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Assessment Of the Reliability Indices of the Equipment of the Traction Electric Rolling Stock Based on the Results of Diagnostics

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ABSTRACT: A numerical calculation of reliability indices of traction electric rolling stock equipment based on the results of diagnostics is conducted and numerical studies are performed in the MathCAD 15 programming environment. As a result, a method for assessing the reliability indices of an electric locomotive wheelset based on data on instrumental and non-destructive testing is proposed.

KEY WORDS: traction electric rolling stock, electric locomotive wheelset, diagnostics, reliability, durability, method for assessing reliability indices, instrumental monitoring of parts, non-destructive testing of equipment.

I. INTRODUCTION

One of the most important areas for improving traffic safety and the economic efficiency of locomotive operations is the further development of a system of non-destructive testing of critical components and parts of electric rolling stock and, first of all, bogies, the condition of which is directly related to traffic safety [2, 3, 4, 5, 8, 9]. Therefore, methods and technologies for non-destructive testing of parts of traction electric rolling stock, their analysis and research are urgent tasks in railway transport.
The article sets scientific and practical tasks for assessing the reliability indices of equipment for electric rolling stock. The studies were conducted on the example of calculating the reliability and durability of the wheelset elements of the VL-80s electric locomotive according to operational tests based on data on instrumental and non-destructive testing.

II. RELATED WORK

We have analyzed a large number of works devoted to this topic. The issues reflected in the article are studied in an extensive section - fracture mechanics, in which the fundamental works are A.A. Griffiths, D.S. Dugdale, N.A. Makhutova, N.F. Morozova, E.M. Morozova, R.V. Goldstein, V.V. Bolotina, Yu.N. Rabotnova, G.P. Cherepanova, J.R. Rice, J. Seeha, J. Knott, E.O. Orowan, S. Tair, M. Tanaki, K. Hellan and others. Leading scientists around the world are conducting research in this direction, such as S.A. Brebbia (Wessex Institute of Technology, UK), G.M. Carlomagno (University of Naples di Napoli, Italy), A. Varvani-Farahani (Ryeson University, Canada), S.K. Chakrabarti (USA), S. Hernandez (University of La Coruna, Spain), S.-H. Nishida (Saga University, Japan). In the CIS countries, these problems were worked out by authoritative scientific schools and prominent scientists of MIIT, PGUPS, MAI, VNIIZhT, JSC VNIKTI, JSC Russian Railways, etc. [1, 2, 3, 4, 5, 6, 7, 8].

III. MATERIALS AND METHODS

The research methodology includes the development of mathematical models to study the reliability indices of traction electric rolling stock equipment based on the results of diagnosing the wheelset of an electric locomotive VL-80s.

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Standard methods of the strength of materials, elasticity theory, vibration theory, dynamics and strength of machines were used for research. Numerical studies were performed in the Mathcad 15 programming environment using approximation methods and spline interpolation.

IV. RESULTS AND DISCUSSION

This article is devoted to the numerical calculation of the reliability indices of traction electric rolling stock equipment based on the results of diagnostics; numerical studies were performed in the MathCAD 15 programming environment.

The methodology for evaluating the reliability indices of electric rolling stock equipment is based on the mechanism of fatigue failure of its components and parts during operation. The fatigue process is associated with the development of plastic strains, which appear during the aging of materials and causes the initiation of the smallest cracks - submicrocracks. Submicrocracks gradually grow and turn into microcracks, which further increase to the size of a macrocrack. The final "catastrophic" destruction occurs - a failure or a breakdown in the system, which can lead to an accident. The growth rate of a fatigue crack is determined by the stress state in the local region near its tip, which can be described in terms of fracture mechanics by the Paris's law [10, 11, 12, 17].

