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Combined Influence of Cyclic Loads and Corrosion on the Technical Condition of Metal Structures of Metro Escalators

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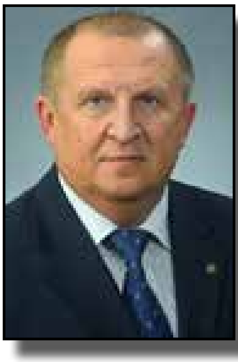

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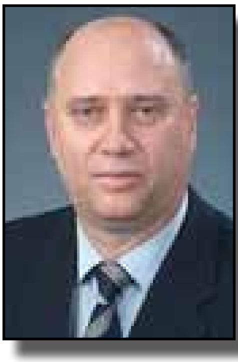

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ABSTRACT

This article examines the influence of loads, conventionally divided into static and cyclic ones, and of corrosion acting together on the structural elements of metal structures of metro escalators. The dynamics of corrosion processes are determined by the environment, the degree of influence of which, depending on the geographical location and based on seasonality, can vary from non-aggressive to highly aggressive. This, with simultaneous occurrence of deformations (a stressed state is created in the structure), can lead to fatigue failures. The state of the metal structure of the escalator in this case is the most important element, since the failure of almost any of its structural elements means a complete stop of the escalator.

The prerequisites for corrosion fatigue for low carbon steels, as the main material in manufacture of metal structures for metro escalators, are also considered.

The main objective of the study is to search for criteria for creating an experimental and computational method for determining the residual life of metal structures of metro escalators with a high degree of reliability. Identification and analysis of criteria for assessing the condition of metal structures was carried out by the authors using experimental research and survey methods, that resulted in a conclusion that the degree of degradation of the main characteristics and properties of metal structure elements is determined not only by the number of loading cycles, but also by the duration of exposure to an aggressive environment.

Keywords: metro, escalator, metal structure, corrosion, fatigue, static and cyclic loads, mathematical modelling and simulation.

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INTRODUCTION

Hoisting and transport machines, including metro escalators, are designed based on the assumption that their metal structures will be operated within the limits of elastic deformations, that is, within the area of such loads where the relationship between the resulting stresses and the resulting deformations is unambiguous. However, in practice, zones of local overloads are found quite often on elements of metal structures, where fatigue failures occur, which can be accompanied by nonlinear elastoplastic and plastic deformation.

Modern technologies based on the implementation of finite element modelling through various software systems make it possible to determine with sufficient accuracy the stress-strain state of nodes and elements of metal structures of escalators [1].

The non-destructive magnetic testing method, based on the interconnectedness of the magnetic and physical-mechanical properties of ferromagnetic materials, makes it possible to actually clarify the location of the most loaded zones of the elements of load-bearing metal structures of metro escalators operating under conditions of long-term cyclic loading, to evaluate the stress-strain state of the metal, and also to determine the level of plastic deformation and fatigue damage [2].

In this case, the structure of the ferromagnetic material acts as a kind of unique sensor of the peak force value, and a number of other controlled magnetic parameters related to the integrity of the metal structure clearly display the force characteristics of the operating modes of the load-bearing metal structure.

The state of the metal structure in this case is the most important element, since its failure means a complete stop of the escalator. Based on this, the main *objective* of this study is to establish the relationship between the corrosion state of metal structures of metro escalators that have completed their standard service life and their technical characteristics, which determines the possibility of calculating the value of the residual resource and extending the period for operation over standard service life [3]. The object of study, which is the metal structure of metro escalators, acts in this case as a poorly organised system with insufficiently studied causal relationships and a lack of determinism in manifestation of many phenomena and implementation of processes. Main research *methods* comprise practical methods for determining and assessing the technical condition of metal structures of metro escalators, regression analysis and statistical modelling, fundamentals of the mechanics of destruction of solids.

The study does not consider the possible loading of the supporting metal structures of escalators, which can occur in case of violation of integrity of building structures for various geological and anthropogenic reasons.

