console, etc.). The wire stressed precast concrete itself, intended for the contact system, is called the "stand". The standard provided for the use of two main types of stands:

S - wire stressed reinforcement (used for AC sections); SO – with wire stressed reinforcement and non-stressed rod reinforcement for foundation sections (used on DC sections).

For the period since 1993, supports with mixed reinforcement or supports with the limited tension of SS type (with wire stressed and with rod non-stressed reinforcement along the entire length of the rack) were widely used. Currently, the specifications for the stands for the contact system supports are regulated by the Russian State Standard GOST 19330-2013 [2]. The scheme of stand reinforcement of types S and SS (SO) is shown in Fig. 1.



1 - spiral; 2 - rods of high-strength wire; 3 - rebar; 4 - mounting rings.

Fig. 1. Scheme of stand reinforcement of types S and SS (SO).

Based on researches conducted and summary of operating experience [3-5], all causes of defect formation can be classified per technological, structural defects and those caused by the impact of external factors.

The Research Institute of Concrete and Reinforced Concrete (NIIZhB) and the All-Union Research Institute of Transport Construction (VNIITS) conducted the studies the results of which helped to identify the relationship between the crack formation process in concrete supports and process technology. It was noted that the crack formation was caused by violations or deviations from the process regulations and requirements for the support manufacture, rigging and transport works, support stacking and installation works.

To prove the above, the results of the study of the Vladivostok-Ussuriysk section of the Far Eastern Railway were taken. In particular, since the start of electrification, the builders and operators revealed the longitudinal and transverse fractures (visually) on the range of concrete centrifuged contact network supports earlier mounted. The crack opening of supports was tested to reveal that a number of supports produced by the Talovsky plant are made of concrete of lower grade of concrete than required, along with gross violations of requirements for the manufacture of reinforced concrete structures. For many supports, the rebar was completely unrelated to the concrete, they were simply placed inside the body of the support. This episode of the study is the classic example to prove the process causes of crack formation.

As for the structural causes of crack formation, it can be noted that one of the main reasons for the fractures in the contact system supports is the stress state of the concrete caused by the pre-stressed reinforcement, the forces applied on supports during their operation, installation and transport works. The experimental and theoretical studies performed by the CNIIS proved that the process of concrete destruction is not instant, it starts with micro-destructions in the structure that occur under the certain intensity of the stress-strained concrete. Moreover, having the platelet structure and the ability to change its volume depending on moisture saturation, the concrete is subject to irregular deformations. So, inherent (structural) and forced stresses occur. Inherent stresses occur because of aggregates (crushed stone, gravel) and rebar that prevent the cement stone to reduce in volume when it loses moisture. Forced stresses are determined by the uneven loss of moisture in the wall thickness of concrete. The inner layers of concrete prevent the free deformation of the outer layer contraction, which results in tensile stresses in the latter.

The structure of external impact is defined by a range of factors that affect the support during operation: static load from the weight of the contact suspension, overhead wires, switching and protective equipment; dynamic exposure to wind and rolling stock (aerodynamic front, ground fluctuations); ambient air temperature and humidity; aggressive effects of soil and atmosphere; electro-corrosion caused by the current leaks, especially on electrified DC roads.

All these factors negatively affect the support. Changes in the stress of the support material occur due to static loads, dynamic exposure to wind and rolling stock, as well as temperature exposure. The influence of current leaks, aggressive impact of the soil and atmosphere leads to changes in the physical and mechanical properties of the support material. The long-term exposure to certain or unfavorable combination of factors can result in defects, and, finally, to the decrease in the bearing capacity of supports.

Numerous observations of the contact system supporting structures, held by various researchers and design entities, and roads have shown that the main problem of damages caused to the contact system supports are the fractures in the concrete − longitudinal and transverse fractures. They can lead to the breakage and fall of the support, cause the break in the wires of the contact network, disrupt the power supply and railway traffic on the relevant section.

To date, the causes of crack formation in reinforced concrete supports have been well studied [6-11].

During operation, significant tensile stresses occur in the contact system supports exposed to climatic and power factors, which unfavorable effect can be combine to cause cracks.

Longitudinal cracks in supports are the most common type of damage. Mainly, the longitudinal cracks in supports appear during the operational period due to the exposure of natural and climatic factors that cause the thermal difference in the body of the support, which leads to stresses in the surface layers of concrete, reducing the tensile strength of concrete.

Cold rains and winds supports cause the rapid decrease in the temperature of the support surface. This results in the temperature difference along the perimeter and wall thickness. Meanwhile, the tensile stresses defined earlier in [12] can reach the values close to the maximum permissible values.