To justify the frequency of non-destructive testing of critical parts and assemblies of the rolling stock (which are, among other things, the axles of wheelsets), a model of its survivability was developed, based on the Paris dependence [15], taking into account the development of fatigue cracks in the following form:

$$\frac{d\ell}{dN} = C(\Delta K)^m , \tag{1}$$

where $\frac{d\ell}{dN}$ is the crack growth rate; C, m are the constants of the material depending on metal crystallography and cycle asymmetry coefficient $R = \frac{K_{min}}{K}$; 2ℓ is the crack length; on average m=1…6; K is the stress intensity factor (SIF) at the tip of the crack, determined by the following formula $K = \beta\sigma\sqrt{\pi\ell}$ [17], where K_{min} and K_{max} are the stress intensity factors at the maximum and minimum stresses of the cycle; σ is the applied uniform tensile stress acting on the sample in the direction perpendicular to the crack plane; β is the dimensionless parameter that depends on the sample geometry; ΔK is the range of stress intensity factor

$$\Delta K = K_{max} - K_{min}. \tag{2}$$

In the case of finite dimensions of the research object, there is a need for a correction function for the SIF parameter, which takes into account the geometric features and the method of loading the full-scale object under study.

With the correction function, equation (1) has the following form

$$\frac{d\ell}{dN} = C\Delta K^m \cdot f(\ell) , \tag{3}$$

The final equation (3) has the form

$$\frac{d\ell}{dN} = C\sigma^m \cdot \sqrt{\pi}^m \cdot \ell^{\frac{m}{2}} \cdot f(\ell), \tag{4}$$

which is a first-order differential equation with separable variables. After separation of variables, equation (4) has the following form

$$\frac{d\ell}{f(\ell)\cdot\ell^{\frac{m}{2}}} = C\sigma^m \cdot \sqrt{\pi}^m \cdot dN . \tag{5}$$

After an artificial transformation of the numerator by adding and subtracting one, equation (5) has the following form:

$$\frac{\ell^{-\frac{m}{2}}\cdot(1-f(\ell))}{f(\ell)} d\ell + \frac{1}{\ell^{\frac{m}{2}}} d\ell = C\sigma^m \cdot \sqrt{\pi}^m \cdot dN . \tag{6}$$

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After integration and grouping, equation (6) takes the following form

$$\int \frac{\ell^{-\frac{m}{2}} \cdot (1-f(\ell))}{f(\ell)} d\ell = C\sigma^m \cdot \sqrt{\pi}^m \cdot N - \frac{\ell^{1-\frac{m}{2}}}{1-\frac{m}{2}}. \quad (7)$$

In equation (7), on the right, there is a value that depends on ℓ and N

$$\int \frac{\ell^{-\frac{m}{2}} \cdot (1-f(\ell))}{f(\ell)} d\ell = S(\ell, N). \quad (8)$$

The resulting function $S(\ell, N)$ can be written as a function of one variable ℓ or N, due to the fact that there is a functional dependence between the values ℓ and N. Having obtained the values for the right side of (8) from the experiment and writing function $S(\ell)$ in explicit form, the correction function is defined as

$$f(\ell) = \frac{1}{1+\ell^{\frac{m}{2}} \cdot \frac{dS}{d\ell}} . \quad (9)$$

Stress intensity factors differ for different fracture configurations. So, for example, for a crack in the finite plate under uniform uniaxial stress (see Figure 1) the stress intensity factor is:

- if the crack is located in the center of a plate of finite width 2b and height 2h, the approximate ratio for the stress intensity factor K_I is

$$K_I = \sigma\sqrt{\pi\ell} \cdot \left[\frac{1-\frac{\ell}{2b}+0.326 \cdot \left(\frac{\ell}{b}\right)^2}{\sqrt{1-\frac{\ell}{b}}}\right], \quad (10)$$

- if the crack is not located in the center or in width, i.e. $d \neq b$, stress intensity factor K_{IA} at tip A of the crack can be approximated by an expansion into a series (see Figure 1)

$$K_{IA} = \sigma\sqrt{\pi\ell} \cdot \left[1 + \sum_{n=2}^{M} C_n \cdot \left(\frac{\ell}{b}\right)^n\right], \quad (11)$$

here coefficients C_n can be determined from matching stress intensity curves for different values of d. A similar expression can be found for tip B of the crack.