RESULTS

Determining the Features of the Influence of Cyclic Loads and Corrosion

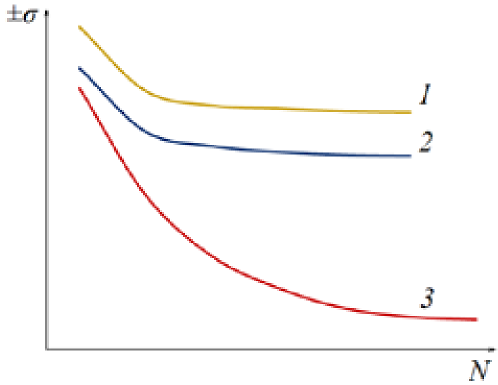
The operation of metal structures of metro escalators is carried out in an environment, the degree of impact of which, depending on the geographical location and based on seasonality, can vary from non-aggressive to highly aggressive, with the simultaneous development of deformations since a stressed state is created in the structure. The loads arising in this case, in combination with the processes of stress-corrosion cracking and corrosion fatigue, can be conditionally divided into two groups: static and cyclic ones [4, 5].

The mechanism of corrosion-fatigue destruction is unique and at the same time dangerous in that it starts in almost any corrosive environment, from slightly aggressive to highly aggressive ones, and can lead to a sharp, sometimes catastrophic decrease in the endurance limit of metal.

The presence of a corrosive environment makes significant adjustments to the process of fatigue destruction of metal structure elements made of low carbon steels, in comparison with dry air or chemically low-active environments. Corrosion fatigue in such cases can manifest itself in the form of the following features:

• *No true endurance limit*. In Pic. 1, the «stress – number of loading cycles» coordinate axes show the endurance curves of steels: line *1* corresponds to pure fatigue, line *2* to adsorption fatigue, and line *3* to corrosion fatigue.

There are no pronounced horizontal sections on all lines. The value of the destructive alternating stress is determined depending on the number of loading cycles; however, at the same time, the relationship between the intensity of the decrease in the value of the destructive stress and the relative corrosiveness of the medium is obvious. Therefore, to characterise corrosion fatigue, such a concept as a conditional endurance limit is used.



Pic. 1. Typical endurance curves for steels [performed by the authors].

• *The inability to establish a relationship between the conditional limit of corrosion endurance and the mechanical properties of the metal* obtained by applying static and cyclic loads when it is in an air environment.

• *Multiplanar nature of destruction*, clearly manifested in low carbon steels in neutral corrosive environments.

Practical tests of St3sp steel [Standard-grade structural carbon steel] samples were carried out using a BISS Nano UT-01–0025 servo-hydraulic testing unit and an Altami MET 3T metallographic digital microscope. Multi-cycle fatigue tests were carried out with a strain changing of 0,4–0,6 % with cycle stress amplitudes of 250–280 MPa. Before testing, the samples underwent preliminary metallographic examination, for which their surface was mechanically ground and etched with a 5 % nitric acid solution to identify grain boundaries. Next, pictures were taken of the same area after each stage of loading.

As can be seen from Pic. 2 St3sp steel has a typical homogeneous microstructure consisting of ferrite and pearlite grains. Already at the first stages of fatigue testing, stable slip bands appear in ferrite grains, which merge during subsequent loading; new slip bands also appear, and their number increases accordingly. Stable slip bands are oriented predominantly across the loading axis.

Intergranular fracture is the most preferable place for occurrence of corrosion processes, following which the surrounding corrosive environment, affecting and changing the microrelief of the fracture surface, can significantly increase the number of elements of brittle fracture, chipping and other structural defects:

