Characteristics of the limit state of the rope

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Abstract. According to the Rules, in the calculation of ropes for strength, one characteristic is used, and it is the same regardless of the loading scheme. In the calculation method for permissible stresses, two strength characteristics are used: the yield strength or the tensile strength of the material of the part. It’s proposed the method for the theoretical determination of the characteristics of the ultimate elastic $P_e$ and ultimate elastic-plastic state $P_u$ under four loading schemes, and taking into account the operational breaks of the wires (two characteristics of tension with winding on a drum with a weight in guides and with a free suspension and two when stretching a straight rope.) The ultimate elastic state is determined by the longitudinal force in the section of the rope, at which the longitudinal deformation of one of the wires reaches the yield point $\varepsilon_T$ according to the schematized wire tension diagram $\sigma - \varepsilon$. The criterion for the ultimate elastic-plastic state of the rope is the achievement of one of the wires of the ultimate uniform deformation according to the diagram $\sigma - \varepsilon$. It is assumed that on the basis of the characteristics $P_e$ of the stretching of the rope according to the ultimate elastic state, it is possible to construct a method for calculating the strength of the ropes, which will have advantages over the existing one. Advantage arguments:
- strength characteristics $P_e$ are directly related to the rope loading scheme
- the values $P_e$ take into account all geometric parameters of single and double lay, as well as deformation properties of wires
- characteristics $P_e$ allow to take into account the effect of wire breaks during the operation of the ropes.

1. Formulation of the problem.

The general essence of strength calculation methods is a comparison of two states of an element of the structure: ultimate and nominal, interconnected by a standard safety factor $[n] \geq 1$. The guarantee of strength consists in the fact that the actual strength state of an element of the structure, changing during operation, will not become ultimate (will not exceed it). This is ensured by the standard safety factor.

The existing methods of strength calculations use different criteria for the nominal and ultimate states. In the method of calculation for "permissible stresses", the ultimate state is the state in which the stress in the element reaches the strength characteristic of its material: the yield point $\sigma_Y$ or ultimate strength $\sigma_B$. With regard to normal stress, the strength condition has the form.

$$\max \sigma \leq [\sigma] = \frac{\sigma_L}{[n]},$$

where $[\sigma]$ is the so-called allowable stress;
$$\sigma_L = \sigma_Y \text{ or } \sigma_L = \sigma_B$$ is ultimate stress.
On the diagram $\sigma - \varepsilon$ (Figure 1), the meaning of condition (1) is determined by three stresses: allowable $[\sigma]$, ultimate $\sigma_L$, and the third stress – current $0 \leq \sigma \leq \sigma_L$, which, under the specified operating conditions, can approach the ultimate one $\sigma_L$ but will not exceed it. This is guaranteed by the standard $[n]$ safety factor.

**Figure. 1** Relation of the standard (permissible) $[\sigma]$ and ultimate stresses $\sigma_L$.

The term "allowable stress" does not quite accurately reflect the essence of the method. More precisely, the term "nominal stress" would answer the essence.

In the method of calculating the loading capacity the nominal state is assumed to correspond to the passport data, for example, the lifting capacity of the crane. The ultimate state is the load capacity of a part or structure as a whole (this is a load, the excess of which leads to destruction).

In work [1] the strength calculation of ropes is mistakenly called the "method of permissible stresses". In fact, this is a calculation of the loading capacity.

In the regulated Rules for the calculation of ropes, one characteristic is used, which in [2] is called the “breaking force of the rope as a whole”, in [3] - Mindest bruchkraft (minimum breaking force of the rope). Generalized essence of these characteristics

$$P_H = KP_C,$$

where $K = 0.83$ according to [2] and $K = 0.75 - 0.90$ according to [3] (the lower value refers to a three-layer double-lay rope, the larger value to single-layer structures);

$P_c$ is the total breaking force of all wires of the rope (where $P_c = F_c \sigma$ ($F_c$ is the total cross-sectional area of the wires, $\sigma$ is their ultimate strength).

In essence $P_c$, roughly represents the loading capacity of the rope under tensile in the guides. It is known that such a characteristic does not take into account the loading scheme of the rope, its structure and the plastic properties of the wires. At the same time reliability is ensured due to large values of standard safety factors (from 3 to 10 and more [1-3]).