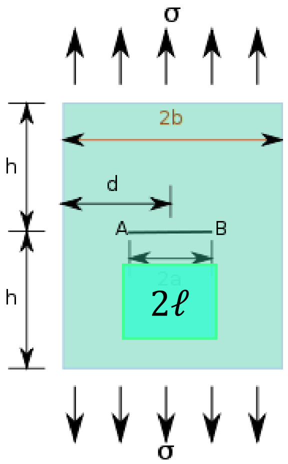

Fig. 1. Crack in the finite plate under uniform uniaxial stress, where 2ℓ is the crack length

Alternative expressions for the stress intensity coefficients at points A and B are

$$K_{IA} = \sigma\sqrt{\pi\ell} \cdot \Phi_A , \quad K_{IB} = \sigma\sqrt{\pi\ell} \cdot \Phi_B , \quad (12)$$

where

$$\Phi_A := \left[\beta + \left(\frac{1-\beta}{4}\right) \cdot \left(1 + \frac{1}{4\sqrt{\sec \alpha_A}}\right)^2\right] \cdot \sqrt{\sec \alpha_A} , \quad (13)$$

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$$\Phi_B := 1 + \left[\frac{\sqrt{\sec\alpha_{AB}}-1}{1+0.21\cdot\sin\left\{8\cdot\tan\left[\left(\frac{\alpha_A-\alpha_B}{\alpha_A+\alpha_B}\right)^{0.9}\right]^{-1}\right\}}\right], \quad (14)$$

here

$$\beta = \sin\left(\frac{\pi\alpha_B}{\alpha_A+\alpha_B}\right); \quad \alpha_A = \frac{\pi\ell}{2d}; \quad \alpha_B = \frac{\pi\ell}{4b-2d}; \quad \alpha_{AB} = \frac{4}{7}\cdot\alpha_A + \frac{3}{7}\cdot\alpha_B .$$

In the above expressions, d is the distance from the center of the crack to the boundary closest to point A.

For an edge crack of length ℓ in the finite plate under uniaxial tension (see Fig. 2), with dimensions $2h \times b$, provided that $\frac{h}{b} \geq 0.5$ and $\frac{\ell}{b} \leq 0.6$, the stress intensity factor at the tip of the crack under uniaxial stress σ is

$$K_I = \sigma\sqrt{\pi\ell}\cdot\left[1{,}122 - 0{,}231\cdot\left(\frac{\ell}{b}\right) + 10{,}55\cdot\left(\frac{\ell}{b}\right)^2 - 2{,}71\cdot\left(\frac{\ell}{b}\right)^3 + 30{,}382\cdot\left(\frac{\ell}{b}\right)^4\right], \quad (15)$$

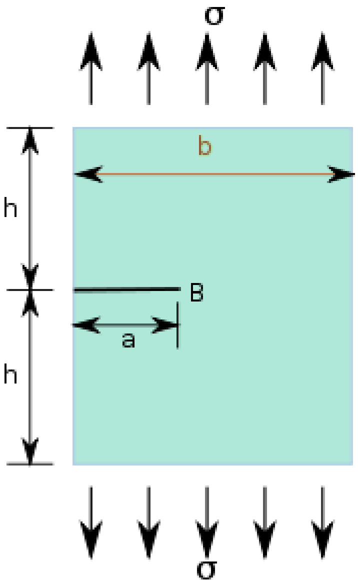

Fig.2. Edge crack of length ℓ in the finite plate under uniaxial tension, with dimensions $h \times b$, under conditioin $\frac{h}{b} \geq 0.5$ and $\frac{\ell}{b} \leq 0.6$

For the case when $\frac{h}{b} \geq 1$ and $\frac{\ell}{b} \geq 0.3$, the stress intensity factor can be approximated as

$$K_I = \sigma\sqrt{\pi\ell}\cdot\left[\frac{1+\frac{3\ell}{b}}{2\sqrt{\pi\frac{\ell}{b}}\left(1-\frac{\ell}{b}\right)^{\frac{3}{2}}}\right], \quad (16)$$

The fracture macrorelief is largely determined by the fatigue crack propagation rate.

