The International Journal of
TRANSPORT & LOGISTICS
Medzinárodný časopis
DOPRAVA A LOGISTIKA

ISSN 1451-107X

STRENGTH INTERPRETATION OF NON-DESTRUCTIVE TESTING OF STEEL-CORD CONVEYOR BELTS

Vladimir P. Radin, Vasily Yu. Volokhovsky, Alexander N. Vorontsov[1] and Vasily V. Sukhorukov[2]

Keywords:

Abstract:

1. Preliminary remarks. Steel-rubber conveyor belt (SRB) is a composite structure containing the steel cord - rubber core, outside rubber facings and rubber ledges. Axial tensile load upon the belt is taken up mostly by steel cord component of the core. Rubber facings protect the core from corrosion, abrasion and impacts by transported load. In regulative documents the conveyor belt strength concept is identified with load level relating to inadmissible operation. According to standard [1], theoretic axial cord belt strength is determined as

$$P_c = P_r \cdot n \cdot K \ . \tag{1}$$

Here P_r is axial break force of one steel rope, n - is a number of ropes in the cord, K - is a coefficient of load irregularity between cord ropes assumed equal to 0,9. The appropriate conveyor belt is selected by condition

$$P_c \geq T_{max} K_s K_d \ , \tag{2}$$

where T_{max} is the maximum traction force of the belt, K_s and K_d are correspondingly coefficients of belt strength safety and relative overload during start-up and braking [2].

The weakest places of SRB are splices. The standard requires the break strength of splice to be 70% at least with respect to minimum belt strength.

Checking the technical state of SRB is being done both visually and by using instrumental means. Flaw detectors INTROKON, developed and produced by the company "Intron Plus" (Russia, Moscow) fix the breaks of steel ropes and decrease of their metallic cross-section relative to nominal value due to corrosion. The analysis of charts gives two numerical indices of belt deterioration: number of steel ropes breaks and value of metallic cord cross-section loss. Rope breaks spacing chart and cord section loss chart are compared with normative values that are accepted in technical documentation [3]. Decision about fitness (or unfitness) of the belt or about its service life time is made by experts' opinion. Expert estimates are based upon empirical criteria of belt's limit state which are exclusively qualitative. These criteria contain no strength parameters. Some working manuals and

[1] ***Vladimir P. Radin, Vasily Yu. Volokhovsky, Alexander N. Vorontsov***, Moscow Power Engineering Institute (Technical University), 14 Krasnokazarmennaya Srt., Moscow, 111250, Russia
[2] ***Vasily V. Sukhorukov*** , Intron Plus Ltd., 17 Krasnokazarmennaya Srt., Moscow, 111250, Russia

instructions for charts decoding make efforts to refine qualitative information of the belt state by introducing correction factors for estimate (1):

$$P_{\text{c}} = P_{\text{r}} \cdot (n - n_{\text{r}}) \cdot K. \tag{3}$$

For example, in case of central rope breaks numbering $n_{\text{r}} \geq 6$ coefficient K is assumed to be 0,4 and in case of similar number of breaks at belt edge $K = 0,2$. Argues for these very values have no grounds. So, detailed analysis of strength of belt having broken and/or corrosion-struck cord ropes is actual [4-7]. Expert estimates must take into account results of strength analysis that can specify the dependence of belt endurance on distribution of defects across the width and along the length of checked section. Objective of this work is the development of theoretical model that allows 1) to analyze the influence of cord damages upon the belt strength and 2) to estimate residual endurance of particular belt passed the technical diagnostics.

2. Mechanical model and algorithm of SRB strength estimation. Consider a regular working specimen of belt located far from the splices. Belt cross-section $B \times h$ with cord ropes step b is shown at Fig. 1.