The outer surface of the support is exposed to the ambient air temperature fluctuations to spread to the inner layers. The temperature drop that occurs along the wall thickness leads to the temperature stresses in the concrete. According to our calculations [13], the greatest tensile stresses occur on the outer surface of the support and can result in premature cracks.

Longitudinal cracks that appear in supports in the long-term operation may also be the result of the frosty increase in the concrete volume in the inner layers. Frost damages normally occurs in those parts of supports where the concrete is highly humidified or water-saturated and is subject to frequent freezing and thawing. The conducted researches established the main factors that determine the frost resistance of concrete. These include the structure and density of concrete, the degree of water saturation and the chemical composition of the dissolved substances, the freezing temperature and the rate of its decrease. As a result of repeated freezing and thawing, the concrete loses its strength and delaminates.

Efficient measures to increase the frost resistance of concrete during operation have not yet been identified. These measures should be taken at the stage of construction, mainly by selecting the proportion of concrete [14].

Another factor, being very important to cause the longitudinal cracks, is the temperature stresses in the support that occur under the sun light. Stresses in concrete supports occur due to uneven thermal distribution over the surface and wall thickness during the regular heating and cooling of the structure.

3 Solution

According to the data obtained by us [15], we defined the values of temperature drop between the outer and inner surfaces and the temperature change on the support surface. We determined, based on calculations, that the maximum tensile stresses occur on the northern side of the support in its lower part having the largest diameter. It is concluded that when the heat beam moves along the surface of the support, tensile tangential stresses appear due to alternating heating of its surface, creating torques to complement the thermal stresses. This phenomenon is called the thermomechanical effect and is, in our opinion, the main reason of longitudinal crack formation. It should be noted that this phenomenon was not previously considered by researchers when describing the operational reliability of reinforced concrete supports.

Most often, force factors are believed to be the cause of transverse cracks. They can also be caused by insufficient coupling of the reinforcement with concrete. Opening of such cracks for more than 0.5 mm is not allowed.

Damage from force effects occurs when the actual loads are incorrectly considered at the stage of design or deviations from the design solution are made during the manufacture, as well as when the load on the structure increases due to the suspension of extra power and reinforcing wires, mounting brackets and other similar effects.

In addition, it is necessary to note another important factor: this is the electromagnetic field of the contact suspension, the exposure to which causes the transverse cracks mainly in the upper part of the support.

We determined that when an electromagnetic field is applied to the support reinforcement, the electric current is induced in it, which, flowing through the reinforcement, heats it up. It is known that even the minor excess of the temperature of the conductor (reinforcement) over the ambient air temperature (concrete supports) leads to drying and gradual cracking of concrete [16].

Heating of the coil reinforcement under the effect of the electromagnetic field of the contact suspension further results in the formation of transverse cracks in the concrete body, reducing its overall bearing capacity.

Many works are devoted to the impact of operational factors on the cause of damages in concrete [17, 18, et al.]. However, the studies focused on the assessment of the bearing capacity of supports considered certain factors only, but not their totality. Therefore, there is a need for the comprehensive assessment, in view of probabilistic characteristics that allow predicting the state of the contact system supports.

In addition to standard loads, the operational effects on the support are proposed to consider in this work. In particular: daily fluctuations in the ambient temperature, exposure to cold wind and rain, and thermomechanical effect, which includes the combined effect of temperature and torsion stresses. The developed model of the support will allow the multi-factor analysis of natural and climatic impacts to be considered.

An intermediate support located on the straight section of the track is used as the design support (Fig. 2). The 13.6-meter-long contact system support is submerged in the loam to 4 meters deep. Loads were determined for two design modes - maximum exposure to wind of 32 m/s (MW) and ice with wind up to 5 mm and 18 m/s (I+W).

Fig. 2 shows:

G_c, G_{cw}, G_{w1}, G_{w2}, G_{bl}, G_f, G_{bf} — vertical load of the weight of contact suspension, console, wiring of longitudinal power supply lines, bracket of longitudinal power supply lines, fiber-optic communication lines, bracket of the fiber-optic communication lines, respectively;

Z_c, Z_{cw}, Z_{cs}, Z_{w1}, Z_{w2}, Z_{bl}, Z_f, Z_{bf} - application arms of loads from the carrier cable, contact wires, console, longitudinal power supply line, longitudinal power supply line bracket, fiber-optic communication line, fiber-optic communication line bracket, respectively;

P_c, P_{cw}, P_{w1}, P_{w2}, P_f - wind loads on the carrier cable, contact wires, longitudinal power supply line, fiber-optic communication lines;

h_c, h_{cw}, h_{w1}, h_{w2}, h_f - elevation of the points of application of forces relative to the base of support;

q_s - wind exposure to the support.