We suggest, by analogy with the method of "permissible stresses" in the calculation of ropes, to use two characteristics of the ultimate state: the tensile force of the rope, corresponding to the ultimate elastic state $P_e$ and the tensile force, equal to the bearing capacity of the rope $P_n$.

2. **Presentation of the main material.**
The purpose of this work is the analytical determination of the force of the ultimate elastic state $P_e$, deformations of the rope and stresses in the wires in this state, as well as the loading capacity $P_n$ of the rope. These studies refer to both the first loading period and the operational state associated with the appearance of wire breaks.
Four schemes of rope loading are considered, two of which are tension with coiling onto a drum (Figure 1, a, b). The other two are stretching of a straight rope. They can be considered as special case of the first two (formally, they are obtained with a drum diameter $D_o \to \infty$).

![Figure 1](image1.png)

**Figure 1.** Rope loading schemes
a) stretching with bending in the guides; b) stretching with bending with free suspension of the load; c) pure stretching; d) free stretching.

2.1. Parameters of the curved axis of the rope. Curved axis equation (Figure 2, a)

$$y = \varphi (1 - e^{-\alpha x}); \quad f = G_{33}/PR;$$

(3)

functions of curvature and rotation angle of rope sections

$$\chi = R^{-1} e^{-\alpha x}; \quad \psi = (G_{33}/PR^2)^{0.5} e^{-\alpha x},$$

(4)

where $G_{33}$ is the bending stiffness of the rope section in the winding plane;

$$\kappa = \left(\frac{P}{G_{33}}\right)^{0.5}; \quad R = 2(D + d_s); \quad d_s \text{ - rope diameter.}$$

2.2. Deformed state of the rope. It is determined by 4 deformations [5]:

$$|DK| = |\varepsilon \theta \chi \zeta| = |G^{-1}| |\Phi|.$$  

(5)

Here the stiffness matrix of the rope [4]:

$$[G] = \begin{bmatrix} G_{11} & G_{12} & G_{13} & G_{14} \\ G_{21} & G_{22} & G_{23} & G_{24} \\ G_{31} & G_{32} & G_{33} & G_{34} \\ G_{41} & G_{42} & G_{43} & G_{44} \end{bmatrix} = \sum_1^5 sc \alpha_\gamma \cdot sc \beta \left[ K \right] \left[ \Phi \right]$$

(6)

where $G_{11}, G_{22}, G_{33}, G_{44}$ are the main stiffness of the rope section (longitudinal, torsional, bending);

$G_{12} = G_{21}; G_{13} = G_{31} \text{ etc.}$ are the stiffnesses of the influence;

$\Phi_\varepsilon = E\pi \delta^2 / 4; \quad \Phi_\theta = E\pi \delta^4 / 80; \quad \Phi_\kappa = E\pi \delta^6 / 64$ are the stiffness of the wire section (longitudinal, torsional, bending; $E$ is elastic modulus; $\delta$ is wire diameter).
The matrix $|K_i|$ of specific deformations of the $i$-th wire, the elements of which are obtained on the basis of the geometric equations of the deformation of wires and strands

$$|K_i| = \begin{bmatrix}
K_{ei} & K_{et} & K_{eb} & K_{en} \\
K_{ed} & K_{et} & K_{eo} & K_{en} \\
K_{ez} & K_{ez} & K_{eb} & K_{ez} \\
K_{c} & K_{c} & K_{c} & K_{c}
\end{bmatrix}$$

$$= \begin{bmatrix}
\bar{K}_{ei} & \bar{K}_{et} & \bar{K}_{eb} & 0 \\
\bar{K}_{ed} & \bar{K}_{et} & \bar{K}_{eo} & 0 \\
\bar{K}_{ez} & \bar{K}_{ez} & \bar{K}_{eb} & \bar{K}_{ez} \\
\bar{K}_{c} & \bar{K}_{c} & \bar{K}_{e} & \bar{K}_{c}
\end{bmatrix} \cdot \begin{bmatrix}
K_{rE} & K_{rE} & K_{rE} & 0 \\
K_{rT} & K_{rT} & K_{rT} & 0 \\
K_{rB} & K_{rB} & K_{rB} & K_{rB} \\
K_{rN} & K_{rN} & K_{rN} & K_{rN}
\end{bmatrix}.$$  \tag{7}

where $|KT_i|$ is the matrix of specific strains in the rope, which includes the $i$-th wire; $|KF_i|$ is the matrix of specific deformations of the $i$-th wire in a strand.