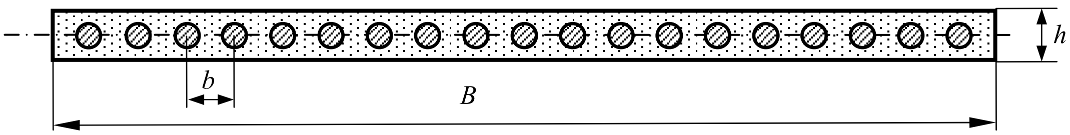

Fig. 1

If the belt is not defected, relative deformation ε_0 appeared in each rope by uniform tension P is determined as

$$\varepsilon_0 = \frac{P}{nEF_0\left(1 + E_{\text{rub}}F_{\text{rub}} / nEF_0\right)} \quad , \tag{4}$$

where EF_0 is tensile rigidity of one rope cross-section, $E_{\text{rub}}F_{\text{rub}}$ is tensile rigidity of belt rubber component. Complete force P_{c} in the cord is equal to $P_{\text{c}} = n\varepsilon_0 EF_0$. Absolute axial extension u_* of the belt with length l is equal to $u_* = \varepsilon_0 l$.

Steel ropes breaks and cross-section losses change the uniform deformation of the cord. The problem appears to determine stress-strain state of individual ropes and to estimate the residual service life of defected belt. The interactive force between the adjacent ropes due to deformation of rubber appears. This force is proportional to shear rigidity c of rubber layer and relative ropes displacement i.e. $c\left(u_k - u_{k-1}\right)$. Assuming that there is no sliding between rubber layer and ropes along contact surfaces the equilibrium equation for $k-$ rope can be written as

$$EF_k \frac{d^2 u_k}{dx^2} - c\left(-u_{k-1} + 2u_k - u_{k+1}\right) = 0. \tag{5}$$

Here EF_k is tensile rigidity of $k-$ rope with eventual cross-section loss. Parameter c, characterizing the shear of inter rope-rubber layer can be estimated by following view. If cross-section of inter rope layer is considered as rectangular $h \times b$ and layer strained state is assumed to be “net sheared”, then $c = G_{\text{rub}} b / h$, where G_{rub} is a shear modulus of the rubber.

With non-dimensional parameters

$$\xi = x / \sqrt{F_0},\ \tilde{u} = u / \sqrt{F_0},\ \eta_k = F_k / F_0,\ \alpha_0^2 = G_{\text{rub}} b / Eh,\ \alpha_k^2 = \alpha_0^2 / \eta_k \tag{6}$$

the equation (5) can be rewritten as

$$\frac{d^2 \tilde{u}_k}{dx^2} - \alpha_k^2 (-\tilde{u}_{k-1} + 2\tilde{u}_k - \tilde{u}_{k+1}) = 0\ . \tag{7}$$

Introducing the vector $\mathbf{y} = [u_1; u_2; \ldots; u_n; \varepsilon_1; \varepsilon_2; \ldots; \varepsilon_n]^T$ equation (7) can be presented in normal Cauchy form

$$\mathbf{y}' = \mathbf{A}\mathbf{y}\,. \tag{8}$$

Matrix $\mathbf{A}$ has the following structure

$$\mathbf{A} = \begin{bmatrix} \mathbf{0} & \mathbf{E} \\ \mathbf{A}_0 & \mathbf{0} \end{bmatrix},$$

where $\mathbf{0}$ is null-matrix, $\mathbf{E}$ is identity $n \times n$ matrix, $\mathbf{A}_0$ – is three-diagonal $n \times n$ matrix. If the metallic cross-section loss occurs each k – row of matrix $\mathbf{A}_0$ should be divided by coefficient η_k. Cauchy problem (8) solution with initial conditions $\mathbf{y}_0$ is given in matrix form

$$\mathbf{y}(\xi) = \mathbf{e}^{\mathbf{A}\xi}\mathbf{y}_0 \quad . \tag{9}$$

Concentration of tensions in ropes adjacent to the broken rope will differ essentially from nominal values. Setting the boundary problem relative to displacements u_k we take the scheme of “tough loading” of the belt. The left end of belt specimen under consideration is fixed and all the ropes at right end get identical displacements $u_* = \varepsilon_0 l$ (see fig. 2).