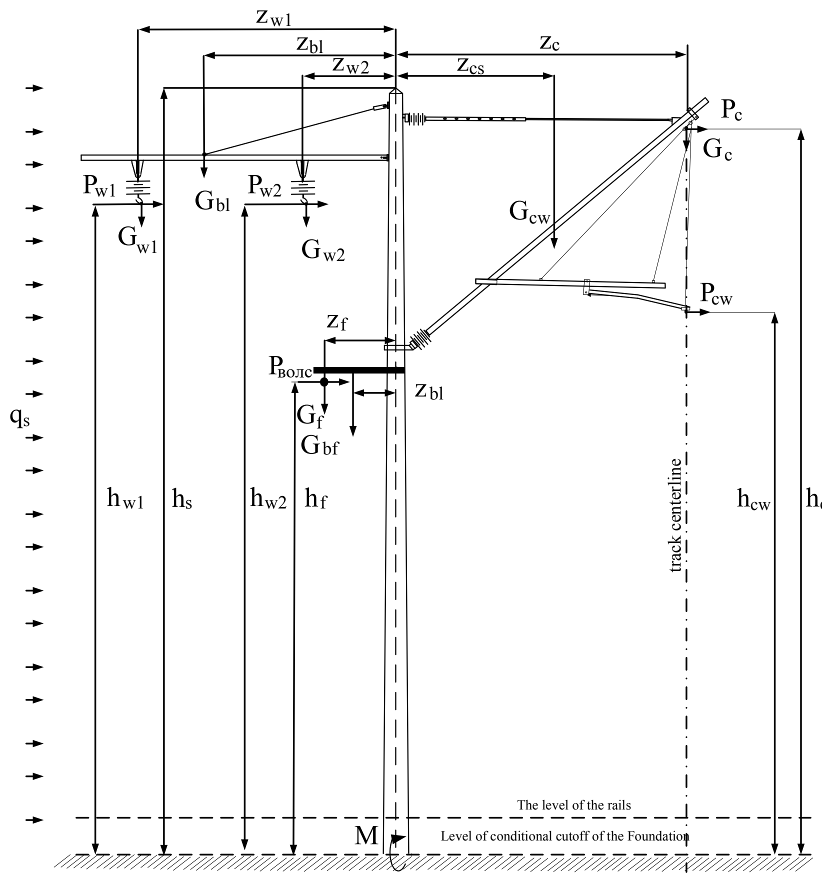


Fig. 2. Design scheme of the intermediate console support.

Currently, the main achievements in various fields of science and technology are loosely connected with the improved computer-aided process. The resources of the advanced information and computer technology made it possible to set and solve mathematical problems which seemed non-realizable in the recent past. This is especially true for modeling large systems, which include the contact network [19].

Today, numerical methods are most widely used with the finite element method [20] to lead. Its advantage is the ability to consider various and complex properties of materials in calculations, the ability to reduce the problem to the system of linear or nonlinear algebraic equations directly, without pre-formulation of their differential analogues.

Currently, there is a great number of automation systems for engineering design and analysis based on the finite element method: Nastran, Abaqus, T-FLEXCAE, Deform, Qform, LS-DYNA, ANSYS, Plaxis, SolidWorks Simulation, etc.

The SolidWorks [21] refers to the category of software for computer-aided design and engineering. Currently, it enhances its position at industrial machine-building enterprises in Russia, and its scope of application still increases.

An intermediate console reinforced concrete support was designed for the visual representation and detailed design of operating load stresses using the SolidWorks software environment. All support elements and their overall dimensions are accepted in accordance with the interstate standard [2]. The initial data for the program are the standard loads applied on the support, defined for two design modes - maximum strength of wind and ice with wind, calculated for the real operating conditions of the Far Eastern region.

All the work was mainly done in the SolidWorks Simulation module [22]. Engineering design was carried out by finite element method, the accuracy of calculations was achieved by the design display in the form of the triangulated mesh. The calculation algorithm was made for each created support triangle, in view of the specified material of all elements of the support structure, fasteners, and applied loads.

The general view of windows of the resulting model of the intermediate console support, in view of directions of operating loads, is shown in Fig. 3.

