Strength, crack resistance and deformability of the power lines’ cylindrical supports

V L Shchutsky, A S Nasevich*, M G Holodnyak, A M Blyagoz
Don State Technical University, 162, Socialisticheskaya Str., Rostov-on-Don, 344022, Russia

E-mail: x609km@mail.ru

Abstract: A numerical experiment was conducted to study the effect on the restrictions’ cylindrical supports design strength on the crack opening and ultimate strains’ width. The analysis of the effect on the cylindrical supports’ fracture toughness and deformability of the relationship between the prestressed and total reinforcement areas (Asp/As,tot). The research results showed that the dependence of the crack opening width on the ratio Asp/As,tot for all cylindrical racks types is close to linear. The reinforcement coefficient μs, tot % does not affect the nature of this relationship. The increase in the torque proportion from the vertical loads Mv/M leads to a significant increase in the crack opening width. The greatest influence on the cylindrical racks’ deflections has the prestressed reinforcement content (Asp/As,tot). In this case, the total reinforcement coefficient practically does not affect the type of function fpr=f(Asp/As,tot).

Introduction
This article presents the results of a numerical experiment to study the bearing capacity of the cylindrical power transmission line supports, taking into account the restrictions on the crack opening width and the maximum permissible deflections.

This work is an integral part of the previous studies on the annular cross section reinforced concrete pillars’ strength [1], the physical and mechanical properties of centrifuged concrete [2], the technological factors’ influence on the change in the centrifuged concrete strength along the wall thickness of a product [3], as well as the influence of the relationship between the tensioned and non-tensioned reinforcement on the bearing capacity of the power transmission line supports [4].

Experiment Program and Research Results
This paper presents the results of a numerical experiment on the study of the crack resistance and cylindrical struts’ deformability.

As the samples under study, the racks of the high-voltage power lines’ cylindrical supports according to GOST 22687.0-85, 22687.3-85 were adopted.

In a numerical experiment, the total reinforcement coefficient was changed for all types of racks μs,tot % within 2,7±4,7% (for CR22 and CR26). In addition, in each series of the 5 elements samples, the ratio of the prestressed reinforcement area to the total changed (Asp/As,tot) and the torque ratio from the vertical to the full load (Mv/M).
In the experiment, a program for calculating reinforced concrete pillars of a circular section according to the deformed scheme [5] developed at the Rostov State Civil Engineering University was used. The calculations for the first and second group of the limit states were performed in accordance with the standards’ requirements [6]. In this case, the nonlinear stress distribution in the reinforcement and concrete along the section height according to the technique developed by V. M. Batashev [7,8] was taken into account.

Table 1. Experimental cylindrical struts’ general characteristics

| No. | Sample references | \( \mu_{s,tot} \) | \( A_{s,tot}[mm^2] \) | \( A_{sp}[mm^2] \) | \( A_s[mm^2] \) | \( \frac{A_{sp}}{A_{s,tot}} \) |
|-----|------------------|-----------------|-----------------|-----------------|-----------------|------------------|
| 1   | CR22.1           |                 | 2.7             | 2728            | 0               | 0.00             |
| 2   | CR22.2           |                 |                 | 682             | 2046            | 0.25             |
| 3   | CR22.3           |                 | 1364            | 1364            | 0.50            |
| 4   | CR22.4           |                 | 2046            | 682             | 0.75            |
| 5   | CR22.5           |                 | 2728            | 0               | 1.00            |
| 6   | CR22.6           |                 | 0               | 3740            | 0.00            |
| 7   | CR22.7           |                 | 935             | 2805            | 0.25            |
| 8   | CR22.8           |                 | 1870            | 1870            | 0.50            |
| 9   | CR22.9           |                 | 2805            | 935             | 0.75            |
| 10  | CR22.10          |                 | 3740            | 0               | 1.00            |
| 11  | CR22.11          |                 | 3740            | 0               | 1.00            |
| 12  | CR22.12          |                 | 3740            | 0               | 1.00            |
| 13  | CR22.13          |                 | 3740            | 0               | 1.00            |
| 14  | CR22.14          |                 | 3740            | 0               | 1.00            |
| 15  | CR22.15          |                 | 3740            | 0               | 1.00            |