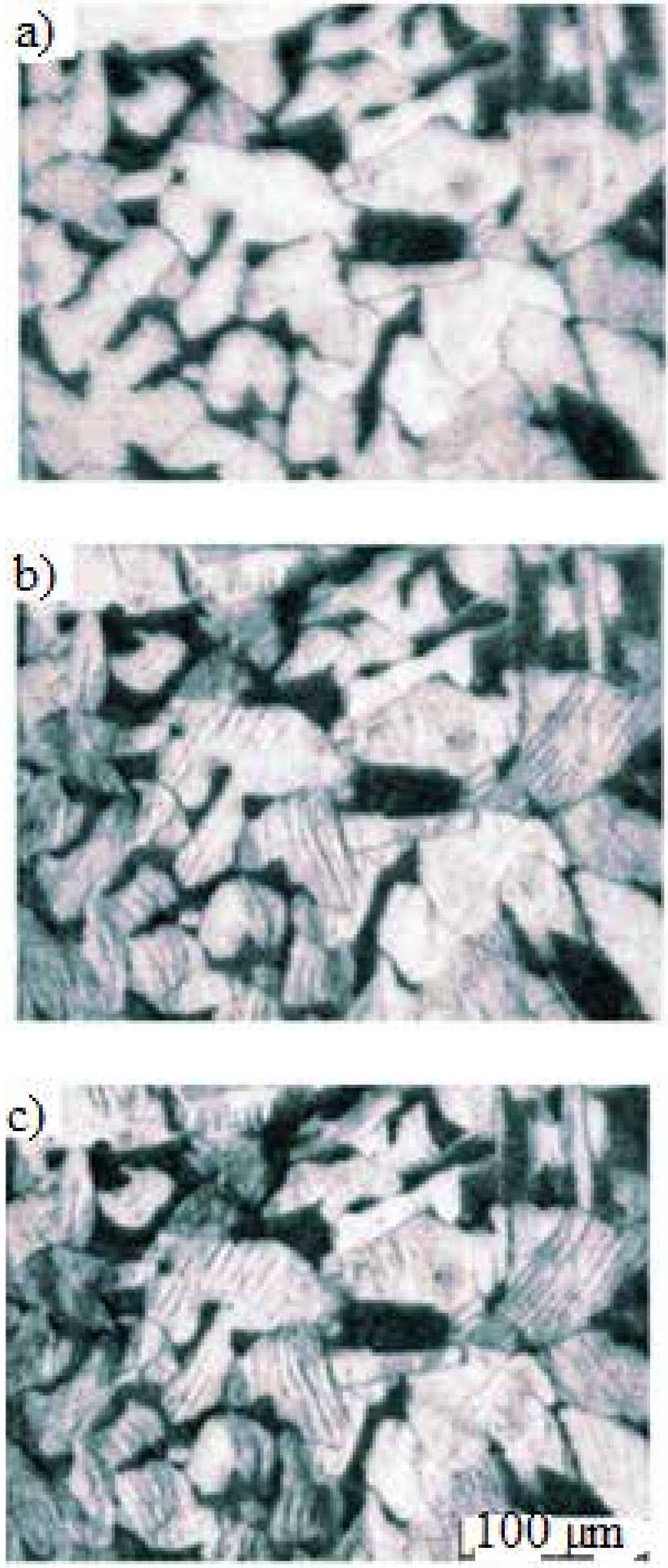
• An increase in the cross-section of the test samples leads to a decrease in the endurance limit regarding fatigue of low carbon steels. This phenomenon is called the scale effect. However, in a corrosive environment, smooth samples may exhibit an inversion of the scale effect.

• Reducing the sensitivity of low carbon steel products located in a corrosive environment to surface microgeometry and mechanical stress concentration due to their anodic dissolution.

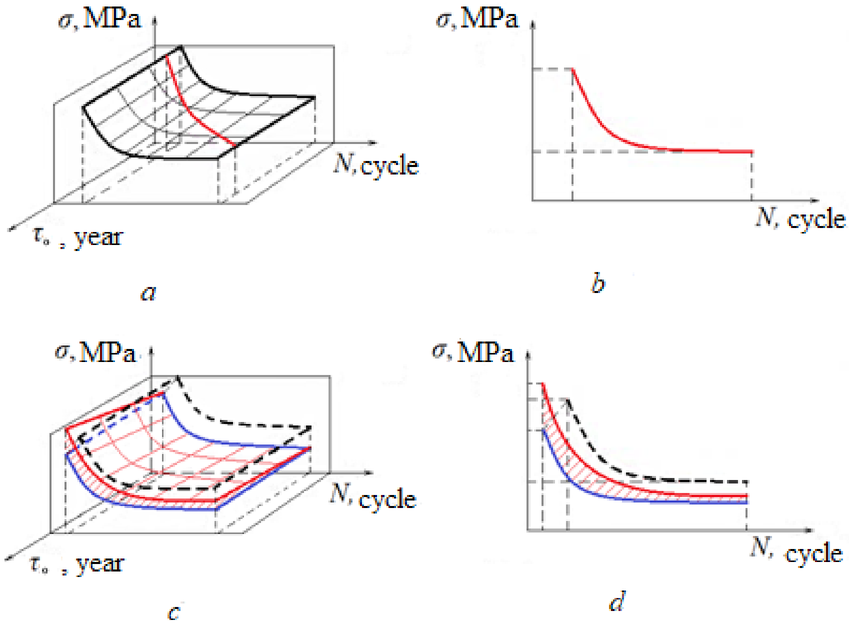
The operation of most metal structures of metro escalators is carried out under conditions of corrosion fatigue when exposed to corrosive environments of varying degrees of aggressiveness, however, cases characteristic of exclusively corrosion-mechanical destruction in specific conditions are quite rare in practices or are not observed at all, based on which the above theoretical provisions need clarification.