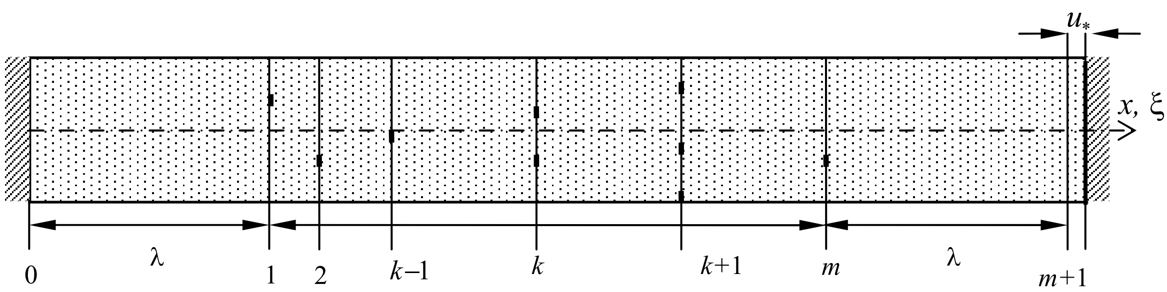

Fig. 2

Total force in cord ropes of non-defected belt under “tough loading” is equal to P_c. In similar case for defected belt the total cord force will be $P_{c*} = \sum_{j=1}^{n} EF_j \varepsilon_j$. For limit state strength analysis percent decrease of endurance ψ of defected belt can be estimated as follows:

$$\psi = \left(1 - P_{c*} / P_c\right) \cdot 100\%\,. \tag{10}$$

If strength analysis is performed by admissible tensions with “bar approach”, then to determine the safety factor it is necessary to know the stress concentration coefficient k_s. It may be written in form

$$k_s = E \cdot \max \varepsilon_k / \sigma_{\text{nom}}\,. \tag{11}$$

Here E is an axial modulus of elasticity of cord ropes, σ_{nom} is a nominal tension determined for the section of rope in which maximum value of relative deformation is occurred, i.e.

$$\sigma_{\text{nom}} = P_{c*} / \sum_{k=1}^{n-n_r} F_k\,, \tag{12}$$

where n_r is a number of broken ropes at belt section in question. Calculation of k_s value should be done for each belt section where rope breaks are available.

To make a numerical scheme the belt section with defects is divided into subsections according to location of defects (Fig. 2). At subsection boundaries one or several rope breaks could be situated. To the left and to the right from defects group two segments λ are added. The value of λ can be chosen from the “boundary effect” point of view (for example, $\lambda \approx 2\pi/\alpha$). This is necessary for decreasing the influence of boundary conditions upon distribution of tensions and deformations within belt specimen with rope breaks. The boundary conditions are: at $x=0$ all $u_k=0$ and at $x=l$ all $u_k=u_*$. Displacements and strains at subsections boundaries will be characterized by vector $\mathbf{y}_k$.

The calculations are performed by transitional matrices method, according to which the vector $\mathbf{y}_k$ at the end of $k-$ subspecimen is determined using transitional matrix $\mathbf{B}_k$ by formula $\mathbf{y}_k=\mathbf{B}_k\mathbf{y}_{k-1}$. Matrices $\mathbf{B}_k$ are calculated by formulae $\mathbf{B}_k=\exp\left(\mathbf{A}\xi_k\right)$. Value of vector $\mathbf{y}_{k+1}$ in $k+1-$ section is $\mathbf{y}_{k+1}=\mathbf{B}_{k+1}\mathbf{y}_k=\mathbf{B}_{k+1}\mathbf{B}_k\mathbf{y}_{k-1}$ etc. Besides, jumps must be taken into account for those components of vectors $\mathbf{y}_k$ that correspond to broken ropes in section *k.*