In the elements of the matrix $|K_i|$, the first index indicates the deformation of the wires in the rope ($E$ - longitudinal; $T$ - torsion; $B$ and $N$ - bending), and the second indicates the deformation of the rope, from which this deformation of the wire occurs.

In the elements of the matrix $|KF_i|$, the first index indicates the deformation of the wire in the strand ($e$ - longitudinal; $t$ - torsion; $b$ and $n$ - bending), and the second - the deformation of the strand, with which this wire deformation is directly related.

Elements of matrices $|KF_i|$ and $|KT_i|$ are obtained on the basis of geometric equations of deformation of wires in a single-lay rope (strand) and strands in a double-lay rope, taking into account transverse narrowing and friction [6].

The vector of internal force factors in the sections of the rope

$$|F| = [T \ M \ L \ I]^T,$$  \tag{8}

where $T$ – is the longitudinal force; $M$ is the torque;

$L = P \ f \ e^{-\omega} \ ; \ \Gamma = -PA_1 / A_2 \ \sin \psi$ – are bending moments.

2.3. Characteristic of the ultimate elastic state of the rope.

It is determined by the internal force $N$, at which the longitudinal deformation of one of its elements reaches the elastic limit (the yield point $\varepsilon_Y$ according to the schematized $\sigma - \varepsilon$ wire diagram):

$$P_e = N = \frac{\varepsilon_Y \lambda}{\max \varepsilon_i}; \ \ i = 1, 2, ..., s.$$  \tag{9}

where $\lambda \leq 1$ – is the coefficient of the influence of torsional deformation and bending of the wire in the rope on its ultimate elastic state (in the first approximation we accept $\lambda = 1$);

$s$ is the number of elements (in the general case, elements are each wire of the rope);

$\max \varepsilon_i$ is the highest (among all the wires of the rope) value of the specific tensile deformation from the action of the end weight $\bar{P} = 1$, which depends on the stiffness characteristics of the rope, the loading scheme, the uniformity of the twisting tension, the presence of wire breaks [6]

$$\max \varepsilon_i = \bar{e} K_{x_e} + \bar{e} K_{x_e} + \bar{e} K_{x_e} + \bar{e} K_{x_e},$$  \tag{10}
\( \varepsilon, \vartheta, \chi, \zeta \) – are specific deformations of tension, torsion, bending of the rope for \( \bar{P} = 1 \) for specific loading schemes (Figure 2).

### 2.3.1. Stretching of the rope with coiling onto a drum with a weight in the guides

\[
\varepsilon = (A_1 \cos \psi - A_{12} (A_{13} \cos \psi + A_{14} \sin \psi) / A_{22} + A_{13} \, e^{-k_1 \xi}) / |D| \quad (11)
\]

\[
\vartheta = (A_{23} \, e^{-k_1 \xi} - A_{24} \, A_{23} / A_{22} \sin \psi) / |D| \quad (12)
\]

\[
\chi = (A_{13} - A_{12} (A_{23} \cos \psi + A_{24} \sin \psi) / A_{22} + A_{23} \, e^{-k_1 \xi}) / |D| \quad (13)
\]

\[
\zeta = (A_{14} \cos \psi - A_{12} (A_{24} \cos \psi + A_{23} \sin \psi) / A_{22} + A_{24} \, e^{-k_1 \xi}) / |D| \quad (14)
\]

where \( |D| \) and \( A_1, A_{12}, ..., A_{14} \) – are the determinant and the algebraic complements of the rope stiffness matrix.

### 2.3.2 Stretching the rope with coiling on the drum with free suspension of the weight

\[
\varepsilon = (A_1 \cos \psi + A_{13} \, e^{-k_1 \xi}) / |D|; \quad \vartheta = (A_{12} \cos \psi + A_{23} \, e^{-k_1 \xi}) / |D| \quad (15)
\]

\[
\chi = (A_{13} \cos \psi + A_{14} \, e^{-k_1 \xi}) / |D|; \quad \zeta = (A_{14} \cos \psi + A_{24} \, e^{-k_1 \xi}) / |D| \quad (16)
\]

Specific deformation (10) \( \max \, \varepsilon \) depends on the corresponding specific deformations of the \( i \)-th wire and on the bending parameters (3), (4), and they are determined by the level of the end weight \( P \). Therefore, calculate the tensile force \( P_e \) (9) of the limiting elastic state for these two loading schemes is possible only by consecutive approximations. As a first approximation, one should take \( P_e \) the one corresponding to the stretching pattern of a straight rope.