Table 2. The results of the cylindrical reinforced concrete racks’ calculation CR-22.1- CR-22.15 with the ratio of moments from the vertical loads to the full \( M_v/M = 0.2 \)
According to these results, Fig. 1 shows the graphs of changes in the rack’s bearing capacity during fracture and the design strength, taking into account the restrictions on the cracks opening width and deflection. A more visual representation of the change in the bearing capacity of cylindrical racks can be seen in the graphs in Figure 1.
The results analysis shows that the bearing capacity of the racks CR22 with a constant cross-section of concrete increases with an increase in the total coefficient of reinforcement $\mu_{(s,tot)}$. However, with the constant $\mu_{(s,tot)}$ with increasing ratio of the prestressed reinforcement area $A_{sp}$ to the full area $A_{s,tot}$ a smooth (close to linear) decrease in bearing capacity is observed (Fig. 1), which increases with increasing the reinforcement percentage. S.A. Dmitriev [9] and A.P. Kudzis [10] came to the same conclusions in their studies.

A similar change in bearing capacity is observed in another series of racks CR26.1-CR26.15. The reason for this phenomenon is associated with the symmetric distribution of the prestressing reinforcement according to the annular section parameter and is explained by the earlier destruction of the compressed zone with an increase in the prestressing reinforcement content. Table 3 shows the comparative data on the relative decrease in the bearing capacity of the studied cylindrical racks for the boundary values of the ratio $A_{sp}/A_{s,tot} = 0÷1.0$. So, for example, in the cylindrical racks 26 m
high (CR26) at a percentage of reinforcement \( \mu_{(s,tot)} = 3.7\% \) change \( \frac{A_{sp}}{A_{s,tot}} \) a change from 0 to 1 led to a decrease in strength by 13.2%.

Table 3. Comparative change data on the cylindrical struts’ bearing capacity

| Rack type | Total reinforcement percentage \( \mu_s \), tot | Load bearing capacity, KN*m by \( \frac{A_{sp}}{A_s} , \ tot=0 \) \( V_1 \) | Load bearing capacity, KN*m by \( \frac{A_{sp}}{A_s} , \ tot=1 \) \( V_2 \) | \( \frac{V_1-v_2}{100} \) \( \% \) |
|-----------|---------------------------------|-----------------|-----------------|----------|
| CR 22     | 2.7                             | 416.9           | 388.3           | 6.9      |
|           | 3.7                             | 510.7           | 458.6           | 10.2     |
|           | 4.7                             | 594.2           | 514.2           | 13.1     |
| CR26      | 2.7                             | 390.7           | 357.7           | 8.4      |
|           | 3.7                             | 478.3           | 415.2           | 13.2     |
|           | 4.7                             | 556.2           | 463.1           | 16.7     |

The pre-stressed reinforced concrete transmission line supports, reinforced with the A-600, A-800 class bar reinforcement belong to the 2nd category of requirements for the crack resistance with the maximum allowable crack width \( a_{cr} = 0.2 \) mm. The design guidelines for power lines [11] limits the deflections when exposed to the standard loads (0.6-0.8) from the destructive loads within (1/15-1/25) \( l_0 \). Taking this into account, the maximum permissible deflection value in numerical experiments is accepted equal to 1/20.\( l_0 \).

Let us analyze the effect of the crack opening width restrictions and allowable deflections on the design strength. The maximum values of the moments corresponding to the ultimate deflection \( (M_f) \) and the maximum crack opening width \( M_{shc} \), for the racks CR22 are given in Table. 2. Based on these data, the graphs of changes in the design strength of the racks according to the conditions of the maximum crack opening width and maximum deflection, are shown in Fig. 1.

The analysis shows that the design strength of the racks under the ultimate deformability conditions and the crack opening width increases with an increase in the total reinforcement coefficient, \( \mu_{s,tot} \) and the relations \( \frac{A_{sp}}{A_{s,tot}} \). This conclusion is valid for all types of racks, regardless of their flexibility.

It should be noted that the strength under the condition of the crack opening width for all types of struts, as a rule, exceeds the strength under the deformability condition. The discrepancy between the changes graphs in strength increases with increasing \( \mu_s,tot \) and the relations \( \frac{A_{sp}}{A_{s,tot}} \). (Figure 1).

The main factors that have a significant impact on the reinforced concrete racks’ crack resistance is the coefficient of the reinforcement \( \mu_{s,tot} \) and the prestressing reinforcement content \( \frac{A_{sp}}{A_{s,tot}} \). Fig. 2 shows the characteristic graphs of the \( M_{shc} \) cracks formation instant dependence on \( \frac{A_{sp}}{A_{s,tot}} \).