For determination of stress-strain state in ropes at belt subsections it is necessary to evaluate $2n+m$ components $X_j,\left(j=1,2,\ldots 2n+m\right)$ of unknown vector $\mathbf{X}$. Here m is the number of rope breaks at belt specimen under consideration. Relative deformations (strains) ε_k are assumed as the first n unknown quantities at left belt edge. Next m unknown quantities are the jumps of displacements in broken ropes. And other n unknown quantities are relative deformations in utmost right section of the belt. Equations for determining the unknown quantities X_k are composed according to the transitional matrices algorithm. First $2n$ equations are based upon the relation

$$\mathbf{y}_{s+1}=\prod_{k=1}^{s}\mathbf{B}_{s-k+1}\mathbf{y}_0 \,. \qquad (13)$$

Here s is a number of sections of the belt where one or several rope breaks are available. The rest of m of equations are derived from conditions

$$\varepsilon_k\left(\xi_j\right)=0\,, \qquad (14)$$

where k is a rope number, ξ_j is a coordinate of rope break. After determination of vector $\mathbf{X}$, displacements and relative deformations in all ropes can be calculated for any coordinate ξ.

The computer program was developed for calculation of stress-strain state at SRB defective specimen.

3. Results and discussion. Some results for belt with cord ropes number $n=50$ and parameters $\alpha_0^2=0,01$, $\varepsilon_0=0,0001$ for the case of breaks at one section are presented at table 1 and in fig. 3, fig. 4.

Table 1

	Breaks at one edge			Breaks in the middle	
Number of broken ropes	Percent of tensile force decrease	Stress concentration coefficient		Percent of tensile force decrease	Stress concentration coefficient
1	0,5	1,54		0,3	1,30
2	1,5	1,84		0,9	1,51
3	2,8	2,01		1,8	1,67
4	4,5	2,11		2,9	1,79
5	6,3	2,16		4,2	1,88
6	8,2	2,19		5,7	1,94
7	10,1	2,20		7,3	1,99
8	12,1	2,21		9,0	2,02
9	14,1	2.21		10,8	2,05
10	16,1	2,21		12,6	2,06

At Table 1 the results for changing of tensile force and stress concentration coefficient are presented for rope breaks numbering from one to ten for two cases. In first the breaks take place at belt edge, in second one – at the middle. The breaks at the edge are more dangerous then those in the middle. With increase of number of adjacent broken ropes stabilization of stress concentration coefficients may be observed**.** Distributions of deformations related to value ε_0 in case of ten rope breaks are shown in Fig. 3 and in Fig. 4. Circle markers correspond to the section with rope breaks and stars markers – to utmost section of belt specimen.

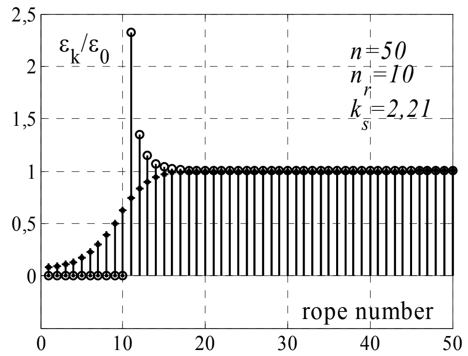

Fig. 3.

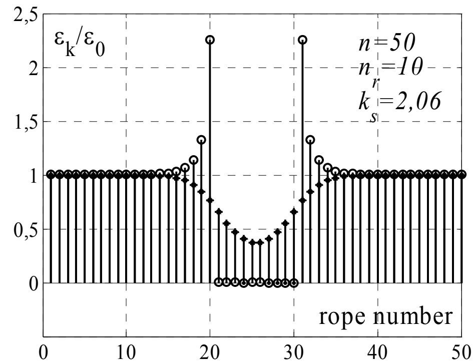

Fig.4.