Accounting for the Time Factor when Assessing the Condition of Metal Structures of Metro Escalators

The degree of influence of the time factor on the state of a real metal structure of a metro escalator cannot be reliably determined using diagrams with typical fatigue curves, since they are obtained in laboratory conditions during testing of standard samples under high intensity cyclic loads at $N > \tau_o$, where τ_o is operation time. It is obvious that the operation of metal structures in real conditions is carried out at $\tau_o >> N$, for example, the standard service life of metro escalators varies from 30 to 50 years. It is also obvious that in real life conditions the escalator does not operate all 24 hours a day, but only a certain number of shifts with redirection of traffic and breaks in operation. On the contrary, expiration of 100 % service life for the test samples is carried out within a few hours or days, which is clearly not enough to demonstrate the actual nature of corrosion-mechanical destruction.



Pic. 2. Metal surface of the sample: a – before testing, b – after 103 loading cycles, c – after 2×103 loading cycles [performed by the authors].



Pic. 3. Typical fatigue curves: a, b – pure fatigue obtained in neutral environments; c, d – fatigue taking into account the influence of primary factors of the corrosive influence of the environment (– – - – pure fatigue (black dotted line in colour image); – taking into account the influence of corrosive wear (red line); – taking into account the influence of adsorption fatigue (blue line)) [performed by the authors].

That is, the results obtained in the laboratory, for cases where $\tau_o >> N$, cannot fully reflect the physical and chemical process under study.

As part of previously conducted on-site studies [6, 7] in the Petersburg Metro State Unitary Enterprise, using various methods for determining the technical condition of metal structures of escalators, the primary factors determining the aggressive impact of the environment were identified: the influence of wear of individual structural elements on the dynamics of changes in the load-bearing capacity of the metal structure as a whole; the occurrence and development of local types of corrosion damage, including pitting corrosion; the phenomenon of adsorption decrease in the mechanical characteristics of the material.

In this case, corrosion, first, means not the process of material destruction, but the entropy, aimed at restoring balance in nature. All steels contain iron, which makes them thermodynamically unstable compounds, which, during redox reactions, are converted into thermodynamically favourable rust, that is into an analogue of ore iron.

Simultaneous exposure to constant and variable loads leads to corrosion fatigue of the material. Assessing the actual corrosion state of a metal structure, as well as the ability to predict the dynamics of this state (that is, to determine the remaining technical life), contributes to the timely adoption of measures to prevent operational failures during operation of metro escalators.

To achieve this goal, a mathematical modelling method was chosen. The main criteria that needed to be paid attention to when creating the model were identification of properties or indicators in the process under study, identification of phenomena and other components that characterise the selected properties or indicators, and their description.

To increase the adequacy of the modelling, numerical modelling was carried out, which consists of combining the application of MathCad and SigmaPlot software packages (MathCad is a computer algebra software package that belongs to the class of automatic design systems; SigmaPlot is a software package designed for the analysis and visualisation of scientific and statistical data with the ability to apply 2D and 3D visualisation of the results).

Mathematical expressions were obtained that describe development and impact of these factors, taking into account the influence of the time factor.

To ensure a clear representation of interconnectedness of the influence of the main factors of corrosion and the degree of accumulation of corrosion fatigue in the metal structures of metro escalators, it becomes necessary to depict all corrosion-fatigue curves in three-dimensional coordinates: «stress (load) – number of loading cycles – time».

Table 1

Accumulation rate of fatigue damage under pure fatigue (σ_{RK} = 85 MPa) [performed by the authors]

σ_{max}, MPa	197	165	150	118	104
N, 10^3 cycle	1	5	10	50	100
$\Delta\sigma_n$, MPa	112	80	65	33	19
υ_{pn}, 10^{-6} mm^3/(MPa·cycle)	0,00893	0,00250	0,00154	0,00061	0,00053

Pic. 3 clearly shows that the schemes are fundamentally different from each other, and it can be noted that with the same number of loading cycles N the main difference lies precisely in the time factor.

