Arch. Min. Sci. **66** (2021), 1, 57-68

Electronic version (in color) of this paper is available: http://mining.archives.pl

DOI 10.24425/ams.2021.136692

STANISŁAW WOLNY[1*]

EXPERIMENTAL VERIFICATION OF THE STATE OF STRESS IN LOAD BEARING CABLES IN A HOISTING INSTALLATION DUE TO RANDOM MISALIGNMENTS AND IRREGULARITIES OF THE GUIDE STRINGS

In order for the ultimate state methods to be applied in dimensioning of the load-bearing elements in a conveyance, it is required that their design loads during their normal duty cycle and under the emergency braking conditions should be first established.

Recently, efforts have been made to determine the interaction forces between the shaft steelwork and the conveyance under the normal operating condition [1,2]. Thus far, this aspect has been mostly neglected in design engineering.

Measurement results summarised in this paper and confronted with the theoretical data [3] indicate that the major determinant of fatigue endurance of conveyances is the force acting horizontally and associated with the conveyance being hoisted in relation to the vertical force due to the weight of the conveyance and payload.

Keywords: dynamics, mining, hoist installation, randomness

1. Introduction

In order for the ultimate state methods to be applied in dimensioning of the load-bearing elements in a conveyance, it is required that their design loads during their normal duty cycle and under the emergency braking conditions should be first established.

Recently, efforts have been made to determine the interaction forces between the shaft steelwork and the conveyance under the normal operating condition [1,2]. This aspect has been mostly neglected in design engineering thus far. The results of works [4,5] clearly indicate the random nature of the forces, and in addition, works [6,7] indicate the fatigue nature of loss of

[1] AGH UNIVERSITY OF SCIENCE AND TECHNOLOGY, AL. MICKIEWICZA 30, 30-059, KRAKÓW, POLAND

* Corresponding author: stwolny@agh.edu.pl

bearing capacity of the main supporting elements of a conveyance. In this study attempts are made to verify the simplifying assumptions underlying the theoretical analyses of those forces [8,9] through stress measurements taken on a real object.

2. Stresses in load-bearing elements of a conveyance

The model used in the computational procedure to find stresses in load bearing elements of a conveyance is based on the technical specification of such devices [3,10], whilst the basic dimensions and masses of individual components are retained.

The model used when investigating the stresses in the conveyance load-bearing elements, particularly in ropes and cables, is shown schematically in Fig. 1.

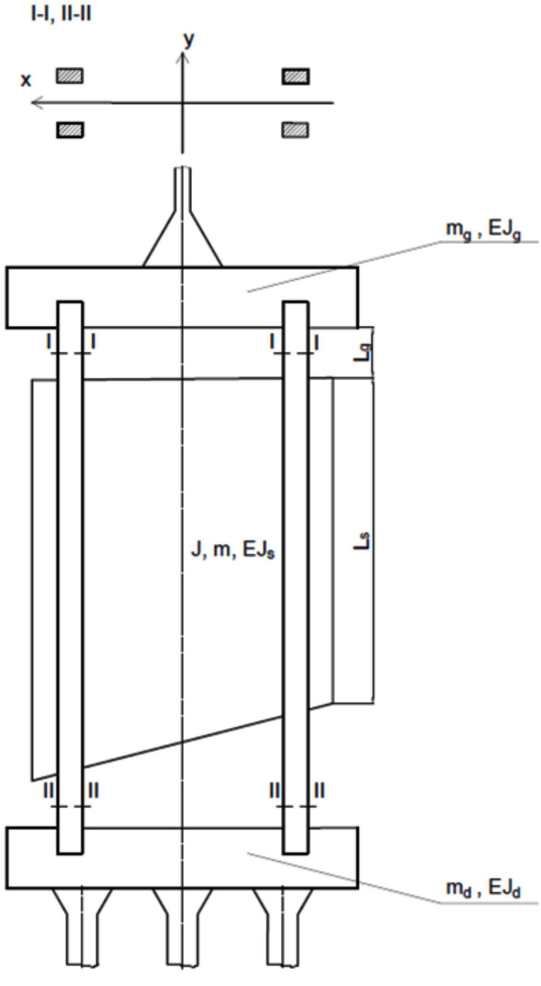

Fig. 1. Skip model used in the computational procedure

In further analyses a simplified model is used (shown in Fig. 2), whereby the skip is divided into two parts along its mid-length and in the plane x-x. [3, 10]