The controlled parameter of the wear part is a continuous random variable, the distribution laws of which can be represented by the distribution density [13,Table 1.3]. The construction of a histogram of the distribution of the controlled parameter is considered in [14].

The technique and algorithm for determining the compliance of samples of controlled parameters with the expected distribution laws were developed and described in [14,15].

One of the well-known criteria, for example, Pearson goodness-of-fit test, can be used to check the compliance of the sample with the expected theoretical distribution law. It allows for determining the probability that, due to random causes, the measure of discrepancy between the theoretical and statistical distributions is greater than the one actually observed [13,16].

Samples of controlled parameters of wear parts correspond to the normal distribution law. The distribution density for a given law is

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$$f(x) = \frac{1}{\sigma_x \cdot \sqrt{2\pi}} \cdot e^{-\frac{(x-m_x)^2}{2\sigma_x{}^2}} \quad , \tag{17}$$

where m_x is the mathematical expectation of the value of the controlled parameter; σ_x is the standard deviation of the value of the controlled parameter; x is the current value of the controlled parameter.

Under the normal distribution law the following constraints are superimposed on a random variable $\sum_{j=1}^{k} P_j^* = 1$ - the sum of frequencies over all intervals is 1 (k is the number of intervals); $m_x = m_x^*$; $D_x = D_x^*$ are the parameters of statistical and theoretical distributions.

Since the numerical characteristics of the normal distribution law can be expressed in terms of the mathematical expectation and the variance of a random variable, the following corresponding estimates are calculated:

the average value of m_x^*

$$m_x^* = \frac{1}{N} \cdot \sum_{i=1}^{N} x_i \tag{18}$$

and estimation of variance (standard deviation σ_x^*)

$$\sigma_x^* = \sqrt{\frac{1}{N-1} \cdot \sum_{i=1}^{N} \left((x_i - m_x^*) \right)^2} \ , \tag{19}$$

where N is the sample size of the controlled parameter;

x_i is the value of the controlled parameter.

The functions of the distribution density of the values of the thickness of the tires and the thickness of the tooth of the large gear wheel (LGW), wheelsets at fixed operating hours of the electric locomotive of the VL-80c series in the locomotive repair depot Uzbekistan are shown in Figs. 3 and 4.

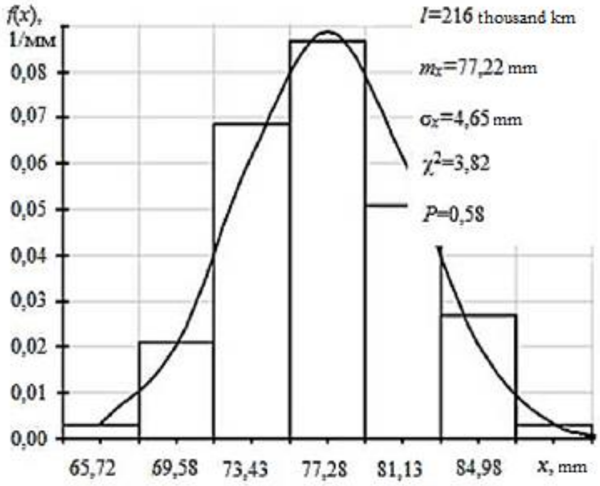

Fig. 3. Distribution of the thickness of the tires of wheelsets
for the VL-80s electric locomotive (according to the data of the locomotive repair depot Uzbekistan)