### 2.3.3 Stretching of a straight rope with a weight in the guides

\[
\varepsilon = (A_{11} - A_{12} / A_{22}) / |D|; \quad \chi = (A_{13} - A_{12} A_{23} / A_{22}) / |D|; \quad \zeta = (A_{14} - A_{12} A_{24} / A_{22}) / |D|. \quad (17)
\]

### 2.3.4 Stretching of a straight rope with a freely suspended weight

\[
\varepsilon = A_{11} / |D|; \quad \vartheta = A_{12} / |D|; \quad \chi = A_{13} / |D|; \quad \zeta = A_{14} / |D|. \quad (18)
\]

### 2.4. Rigidity of the rope section taking into account wire breaks. The basis for determining the rigidity of the rope is the formula (6). In this case, the stiffness of wires with breaks depends on their number and location relative to the calculated section of the rope, which is taken into account on the basis of [6] in this way:

\[
\Phi_r = \frac{\pi b^2}{4} E (1 - e^{-\rho}); \quad b = \frac{2\pi \sin \alpha}{h \cos \beta}, \quad (19)
\]

where \( f \) – is the coefficient of friction; \( l \) – is the distance from the break point to the calculated section of the rope;

\( h \) – is the wire lay step; \( \alpha \) and \( \beta \) – are wire and strand lay angles.

According to the proposed method, calculations were performed for several single and double lay ropes.
As an example, calculations are given for two ropes, the cross-sections of which with wire numbering are shown in Figure 3 and 4, where wires with breaks are indicated by shading.

![Figure 3. Rope 1+6+12](image1)

![Figure 4. Rope 12(1–6) – (1+6) +о.с.](image2)

Single lay rope (figure 3) construction 1/1.15 + 6/1 + 12/1; diameter 5.15 mm; \( F_c = 15.175 \text{mm}^2 \); the total breaking force of all wires \( P_c = 27315H \); the pitch of the wires of the outer layer \( h = 45 \text{mm} \); lay angles \( \alpha_2 = 16.75^\circ \); \( \alpha_3 = 16.16^\circ \) deformation of the yield point of the wire \( \varepsilon_f = 0.0073 \). Double lay rope (Figure 4) of the structure 12(1–6) – 6(1+6) +о.с.; diameter 9.3 mm; \( F_c = 35.625 \text{mm}^2 \); lay pitch of the outer layer of strands \( H = 256 \text{mm} \); wire lay spacing in strands \( h = 112 \text{mm} \); wire diameters \( \delta = 0.6 \text{mm} \); strand angles \( \beta_2 = 17.5^\circ \); \( \beta_3 = 19.5^\circ \) total cross-sectional area of wires \( F_c = 35.625 \text{mm}^2 \); \( P_c = 5700N \), deformation of the yield strength of the wire \( \varepsilon_f = 0.00665 \).

Table 1 shows the value of the cross-sectional stiffness of these ropes for three situations: 1 - without wire breaks; 2 - cliffs are evenly spaced within one step; 3 - breaks in one section (this means in formula (19) \( b = 0 \)).

| Situation | \( G_{11} \), \( H \) | \( G_{22} \) | \( G_{33} \) | \( G_{44} \) | \( G_{12} \) | \( G_{13} \) | \( G_{14} \) | \( G_{23} \) | \( G_{24} \) | \( G_{34} \) |
|------------|----------------|---------|---------|---------|--------|--------|--------|--------|--------|--------|
|            | \( \text{Nmm}^2 \) | \( \text{Nmm}^2 \) | \( \text{Nmm}^2 \) | \( \text{Nmm}^2 \) | \( \text{Nmm}^2 \) | \( \text{Nmm}^2 \) | \( \text{Nmm}^2 \) | \( \text{Nmm}^2 \) | \( \text{Nmm}^2 \) | \( \text{Nmm}^2 \) |
| Rope 1+6+12; diameter 5.15 mm; \( h = 45 \text{mm} \) | | | | | | | | | | |
| 1 | 270 | 85.9 | 24.4 | 24.5 | 127 | ~0 | ~0 | ~0 | ~0 | ~0 |
| 2 | 233 | 72.5 | 23.3 | 23.9 | 104.6 | -6.2 | -3.2 | -3.7 | -1.9 | -0.43 |
| 3 | 229 | 68.3 | 20.5 | 20.8 | 101.8 | -6.7 | -3.9 | -4.2 | -3.4 | 0.063 |
| Rope 12(1-6) – 6(1+6) +о.с.; diameter 9.3 mm; \( h = 112 \text{mm} \); \( H = 256 \text{mm} \) | | | | | | | | | | |
| 1 | 473 | 631 | 17.9 | 17.9 | 337 | ~0 | ~0 | ~0 | ~0 | ~0 |
| 2 | 436 | 565 | 17.6 | 17.8 | 287 | -2.6 | 0.42 | -3.5 | 0.54 | 0.039 |
| 3 | 419 | 535 | 16.1 | 15.9 | 266 | -3.7 | 1.03 | -5.08 | 0.95 | 0.45 |