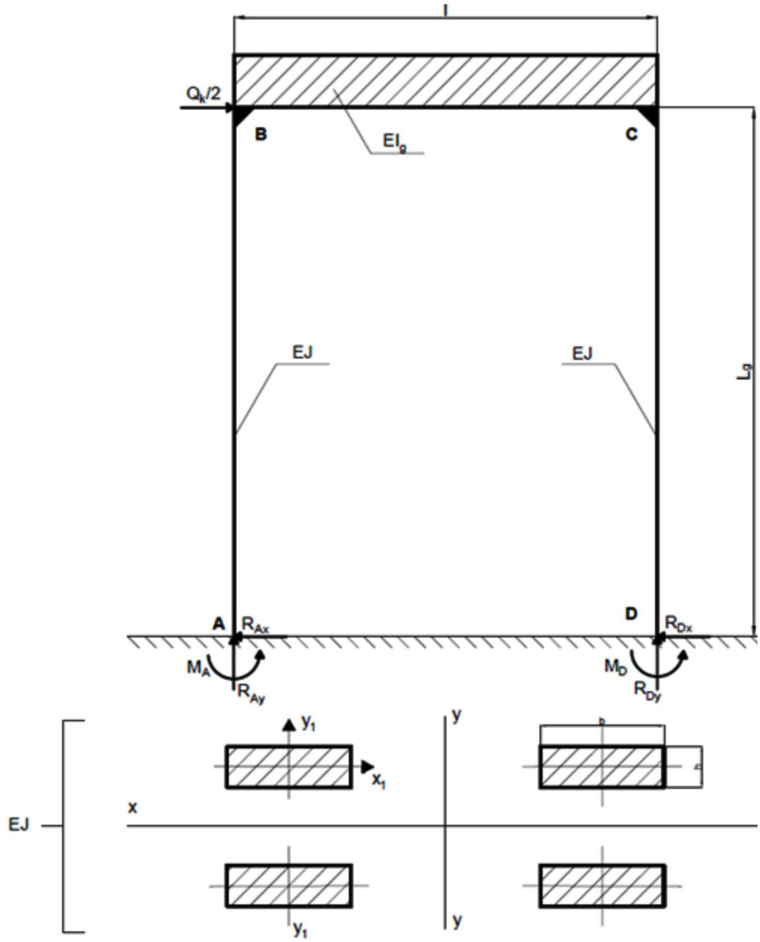

Fig. 2. Simplified model of the skip used in the computational procedure

For the model used in the computational procedure in the form of a 2D diagram, the shearing forces were established that were induced by the force $Q_k/2$ applied as shown in Fig. 2 and the force generated in the skip head-skip hopper system during the conveyance travel at the constant velocity V_0 = const.

Plots of bending moment and the shearing and longitudinal forces acting upon the frame, as shown in Fig. 2, are given elsewhere [3,10].

This study is limited in scope and is restricted to providing the relationship between the variance of amplitude of the maximal stress in cables connecting the skip hopper and its head and the variance of amplitude of the skip head-shaft steelwork interaction force.

This relationship is given as [11-13]:

$$D_\sigma = \frac{3}{8}\frac{l_g}{bh^2}\cdot D_{Q_k} \tag{1}$$

where:

D_σ — variance of the maximal stress amplitude in cables connecting the ship hopper to the skip head;

D_{Q_k} — variance of the shearing force amplitude at the point the cable is attached to the skip head;

Recalling Eq. 20 [13] and rearranging, we obtain:

$$D_\sigma = \frac{3}{2}D_x \cdot n \cdot k_g^2 \frac{l_g}{bh^2} I_{50} \tag{2}$$

where:

D_x — parameter associated with spectral density of the guide string misalignment as a stochastic process [9],

n — parameter;

k_g — shear modulus of the cables at the attachment points to the skip head;

$$I_{50} = \frac{M_{50}}{a_0 \Delta_{50}} \tag{3}$$

$$M_{50} = -a_0 \begin{Bmatrix} a_5\left[b_1\cdot(a_3a_4 - a_2a_5) + b_2\cdot(a_0a_5 - a_1a_4) + b_3\cdot(a_1a_2 - a_0a_3)\right] + \\ +b_4\cdot\left[a_1(a_1a_4 - a_2a_3) + a_0\left(a_3^2 - a_1a_5\right)\right] \end{Bmatrix}$$

$$\Delta_{50} = -a_5 \begin{Bmatrix} a_0^2\cdot a_5^2 - 2a_0a_1a_4a_5 - a_0a_2a_3a_5 + a_0a_3^2\cdot a_4 + \\ + a_1^2\cdot a_4^2 + a_1a_2^2\cdot a_5 - a_1a_2a_3a_4 \end{Bmatrix}$$

$$a_0 = 1,\ a_1 = 2n_2 + n,\ a_2 = 1 + n_1(1 + 2n_3) + 2n_2\cdot n$$

$$a_3 = 2n_2 + n + n_1\cdot n(1 + 2n_3),\ a_4 = 2(n_1\cdot n_3 + n_2 n),\ a_5 = 2n_1n_3n$$

$$b_0 = 1,\ b_1 = 2(1 + n_1),\ b_2 = (1 + n_1)^2,\ b_3 = 0,\ b_4 = 0$$

$$n_1 = \frac{m_A}{m_g},\ n_2 = \frac{h}{m_g}\sqrt{\frac{m_A}{k_g}},\ n_3 = \frac{k}{k_g},\ n = \alpha\sqrt{\frac{m_A}{k_g}}$$

Since $\frac{h_g}{h} \le 1$ it is assumed that $h + h_g = h$ and that $h_g \approx 0$.

The product $n\cdot D_x$ in Eq. 2 expresses the random input parameters whilst the expression (3) is associated with the features of the investigated object.

The plot of I_{50} depending on $n_1 = \frac{m_A}{m_g}$ for two values of n_2 ($n = \alpha\sqrt{\frac{m_A}{k_g}} = 0{,}1$); $n_2 = \frac{k}{k_g} = 0{,}01$ associated with the features of the investigated object) is shown in Fig. 3.

Variability range of parameters n_1, n_2, n_3, n was chosen such that they should be applicable to typical hoisting installations currently designed and operated in Poland.

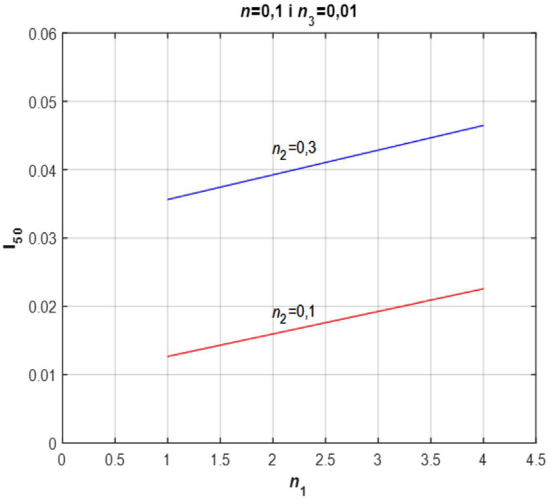

Fig. 3. I_{50} (3) is relation to $n_1 = \frac{m_A}{m_g}$ for n = 0,1 and n_3 = 0,01

To check the adequacy of the simplifying assumptions at the stage of model development and mathematical analyses, the experiments were performed on a real object throughout its entire duty cycle and the following parameters were determined:

- forces acting in load-bearing ropes
- state of stress in load-bearing cables
- state of stress in load-bearing cables due to the conveyance-shaft steelwork interaction forces

3. Measurements on a real object

To determine the real state of stress experienced in cable cross-sections subjected to maximal loads and cracking due to fatigue, stress and strain measurements were taken in one of the Polish collieries underservice conditions [3].

The measurement equipment (Fig. 4) includes bridge extensometers and computers for measurement data recording and processing.

The positions of measurement points on the conveyance are shown in Fig. 5. Sensors 1,2,3,4 were attached to the cables and at the root of the skip head, and the remaining sensors were attached below the first frame in the hopper – Fig. 5. Photo 1 shows the positions of sensors 5, 5', 6, 6' beneath the first frame in the hopper [3]. Sensors 5, 5', 6, 6', 7, 7", 8, 8' fixed on the opposite sides of the cable were arrayed in the bridge configuration and duly connected to the measurement channels. Consequently, measurements were taken of those stresses only which were due to the bending moment acting in the plane normal to the planes determined by the relevant sensors.