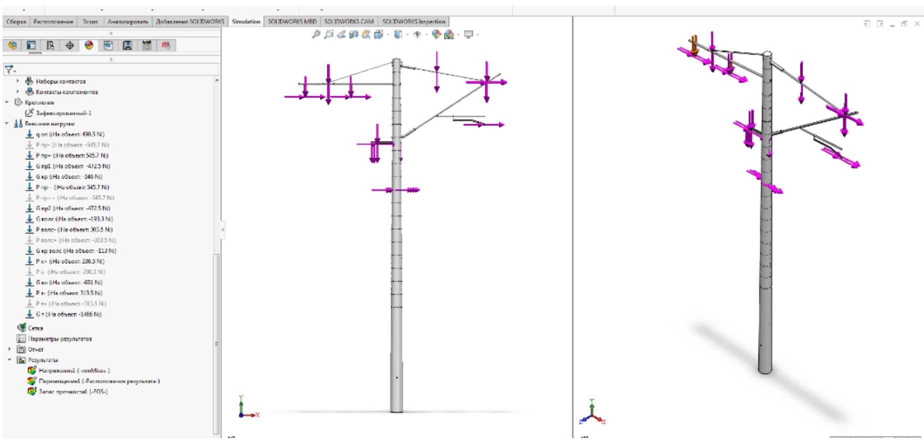


Fig. 3. Model of intermediate console support based on directions of operating loads in the SolidWorks software environment.

After performing the extended program analysis in the previously described 3D model, due the influence of simultaneous exposure to operational factors, we get the resulting values of mechanical stresses in the height of the support (Fig. 4).

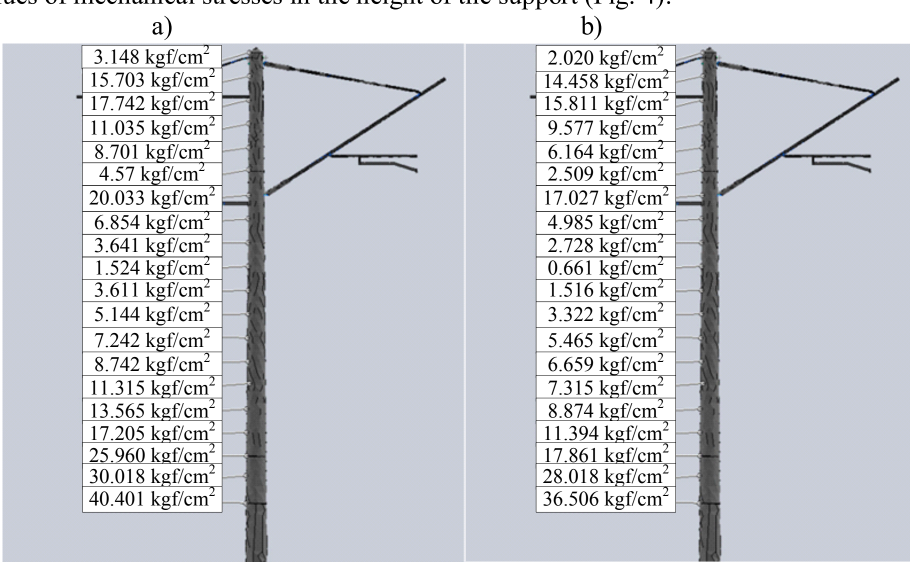


Fig. 4. Results of calculations of mechanical stresses caused by the maximum wind (a) and ice with wind (b) in the SolidWorks software environment, considering the impact of operational factors.

4 Conclusions

The evolutionary way of development of the centrifuged poles of the Russian railway contact system has shown that at the initial stage of mass electrification in the 1960's, the principle of economic efficiency of the stand structures was mainly applied. All this resulted in the production of supports based on this principle to be of low operational reliability. Supports with mixed reinforcement manufactured in recent decades have proved to be more reliable and crack-resistant. The ways of their design solutions are almost exhausted, since the concrete has reached its best efficient strength. However, despite the results achieved in the field of design, supports made by older projects are still used today in the support fleet of Russia. Therefore, issues of the strength assessment of concrete remain unsolved.

The defect formation was studies to note that during operation, a number of factors affect the reinforced concrete supports of the contact system, which lead to the defects and, as a result, to the decrease in their bearing capacity. However, the studies focused on the assessment of the bearing capacity of supports considered certain factors only, but not their totality. Therefore, there is the need for the comprehensive assessment of supports in view of their probabilistic characteristics.

To assess the concrete part of the support, a 3D model has been developed to consider the exposure to operational factors. It helps to assess the stress of the reinforced concrete support exposed to a range of extra operational factors: daily temperature fluctuations, sun radiation, wind and rain. For this combination of loads at specific points of support, in particular, at the level of UOF, the design stress values are more than 1.5 times higher than the maximum permissible values of the concrete tensile resistance. This fact indicates that these parts of the support are mostly susceptible to develop longitudinal cracks if their safety factor is exhausted. Since each support has its own individual characteristics, we recommend that the assessment of the stand based on the created 3D model was added to the datasheet of the support that is kept in operation of the supporting structures. This allow to predict the state of the supporting structures.

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