The analysis shows that the moment of cracking \( M_{shc} \) increases significantly with increasing \( \mu_{s,tot} \) and the content of prestressing reinforcement \( \frac{A_{sp}}{A_{s,tot}} \). Larger \( \mu_{s,tot} \) corresponds to a larger increment \( M_{cr} \). So, for example, in cylindrical racks CR22.1-CR22.5 (Table 2) with \( \mu_{s,tot} = 2.7\% \) the change \( \frac{A_{sp}}{A_{s,tot}} \) from 0 till 1 for the increased \( M_{shc} \) 3.24 times. The similar change \( \frac{A_{sp}}{A_{s,tot}} \) in the racks CR22.11-CR22.15 with \( \mu_{s,tot} = 4.7\% \) led to the \( M_{shc} \) 4 times increase.
Figure 2. The dependence of the cracks formation moment from $A_{sp}/A_{s,tot}$

a) CR22; b) CR26

$M_{shc}$ kNm

The change $M_{v}/M$ from 0 till 0.4 leads to an insignificant increase in the crack resistance of the struts by (2-6)%, regardless of the ratio $A_{sp}/A_{s,tot}$.

Figure 3 shows the graphs of changes in the racks cracks’ opening width depending on $A_{sp}/A_{s,tot}$ upon destruction. An analysis of these graphs shows that the dependence of the crack width $acr$ from $A_{sp}/A_{s,tot}$ are very close to linear. The reinforcement percentage $\mu_{s,tot}$ has almost no effect on the nature of this dependence in cylindrical racks. Therefore, the graphics $acr=f(A_{sp}/A_{s,tot})$ for racks of the same type with different $\mu_{s,tot}$ remain parallel.

Typical graphs of changes in crack width depending on $\mu_{s,tot}$ is shown in Fig. 4. An analysis of these graphs shows that the dependence $acr=f(\mu_{s,tot})$ is nonlinear. Moreover, in cylindrical racks, the ratio $A_{sp}/A_{s,tot}$ does not affect the nature of this dependence.
Figure 3. The dependence of crack opening width at fracture

a) CR22  b) CR26

The attitude \( \frac{M_v}{M} \) has a significant effect on the crack opening width. For all types of racks the increase \( \frac{M_v}{M} \) leads to an increase \( a_{cr} \), but is not equivalent for various \( \frac{A_{sp}}{A_{s,tot}} \) (Fig. 4).

With the \( \frac{M_v}{M} \) change from 0 till 0.4 the increment of crack opening width at low values \( \frac{A_{sp}}{A_{s,tot}} = 0.25 \) reaches (22-53)\%, and at high values \( \frac{A_{sp}}{A_{s,tot}} = 0.5-1.0 \) and the large percentages of reinforcement, \( \mu_{s,tot}=(2.5-4.5)\% \) crack opening width increases several times.

Let us analyze the influence of various factors on the racks’ deformability. As expected, the number of the prestressed reinforcement had the greatest influence on the deflection of the uprights \( A_{sp} \). Fig. 5 shows the graphs of changes in the cylindrical columns’ deflections depending on \( \frac{A_{sp}}{A_{s,tot}} \).

The analysis of these graphs shows that the deflections’ dependence on the ratio \( \frac{A_{sp}}{A_{s,tot}} \) for all the types of racks is non-linear. In this case, the function type \( f_{pr}=f(\frac{A_{sp}}{A_{s,tot}}) \) for each type of struts practically does not depend on the total coefficient of the reinforcement \( \mu_{s,tot} \).

An increase in the reinforcement percentage of the uprights, ceteris paribus, very slightly reduces the uprights deflection (by 0.2-2.1\%).

The increased moment from the vertical loads and relationships \( \frac{M_v}{M} \) leads to the increased deflections. This is true for all types of struts at any percentage of reinforcement, as graphically illustrated in Fig. 5. With increasing the attitude \( \frac{A_{sp}}{A_{s,tot}} \), the influence \( \frac{M_v}{M} \) deflection decreases.

For the most typical relationship \( \frac{A_{sp}}{A_{s,tot}}=0.5-0.75 \) the change \( \frac{M_v}{M} \) from 0 till 0.4 led to an increase in the cylindrical racks’ deflections CR22 for (11-15)\%, CR26 (6-12)\%.
Figure 4. The crack opening dependence width on $\mu_s,_{tot}$

- a) CR 22
- b) CR 26

$A_{sp}/A_{s,_{tot}} = 0.25; \quad A_{sp}/A_{s,_{tot}} = 0.75$

Figure 5. Changing the racks’ deflection

- a) CR 22
- b) CR 26

$M_v/M = 0$

$M_v/M = 0.2$

Summary
1. For all types of racks with an increase in the prestressed reinforcement content in the section \((A_{sp}/A_{s,\text{tot}})\) a linear decrease in the bearing capacity is observed, which is increased with an increase in the total reinforcement coefficient \(\mu_{s,\text{tot}}\).