Fig. 4. Equipment for strain measurements

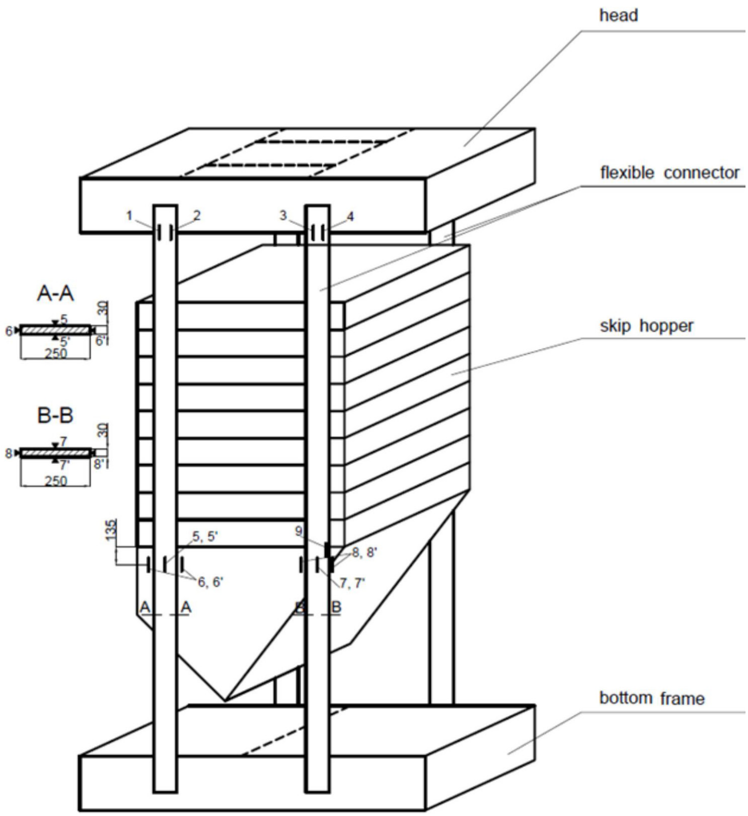

Fig. 5. Positions of measurement points

The equipment being zeroed, the hoisting machine was started and the measurements begun, covering the full cycle of the hoist operation. The velocity of the conveyance travel during the measurements was $V_0 = 20$ m/s and all manoeuvres were performed in the same manner as during the normal duty. The device for measuring forces acting in load-bearing ropes, provided in the hoisting installation, was switched on during the conveyance travel.

Processed measurement data are given as plots of registered stressed vs time and collated in the monograph [3]. This study provides only the state of stress in the cross-sections of cables connecting the bottom frame with the ship hopper.

4. Measurement results – discussion

To better visualise the measurement results, particularly the stress levels in cables, the selected plot sections are shown in the expanded time scale. Measurement results registered as digital data sets were analysed using the MATLAB software and the result of computer-assisted analysis are shown in the graphic form in Figs 6-9. [14]

Actually, plots of force in load-bearing ropes (Fig. 6) and plots of stress at selected measurement points (point 1 – Fig. 7) are found to be very similar. The plots of stress resemble those of force in load-bearing ropes, though with certain distortions, attributable to the action of shaft steelwork-conveyance interaction forces involved in the hoisting, loading and re-loading operations. The zero on the stress plot actually corresponds to the stress levels at measurement points due to the weight of the structure itself and of the payload. As mentioned previously, the array of sensors 6,7,8 in the half-bridge configuration eliminates in the measurement circuit the stresses due to cable extension, which suggests that stresses registered at measurement points are only those induced by the bending moment. The aim was to evaluate the values of stress due to the bending moment, caused by the conveyance-shaft steelwork interaction forces and to relate them to the stress levels due to the axial extension of cables.