It is evident from the diagrams that rope break mostly effects upon adjacent rope where relative deformation and consequently the tensions may be near $1{,}5 \div 2{,}5$ times higher than their nominal values. It should be noted that effect of rope break spreads only to five nearby ropes. This event depends essentially upon rigidity of rubber inter-ropes layers. Irregularity of strains distribution decreases with decreasing of rubber rigidity.

Changing of displacements u_k and relative deformations ε_k with longitudinal coordinate ξ for first ten ropes in case of breaking five edge ropes is illustrated it Fir. 5 and in Fig. 6.

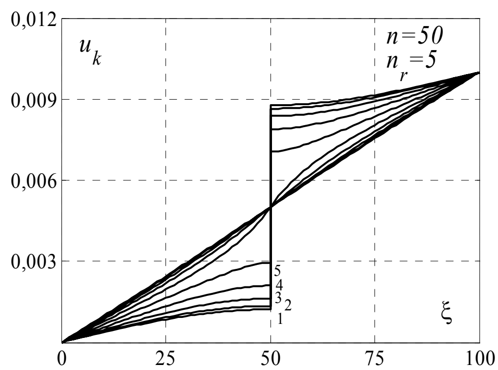

Fig. 5.

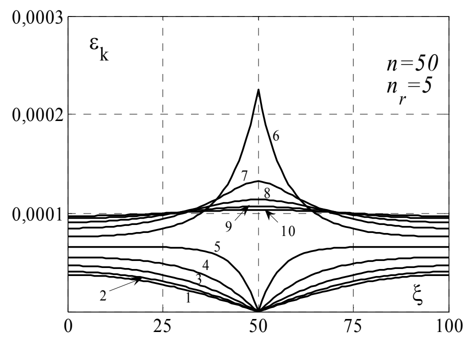

Fig. 6.

Results in Fig. 7 are related to the break of also five ropes but when rope breaks are located in different belt sections. In the first section ropes 1 and 3 are broken. In the second, with coordinate ξ =10, ropes 2 and 4 are broken. In the third section with coordinate ξ =20 rope 5 is broken.

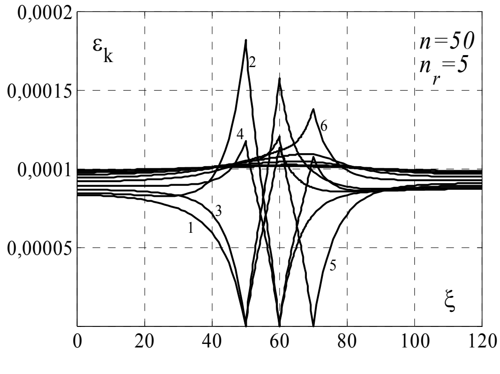

Fig. 7.

Percentage decrease of tensile force in this case was just 1,6% instead of 6,3% in the case when rope breaks take place in one belt section (see Table 1). Stress concentration coefficient k_s proved to be the least sensible towards considered location of defects being k_s =1,66 instead of k_s =2,16 (the last corresponds to the case of rope break in one section).

The model allows reviewing the problem of limit state of SRB. Consider the case when the ropes are broken in turn one by one from one side with total number of cord ropes $n=50$. Let ε_* be the limit relative deformation of broken rope. Assume that with $\varepsilon<\varepsilon_*$ linear-elastic dependence between forces and displacements is maintained and remind that for undamaged belt destructive force $P_{c*}=nEF_0\varepsilon_*$. Considering that there is no interaction between ropes due to rubber we get a simple formula giving the value of limit load for the belt with k broken ropes - $P_{c*,k}=(n-k)EF_0\varepsilon_*$. In coordinates $P_{c*,k}/P_{c*}$ – k at Fig. 8 linear dependence represented by dashed line corresponds to decrease of destructive force. But in case of first rope break due to concentration of tensions the destructive force will be determined by reaching the limit relative deformation ε_* in second rope while in other ropes it can be much less. At values more than $k=10$ due to stabilization of stress concentration coefficient (see Table 1) the dependence $P_{c*}(k)$ becomes practically linear. But ordinates of this dependence are approximately 2,2 times less that corresponding ordinates in case when concentration of tensions is neglected.