Tables 2 and 3 shows the calculated values for 3 situations of tensile forces \( P_c \) (9) of the limiting elastic state of the indicated ropes during deformations \( \varepsilon_f \). The forces are presented in relative...
dimensions: $\overline{P}_e = P_e / P_c$. Next to the values $P_e$ in brackets are the numbers of the wires in which the ultimate elastic tensile deformation is reached first, equal to $\varepsilon_T$. Further in table. 2 and 3 is shown the deformation of the ropes $\varepsilon, \theta, \chi, \zeta$ in the ultimate elastic state; experimental values of tensile stresses of wires $\max \sigma$ and $\min \sigma$ (in brackets wire numbers are indicated according to Figure 2 and 3); parameter $\bar{\sigma} = \min \sigma / \max \sigma$, finally, the average tensile stresses are indicated: $\sigma = P_e / F_e$ (this stress is conditional, but it is convenient for an integral assessment of the stress state of the ropes [1]).

### Table 2. Parameters of the ultimate elastic state of the rope 1+6+12.

| Calculation parameters | 1 | 2 | 3 | 4 |
|------------------------|---|---|---|---|
| $\overline{P}_e = P_e / P_c (\bar{N})$ | 0.522 (2) | 0.223 (1) | 0.723 (1) | 0.222 (1) |
| $\varepsilon \cdot 10^4$ | 52.7 | 73 | 73 | 73 |
| $\theta \cdot 10^4, rad/mm$ | ~0 | -107 | 0 | -108 |
| $\chi \cdot 10^4, rad/mm$ | 125 | 125 | ~0 | ~0 |
| $\zeta \cdot 10^4, rad/mm$ | 14.2 | ~0 | ~0 | ~0 |
| $\max \sigma, N/ mm^2 (\bar{N})$ | 1460 (2) | 1459 (1) | 1459 (1) | 1460 (1) |
| $\min \sigma, N/ mm^2 (\bar{N})$ | 472 (5) | -328 (14) | 1338 (5) | 151 (11) |
| $\bar{\sigma}$ | 0.230 | -0.225 | 0.911 | 0.103 |
| $\sigma, N/ mm^2$ | 845 | 401 | 1301 | 400 |

2. Wire breaks № 8+10 within a step $h = 45 mm$

| Calculation parameters | 1 | 2 | 3 | 4 |
|------------------------|---|---|---|---|
| $\overline{P}_e (\bar{N})$ | 0.389 (1) | 0.218 (1) | 0.618 (1) | 0.221 (1) |
| $\varepsilon \cdot 10^4$ | 47.3 | 73 | 73 | 73 |
| $\theta \cdot 10^4, rad/mm$ | 4.96 | 98.7 | 0 | -105 |
| $\chi \cdot 10^4, rad/mm$ | 139 | 129 | 19.6 | 2.64 |
| $\zeta \cdot 10^4, rad/mm$ | 18 | 4.19 | 10.2 | 1.37 |
| $\max \sigma, N/mm^2 (\bar{N})$ | 1445 (19) | 1463(1) | 1459 (1) | 1459 (1) |
| $\min \sigma, N/mm^2 (\bar{N})$ | 348 (5) | -239 (16) | 1261 (5) | 169 (15) |
| $\bar{\sigma}$ | 0.24 | -0.163 | 0.864 | 0.116 |
| $\sigma, N/ mm^2$ | 701 | 392 | 1112 | 397 |