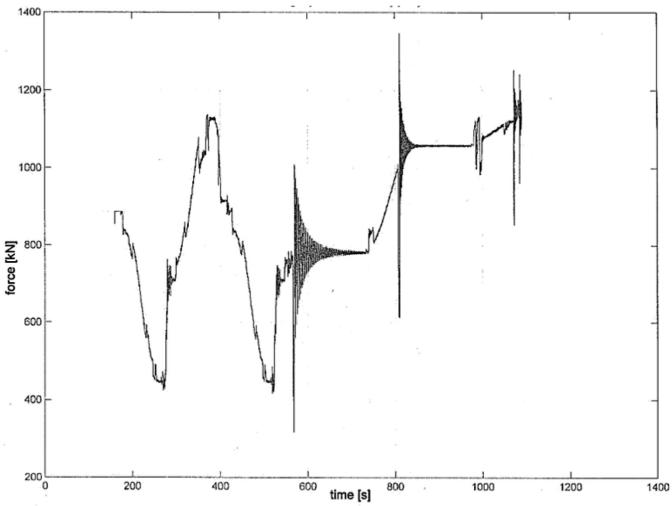

Fig. 6. Forces in rope-bearing ropes throughout the entire duty cycle of the hoisting installation

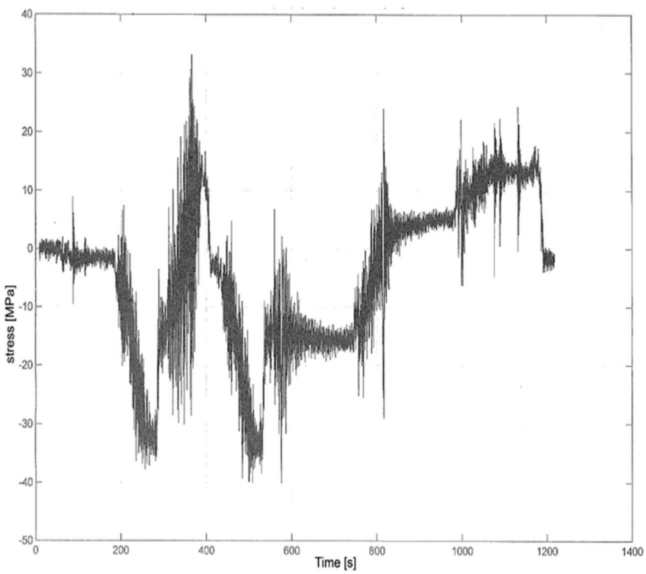

Fig. 7. Stresses registered at point 1 throughout the entire duty cycle of the hoisting installation

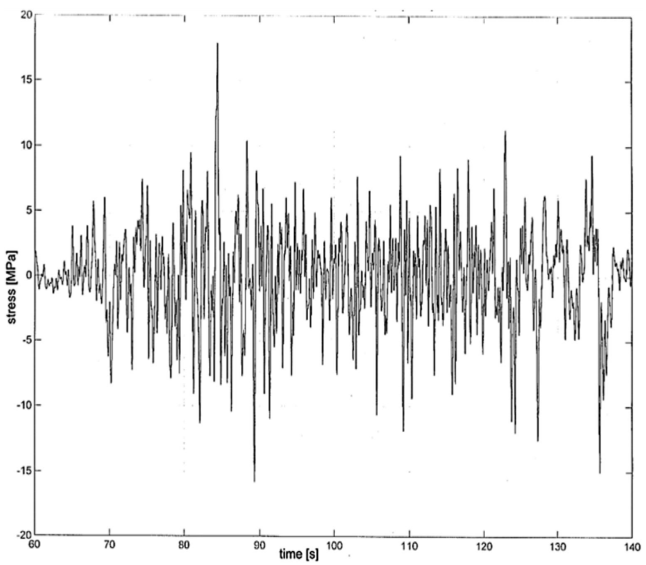

Fig. 8. Stresses registered at point 7 during the downward travel of an empty conveyance

Fig. 8 shows the stresses experienced by the cable during the downward travel of an empty conveyance to the bottom station (registered by sensor 7) and Fig. 9 shows stresses registered by the same sensor during the upward travel of a full conveyance. For clarity of presentation, the time scale is zoomed (as compared with Fig. 7).