Throughout their entire life cycle, structural elements of metal structures of metro escalators, like of any other hoisting and transport machines, are subject to corrosive wear, the degree of accumulation of which over time determines the dynamics of a decrease in the load-bearing capacity of the metal structure and an increase in stress under a constant load over time (Pic. 3). As a result, there is a need to actually determine the value of the residual life and organise constant monitoring of the level of applied loads to maintain the operability of the structure for a certain number of loading cycles [8, 9].

Adsorbed surfactant components of the medium also cause changes in the fatigue strength of the material, which is explained by the Rehbinder effect, especially under the action of cyclic stresses. The curves of adsorption fatigue and pure fatigue obtained in neutral media are similar (Pic. 1). Here, as mentioned above, there is also the absence of a pronounced horizontal section, however, unlike corrosion fatigue, the limit of adsorption fatigue is not a conventional value and can be determined quite accurately. The similarity of the curves allows us to conclude that adsorption fatigue simply leads to a decrease in the endurance limit of the material.

To determine the value of the adsorption fatigue limit $\sigma_{-1\kappa}$, it is possible to use the formula [6, 7]:

$$\sigma_{-1\kappa} = \sigma_{-1o} \cdot \left(\frac{T_o}{T}\right)^{\beta} \cdot \gamma_d \cdot k_t, \quad (1)$$

where σ_{-1o} – endurance limit of the material at temperature T_o = 293K (20 °C);

T – ambient temperature;

β – characteristics of cross-sectional stability against corrosion;

γ_d – adsorption strength reduction coefficient;

k_t – time component characterising the dynamics of changes in the coefficient of adsorption strength reduction over time.

It should be noted that the adsorption effect of the environment is levelled out and the properties of the material can be restored to the level of pure fatigue if it is ensured that the material does not come into contact with an aggressive environment, for example, using paints and varnishes [10, pp. 173–174].

Pitting in a material manifests itself in the form of stress concentrators, which are local defects, from which fatigue cracks can develop [11].

Let us consider a model that describes the stage of initiation of fatigue cracks in low carbon and low-alloy steels at the stage of diffuse damage [12]:

$$N_T = -\frac{1}{C_N}\int_{\omega_o}^{1}\frac{\left(1-\omega_{nT}\right)^{m_c}}{\Delta\sigma_n^{m_c}}d\left(1-\omega_{nT}\right), \quad (2)$$

where N_T – number of cycles at the stage of diffuse damage;

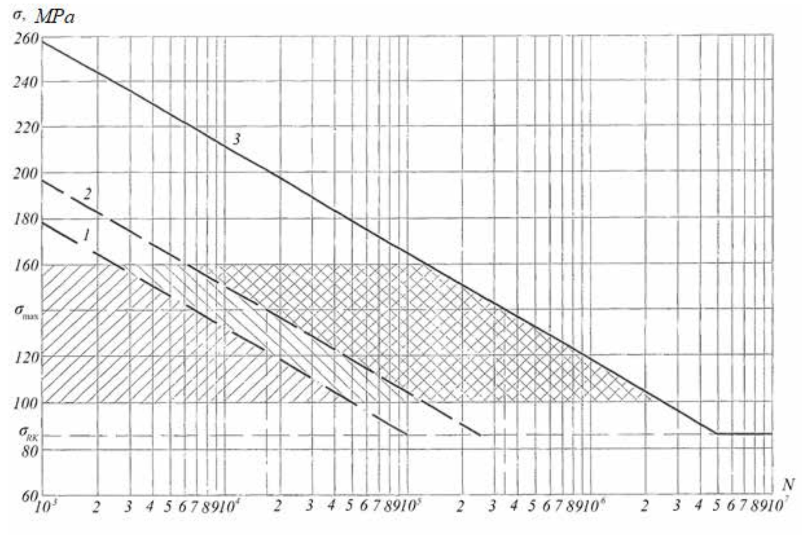
C_N and m_c – coefficients determined by the physical and mechanical properties of the material;