3. Wire breaks № 8+10 in one section

| Calculation parameters | 1 | 2 | 3 | 4 |
|------------------------|---|---|---|---|
| $\overline{P}_e (\bar{N})$ | 0.369 (1) | 0.204 (1) | 0.603 (1) | 0.205 (1) |
| $\varepsilon \cdot 10^4$ | 45.07 | 73 | 73 | 73 |
| $\theta \cdot 10^4, rad/mm$ | 7.79 | -101 | 0 | -109 |
| $\chi \cdot 10^4, rad/mm$ | 141 | 128 | 23.7 | 1.4 |
| $\zeta \cdot 10^4, rad/mm$ | 2.49 | -3.16 | 13.6 | -4.1 |
| $\max \sigma, N/mm^2 (\bar{N})$ | 1430 (2) | 1460 (1) | 1460 (1) | 1459 (1) |
| $\min \sigma, N/mm^2 (\bar{N})$ | 314 (5) | -266 (14) | 1242 (15) | 121 (12) |
| $\bar{\sigma} = \min \sigma / \max \sigma$ | 0.220 | -0.182 | 0.851 | 0.0829 |
| $\sigma, N/ mm^2$ | 665 | 367 | 1086 | 369 |
The loading capacity is determined on the basis of a study of the deformation of the rope beyond the elastic limit, which occurs when the stiffness of its section changes. Taking a discrete change in stiffness, we divide the rope deformation process into intervals with constant stiffnesses within each of them. The loading capacity of the rope is determined by the sum of the increments of the longitudinal force in its section for each interval. The first interval represents elastic deformation. Subsequent - intervals of elastic-plastic deformation.

Table 3. Parameters of the ultimate elastic state of the rope 12(1−6) − 6(1+6) +o.c.

| Calculation parameters | Stretching schemes |
|------------------------|--------------------|
|                        | 1                  | 2                  | 3                  | 4                  |
| Nominal rope condition |                    |                    |                    |                    |
| $P_e = \frac{P}{P_e (N_0)}$ | 0.612 (123) | 0.301* (3) | 0.669 (44) | 0.308 (2) |
| $\varepsilon \cdot 10^4$ | 73.7               | 58.6               | 80.6               | 60                  |
| $\theta \cdot 10^4$, rad/mm | ~0                 | -31.3              | 0                  | -32.1               |
| $\chi \cdot 10^4$, rad/mm | 69.4               | 69.4               | ~0                 | ~0                  |
| $\zeta \cdot 10^4$, rad/mm | 21.8               | ~0                 | ~0                 | ~0                  |
| $\max \sigma$, N/mm² ($N_0$) | 1330 (117) | 1333 (3) | 1305 (2) | 1305 (2) |
| $\min \sigma$, N/mm² ($N_0$) | 974 (123) | 100 (87) | 1230 (3) | 232 (44) |
| $\bar{\Delta}$ | 0.73               | 0.075              | 0.94               | 0.174               |
| $\sigma$, N/mm² | 979                | 482                | 1071              | 493                 |

Wire breaks № 44–57 within a step $h = 66.5mm$

| Calculation parameters | Stretching schemes |
|------------------------|--------------------|
|                        | 1                  | 2                  | 3                  | 4                  |
| Nominal rope condition |                    |                    |                    |                    |
| $P_e (N_0)$ | 0.586 (123) | 0.301 (3) | 0.649 (44) | 0.308 (2) |
| $\varepsilon \cdot 10^4$ | 72.9               | 58.8               | 80.7               | 61.2               |
| $\theta \cdot 10^4$, rad/mm | 0.14               | -30.7              | 0                  | -30.4               |
| $\chi \cdot 10^4$, rad/mm | 73.9               | 70.4               | 18.9               | 4.9                 |
| $\zeta \cdot 10^4$, rad/mm | 22.3               | -0.6               | -5.8               | -2.3               |
| $\max \sigma$, N/mm² ($N_0$) | 1329 (117) | 1333 (3) | 1329 (58) | 1329 (2) |
| $\min \sigma$, N/mm² ($N_0$) | 950 (123) | 112 (87) | 1189 (24) | 291 (58) |
| $\bar{\Delta}$ | 0.71               | 0.084              | 0.93               | 0.219               |
| $\sigma$, N/mm² | 938                | 481                | 948               | 492                 |