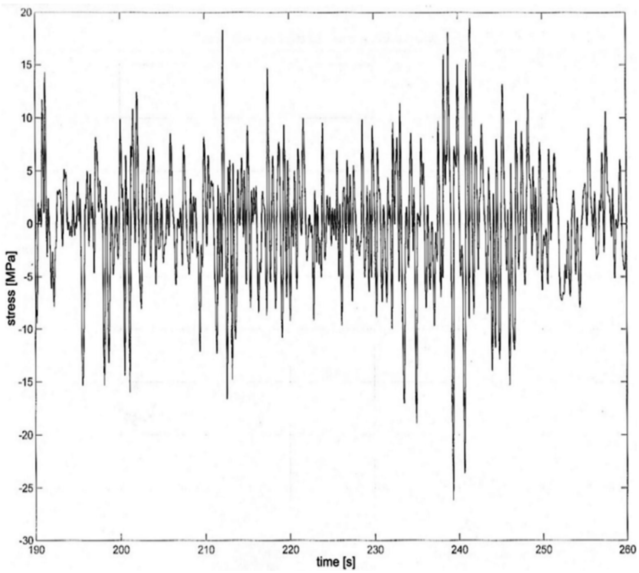

Fig. 9. Stresses registered at point 7 during the upward travel of a full conveyance

Based on measurement results [3], Table 1 summarises the values of extreme variability ranges of stress due to instantaneous changes of loads acting on the cable associated with the shaft steelwork-conveyance interaction forces.

TABLE 1

Forces in rope-bearing ropes throughout the entire duty cycle of the hoisting installation

Measuring point, No.	Maximum range variation of stress $\Delta\sigma$, MPa
1	75
2	50
3	35
4	25
5	40
6	75
7	45
8	120

5. Conclusions

The measurement point 7 was located near the point where the bearing cable on the bottom frame-end is connected to the skip hopper (as the system is symmetrical, the identical conditions occur at the point when the cable on the skip head-end is connected to the skip hopper). In the context of the schematic model of the skip used in the computational procedure (Fig. 2), it appears that the cable at this point will have to carry the maximal bending moment [10].

Hence the variance of the maximal stress amplitude in cables is governed by Eq. 2.

These values become [13]:

$n = 0{,}1$

$k_g = 500$ kN/m

$l_g = 1{,}0$ m, $b = 0{,}03$ m, $h = 0{,}25$ m.

$I_{50} = 0{,}02$ (read off from the plots in Fig. 3, for $n = 0{,}1$, $n_1 = 3$, $n_2 = 0{,}1$, $n_2 = 0{,}1$, $n_3 = 0{,}01$).

Recalling the work by S. Kawulok [15], the Author determined the spectral density of 'general irregularities' as the envelopes of spectral densities of misalignments of the guide string in the shaft in which the experiment was conducted [1], for velocity $V_0 = 10$ m/s, as during the stress measurements.

These envelopes are approximated by the relationship:

$$S_x(\omega) = \frac{2D_x\alpha}{\alpha^2+\omega^2} = \frac{80}{32+\omega^2}, \ \text{mms}^2$$

The power spectral density expressed by the dimensionless frequency can be given as:

$$S_x(\omega) = \frac{2D_x\alpha' p_{10}}{(\alpha' p_{10})^2 + (\omega' p_{10})^2} = \frac{2\cdot 7{,}07\cdot\alpha' p_{10}}{p_{10}{}^2\left[(\alpha')^2+(\omega')^2\right]}$$

where [9]:

$$\omega' = \frac{\omega}{P_{10}}, \ \alpha' = \frac{\alpha}{p_{10}}$$

Assuming that $a' = n$, where n is a dimensionless parameter, we obtain:

$$S_x = \frac{2D_x\cdot n}{p_{10}\left[n^2+(\omega')^2\right]} = \frac{2\cdot 0{,}0707\cdot 5{,}66}{p_{10}\left[5{,}66^2+(\omega')^2\right]}, \ \text{mm}^2$$

Variance of the maximal stress amplitude in the cable cross section is equal to the value derived by Eq. 2:

$$D_\sigma = \frac{3}{2}\cdot 7{,}07\cdot 10^{-4}\cdot 0{,}1\cdot 5^2\cdot 10^{14}\cdot\frac{1{,}0}{0{,}03\cdot 0{,}25^2}\cdot 0{,}02 \cong 2{,}828\cdot 10^{12}, \ \left(\frac{\text{N}}{\text{m}^2}\right)^2$$

Standard deviation of the maximal stress amplitude becomes:

$$\sigma(D_\sigma) = \sqrt{D_\sigma} \cong 1{,}65 \ \text{MPa}$$

As mentioned in previous sections, results obtained as computer-derived digital data sets can be further processed and thus the obtained final results presented as histograms and plots of stress distribution function are collated in the work [3]; this study is limited in scope, providing only the results obtained for the measurement point 7 alongside the calculated predictions of respective quantities.