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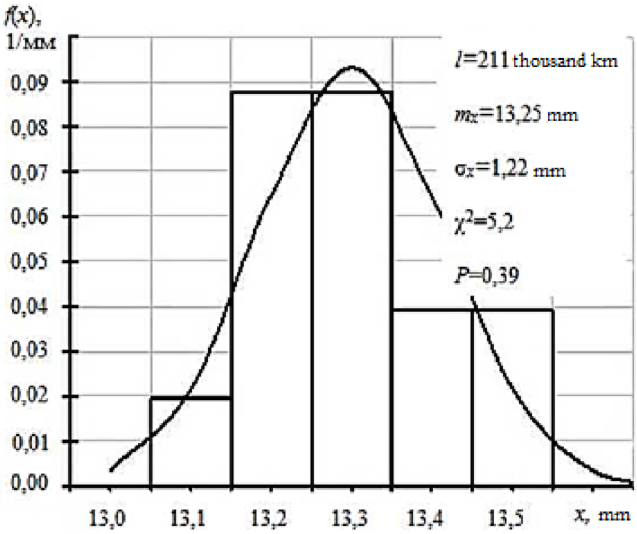

Fig. 4. Distribution of the thickness of the gear tooth of the large gear wheel (LGW) of wheelsets for the VL-80s electric locomotive (according to the data of the locomotive repair depot Uzbekistan)

The values of the numerical characteristics of the distribution law of the controlled parameter make it possible to predict their changes at the highest operating time, which in turn determines the resource. For this, the analytical dependences of the average values of m_x and standard deviations σ_x on the run are determined.

An analytical dependence can be represented as a certain nonlinear function $y = f(a_1, a_2, \dots, a_S, \ell_i)$ of one argument ℓ_i the expression of which includes S parameters $a_1, a_2, \dots, a_S$. Using this function, it is necessary to approximate the empirical regression given as $\boldsymbol{n}$ points (ℓ_i, y_i) **for** $i = 1, 2, \dots, n$ **,** where y is taken as one of the parameters of the distribution law under consideration.

V. CONCLUSION

The described methods for assessing the propagation of fatigue cracks are used in practice to predict the growth of cracks in real structures. In accordance with the presented mathematical model (1)-(19), it is obvious that the growth rate of a fatigue crack in the units and parts of the equipment of the electric rolling stock, specifically in the wheelsets of the VL-80s electric locomotive, is proportional to the crack opening and the yield strength of the material [17].

The results of the numerical calculation of the coefficients of empirical regression equations were obtained in the programming environment Mathcad 15 using methods of approximation and spline interpolation.

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Table 1. Results of numerical calculation of coefficients of empirical regression equations

Controlled parameter	Coefficients of dependencies				X_{add} , mm
	$m_x(\ell)$		$\sigma_x(\ell)$		
	a, mm/thous km	*b* , mm	*a*, mm/thous km	*b* , mm	
Bandage thickness	-0.0859	96.8304	0.02321	1.5595	45
Wear of the gear tooth of LGW	0.0101	0.010	1.3700	0.2740	3

The regression equation for the dependence on the mileage of the average value of the tooth wear of the large gear wheel (LGW) of the traction gearbox in this case has the following form

$\boldsymbol{m_x(\ell)}$ = 0.0002398 * *l* + 0.2516718, correlation coefficient r = 0.948.

The regression equation for the dependence on the mileage of the standard deviation of the tooth wear of the gear of the large gear wheel of the traction gearbox in this case has the following form

$\boldsymbol{\sigma_x(\ell)}$ = 0.0000171 * x + 0.2582241, correlation coefficient r = 0.195.

Since the correlation coefficient is rather small, it was tested for the significance of the difference from 0. It was found that at a significance level of 0.05 it does not statistically differ from 0, so the dependence $\boldsymbol{\sigma_x(\ell)}$ can be considered constant.

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