2. The design strength of the cylindrical racks under the conditions of the crack opening maximum width and the maximum deflection increases with increasing the total reinforcement coefficient \(\mu_{s,\text{tot}}\) and the content of prestressing reinforcement \(A_{sp}/A_{s,\text{tot}}\). In this case, the strength under the condition of the crack opening limiting width exceeds the strength under the deformability condition.

3. With an increase in the proportion of torque from the vertical loads \(M_i/M\), the design strength under the condition of ultimate deformability \(M_i\) and the condition for the maximum crack opening width \(M_{\text{crc}}\) declining. There is a greater influence of the relationship \(M_i/M\) to reduce crack resistance than to reduce deformability.

4. The moment of the cylindrical struts’ cracking increases nonlinearly with an increase in the content of prestressed reinforcement \(A_{sp}/A_{s,\text{tot}}\) and the total reinforcement coefficient \(\mu_{s,\text{tot}}\).

5. The dependence of the cracks opening width on the relationship \(A_{sp}/A_{s,\text{tot}}\) for all types of racks is close to linear. The reinforcement coefficient \(\mu_{s,\text{tot}}\) does not affect the nature of this dependence in cylindrical racks.

The increase in the torque proportion from the vertical loads \(M_i/M\) leads to a significant increase in the crack opening width both in the fracture stage and in the operational stage. At the same time, a larger total reinforcement coefficient and a larger ratio \(A_{sp}/A_{s,\text{tot}}\) corresponds to a larger increment \(a_{\text{crc}}\) which varies widely.

6. The greatest influence on the cylindrical racks’ deflection has the ratio \(A_{sp}/A_{s,\text{tot}}\). The deflections’ dependence on \(A_{sp}/A_{s,\text{tot}}\) for all types of racks is non-linear. In this case, the total reinforcement coefficient practically does not affect the function type \(f_{pr}=f(A_{sp}/A_{s,\text{tot}})\).

References

[1] Shchutskiy V L, Nasevich A S., Chubarov V E, Blyagoz A M 2019 The research on bearing capacity of supports with annular section CATPID-2019 IOP Conf. Series: Materials Science and Engineering 698 022089. doi:10.1088/1757-899X/698/2/022089.

[2] Dedukh D A, Schuzkiy V L, Kuzmenko A A 2017 Spun concrete properties of power transmission line supports Magazine of Civil Engineering 7.

[3] Shchutsky V L, Dedukh D A, Gritsenko M Yu 2016 The design of the experiment in the study of the properties of centrifuged concrete Scientific Review12 89-96.

[4] Schutsky V L, Talipova T D The strength of the cylindrical supports of power lines, taking into account the limitations of the second group of limit states Science of Science 8 (2) 2016.

[5] The program for calculating reinforced concrete pillars of annular cross section according to the deformed scheme, Certificate of state registration of computer programs 2012 660898. Information on http://www.rgsu.ru/structure/ipdepartment/list-of-certificates.php.

[6] SP 63.13330.2012, Concrete and reinforced concrete structures. The main provisions, SNiP 52-01-2003, M., 2012, 161.

[7] Batashev V M 1978 Strength, crack resistance and deformation of reinforced concrete elements with multi-row reinforcement (Budivelnik Kiev).

[8] Schutsky V L, Nasevich A S 2014 The method of calculating the reinforced concrete supports of power lines for strength, Publishing House “Scientific Review 10 (3) 659-661.

[9] Dmitriev S A 1962 Refinement of the calculation of the strength of ordinary and prestressed elements of the annular section Proceedings of SRI RC “Study of the strength, stiffness and crack resistance of reinforced concrete structures” 26.

[10] Kudzis A P 1964 Influence of prestressing on the strength of bent reinforced concrete elements of circular section Concrete and reinforced concrete 3 179-181.

[11] Guidelines for the design of power transmission towers and substation switchgears. Reinforced concrete supports and foundations № 3041TM-11, VSPI SRI Electric Network, North-West Branch, 1973, 137.