For example, Fig. 10 and 11 show a histogram and the distribution function of stress variations registered at the measurement point 7. Fig. 10 illustrates the full duty cycle of the hoisting installation (upward and downward travel) and Fig. 11 covers only the downward travel of an empty conveyance. These plots are restricted to stresses generated due to irregularities and misalignments of the guide strings. Assuming that the thus obtained stress distributions follow the normal distribution patterns (which would require a separate analysis), the parameters of displacement μ and scale σ were obtained accordingly, yielding:

- For the first case $\mu = 0$, $\sigma = 6$ MPa,
- For the second case $\mu = 0$, $\sigma = 5$ MPa.

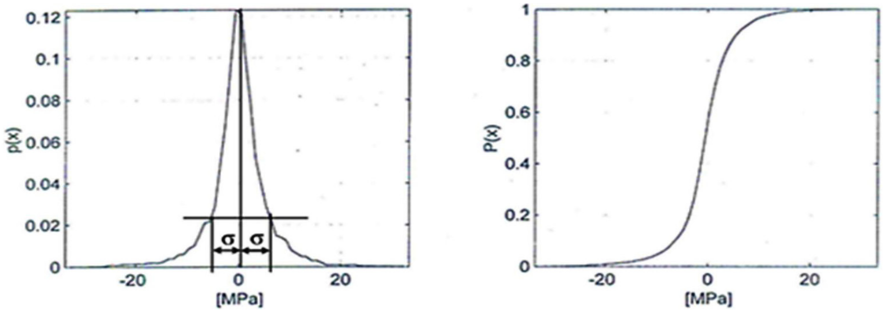

Fig. 10. Histogram (a) and distribution function (b) of stress variations registered by the sensor 7 throughout the full hoisting cycle

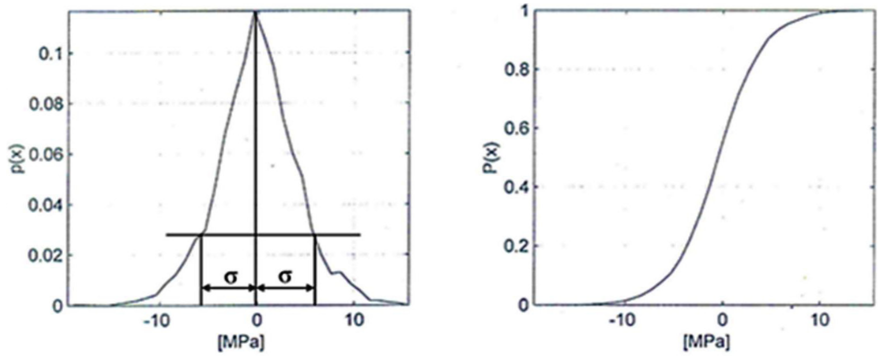

Fig. 11. Histogram (a) and distribution function (b) of stress variations registered by the sensor 7 during the downward travel of an empty conveyance

Predicted standard deviations of maximal stress in load-bearing cables are decidedly lower than measured values registered on a real object. Such marked discrepancy has been revealed because the theoretical considerations relied on spectral densities of guide string irregularities obtained in accordance with the procedure proposed by Kawulok [15] based on applicable normative guidelines [16] having relevance to the installation of guiding systems. It means that if the guide strings were mounted in the shaft in accordance with normative guidelines, the impacts of irregularities and misalignments of the guide strings on stress levels in load-bearing components of conveyances and load-bearing cables would be minimal and thus negligible in endurance analyses.

However, the actual arrangement of the guide strings in the shaft differs from that specified in normative reference [1], and the correlation functions and spectral densities of guide string irregularities and misalignments are different from the theoretical data adopted in theoretical considerations.

Comparing and contrasting experimental results with predicated data would be merited provided that the theoretical studies take into account the real parameters of the guide string irregularities and misalignments. This aspect will be addressed in a separate study.

Acknowledgement

Financial support from the statutory research No. 16.16.130.942 is acknowledged.

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