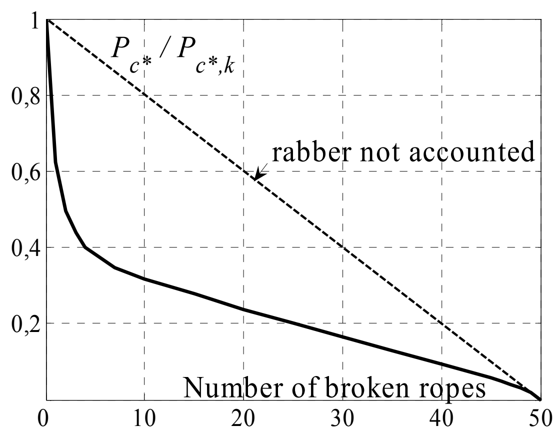

Fig. 8.

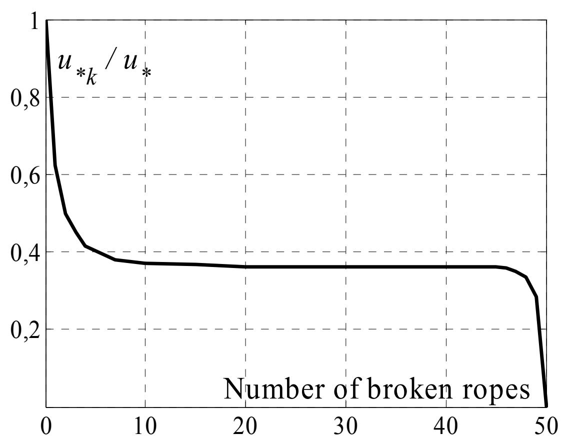

Fig. 9.

Concentration of tensions determines also the value of destructive displacement of utmost sections of belt specimens. If for undamaged belt it is equal to $u_*=\varepsilon_* l$ in case of rope breaks dependence $u_{*k}(k)$, presented in Fig. 9 abruptly decreases at initial and end specimens. In wide range of values of k it is practically constant and is approximately 2,7 times less than u_*.

References

[1] Branch standard. Conveyor belts shaft nonflammable rubber-rope. OST 153-12.2-004-99. 40 pp. (in Russian)

[2] Manual for operation of underground belt conveyors in coal and slate mines. Moscow, Rostechnadzor, 1995. 250 pp. (in Russian).

[3] Methodic instructions for implementation of expert examination of industrial operation of belt conveyor devices. Rostechnadzor, RD – 15-04-2006 (in Russian)

[4] Langebrake, F., Klein, J. & Gronau, O. (1998) Non-destructive testing of steel cord conveyor belts. Bulk Solids Handling, Vol.18, No 4, pp. 565-569.

[5] Sukhorukov, V. Steel-cord conveyor belt NDT. “Application of contemporary non-destructive testing in engineering”. Conference proceedings. The 8th International Conference of the Slovenian Society for NDT, Portoroz , September 2005, pp. 237-244

[6] Vorontsov, A.N., Volokhovsky, V.Yu, Shpakov, I.I., Girnov, A.V. (2005) Otsenka prochnosty rezinotrosovykh lent. Stal’nye kanaty, Vypusk 4, Odessa, pp. 68-76

[7] Vorontsov, A., Volokhovsky, V., Sukhorukov, V. & Shpakov, I. Strength interpretation of non-destructive testing of steel ropes and steel-cord conveyor belts. OIPEEC Conference proceedings, Athens, March 2006, pp.137-144.