ω_o – quantitative proportion of structural damage before loading;

Table 2

The rate of accumulation of fatigue damage considering the adsorption effect of the environment (σ_{RK} = 72,3 MPa) [performed by the authors]

σ_{max}, MPa	167,5	140,3	127,5	100,3	88,4
N, 10^3 cycle	1	5	10	50	100
$\Delta\sigma_n$, MPa	95,2	68	55,2	28	16,1
υ_{pn}, 10^{-6} mm^3/(MPa·cycle)	0,01050	0,00294	0,00181	0,00071	0,00062



Pic. 4. Diagram of fatigue damage 1 – line of the end of the incubation period of fatigue; 2 – line of the end of the period of initiation and development of submicroscopic cracks to microscopic sizes (Paris' Law line); 3 – curve of the end of the period of development of microcracks to macrocracks of critical size [15].

ω_{nT} – quantitative fraction of fatigue damage accumulated during loading;

$\Delta\sigma_n$ – value of damaging stresses.

The value of damaging stresses can be determined using the formula [13, 14]

$$\Delta\sigma_n = \sigma_{\max n} - \sigma_{RK}, \quad (3)$$

where σ_{RK} – endurance limit.

Analysis of formula (3) allows making the following assumptions and conclusions at a preliminary stage: the increase in the level of damaging stresses is influenced, firstly, by the presence of an aggressive environment, which causes increased corrosive wear, which results in an increase in $\sigma_{\max n}$, and secondly, adsorption environmental influences that cause a decrease in σ_{RK}. The option cannot be ruled out when a simultaneous change in the corresponding quantities may occur, which leads to a general increase in the level of damaging stresses.

Since during the research it is difficult to determine individual real characteristics, we will assume that in the presence of a 0,1 mm long microcrack, the critical volume of damage $V_{n\gamma}$ will be equal to 0,001 mm^3.

It is obvious that the increase in the rate of formation of fatigue cracks is a consequence of the influence of primary factors that determine the aggressive influence of the environment, then, based on the assumptions and conclusions obtained from the analysis of formula (3), and the accepted value of the volume $V_{n\gamma}$, their influence on the dynamics of fatigue crack development can be assessed.

The values of the maximum permissible stresses, determined by the applied external load, according to model (2), can reach the level of the yield strength σ_T. At the same time, the mechanical characteristics of the metal are affected by the adsorption effect of the environment, which manifests itself in the form of a decrease in σ_{RK} and σ_T by a maximum of 15 % (under conditions of highly aggressive environment).

To determine the rate of accumulation of fatigue damage, we use the formula

$$\upsilon_{pn} = \frac{V_{n\gamma}}{N \cdot \Delta\sigma_n}. \quad (5)$$

Pic. 4 shows a diagram of the fatigue damage of the studied samples made of St3sp steel under cyclic tensile conditions with a cycle asymmetry $R = 0,3$.

Using the diagram and formula (4) allows us to determine the dynamics of changes in the rate of accumulation of fatigue damage in the considered case of pure fatigue (see Table 1). In this case, the value of the maximum stresses $\sigma_{\max}$ is selected according to the Paris' Law.

For the case that considers the adsorption effect of the environment on the fatigue process (under conditions of a highly aggressive environment), all indicators decrease by 15 % (see Table 2).

Analysing the data obtained in Tables 1 and 2, the following conclusions can be drawn: the overall level of damaging stresses for St3sp steel in a highly aggressive environment (with equal structural resources for two cases under consideration) decreases; the rate of accumulation of fatigue damage is different and when operating in a highly aggressive environment it increases by an average of 17,2 %.

CONCLUSION

An increase in the rate of formation of fatigue cracks is determined by the presence of primary factors of corrosion action on metal structure elements, and this increase is gradual and is determined by the service life duration, which allows us to qualify the time factor as a determining factor.

The level of degradation of the main characteristics and properties of metal structure elements, along with the number of loading cycles, is also determined by the duration of exposure to an aggressive environment, which uniquely determines the rate of accumulation of fatigue damage.

The inclusion in the model [5, 6] of the presented model (5) to determine the rate of accumulation of fatigue damage, considering model (1) to determine the limit of adsorption fatigue and taking into account the time component, will more fully reflect the process of the combined effect of corrosion and cyclic loads on the metal structures of metro escalators.

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