Wire breaks № 44-57 in one section

| Calculation parameters | Stretching schemes |
|------------------------|--------------------|
|                        | 1                  | 2                  | 3                  | 4                  |
| Nominal rope condition |                    |                    |                    |                    |
| $P_e (N_0)$ | 0.582 (123) | 0.301 (5) | 0.630 (44) | 0.308 (3) |
| $\varepsilon \cdot 10^4$ | 72.6               | 58.8               | 80.7               | 60.7               |
| $\theta \cdot 10^4$, rad/mm | 0.15               | -30.7              | 0                  | -30.9               |
| $\chi \cdot 10^4$, rad/mm | 74.5               | 70.5               | 12.0               | 2.96                |
| $\zeta \cdot 10^4$, rad/mm | 24.1               | 1.3                | -1.94              | -0.5                |
| $\max \sigma$, N/mm² ($N_0$) | 1329 (123) | 1333 (3) | 1329 (14) | 1329 (2) |
| $\min \sigma$, N/mm² ($N_0$) | 944 (24) | 113 (87) | 1204 (44) | 272 (122) |
| $\bar{\Delta}$ | 0.71               | 0.085              | 0.906              | 0.205               |
| $\sigma$, N/mm² | 931                | 480                | 986               | 493                 |

* The value $\bar{P}_e = 0.301^*$ with a discrepancy of 3 - 5% (depending on $\varepsilon_T$ in formula (9)) coincides with the experimental data of [7].
where $\Delta N_j$ is the longitudinal force in the section of the rope for the $j$ interval.

Calculation methods of $\Delta N_j$ for various rope loading schemes are similar to determining the force $P_e$.

3. Conclusions.

The strength characteristics $P_e$ of the ultimate elastic state of the ropes very significantly depend on the loading scheme, the design of the rope and the presence of wire breaks, as well as on the unevenness of the twisting tension of the wires and strands. For the convenience of the analysis, they are presented in a relative dimension $\bar{P}_e = P_e / P_c$, in fact, adequately to the coefficient $K$ in formula (2), which is approximately equal to the third loading scheme of the rope.

The main reason for the low values of the characteristics $\bar{P}_e$ is the uneven deformations and tensile stresses of the wires in the rope. This is primarily due to the deformation $\theta$ of twisting of the rope, and secondly to the deformation $\chi$ of bending. The values $\bar{P}_e$ for the 2nd and 4th tension schemes significantly depend on the stiffness of the influence $G_{i_{12}}$, with which the twisting deformation of the rope is associated. So for a rope of construction $1 + 6 + 12$ $G_{12} = 1270 kNm$ and $\bar{P}_e = 0.222$. In the case of $1–6 + 12$ construction with opposite direction of layers $G_{12} = 736 kNm$ and $\bar{P}_e = 0.47$.

The values of the average conditional stress $\sigma = P_e / F_e$ show that their level in the ultimate elastic state of the ropes is less than the advising parameter at working (operational) loads [1]. It is useful to take this into account when analyzing the standard safety factors for specific rope loading schemes.

The presence of wire breaks leads to the appearance of the stiffness of influence: longitudinal-bending $G_{13}, G_{14}$; torsionally-bending $G_{23}, G_{24}$, as well as bending-bending $G_{34}$. When the ropes are stretched in a state with these stiffnesses, additional deformations of bending and twisting of the rope appear, and therefore deformations of the wires, both upward compared to the nominal state, and downward.

The characteristics $\bar{P}_e$ in the states with wire breaks in the 1st and 3rd schemes are reduced. With the 2nd and 4th, they remain practically unchanged, because torsional deformations $\theta$ change slightly.

For the 3rd tension scheme, the ratio between the characteristic $P_e$ of the ultimate elastic state of the rope and the characteristic of its bearing capacity is $P_e (0.7–0.75)P_c$. For other stretching schemes associated with torsion and bending, the ratio is less stable (depends on the stiffness of the influence and the ratio of the drum diameter to the rope diameter).

We assume that, based on the characteristics $P_e$ of the stretching of the rope according to the ultimate elastic state, it is possible to construct a method for calculating the strength of ropes, which will have advantages over the existing one, based on the characteristic (1). Advantage arguments

- strength characteristics $P_e$ are directly related to the rope loading scheme;
- the value $P_e$ takes into account all geometric parameters of single and double lay, as well as deformation properties of wires;
- characteristics $P_e$ allow taking into account the effect of wire breaks during the operation of ropes both within the rejection norm and in the direction of optimizing the norms.

4. References

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