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EVALUATION OF THE RELIABILITY OF LIFTING CRANESMETAL STRUCTURES

The methodfor assessing the residual life is considered, which makes it possible to predict the loss of the metal structures strength as a result of exhausting and corrosion damage. After analyzing the results of calculating the survivability of the structure, a decision is made on further exploitation. If the results of calculating Q(t), taking into account the change in σ_{-1D} *in terms of the coefficient of variation, exceed the values of the durability of 25 years, then it is impractical to calculate the survivability.*

Keywords: *metal construction, reliability, the damaged, fatigue crack, corrosion, term of exploitation, residual resource.*

Introduction

The need to search for additional methods to reduce the accident rate and to improve the safety of the crane fleet is due to the statistics of injuries and accidents at lifting structures, which rank the third after injuries and accidents in the coal and mining industries.

A crane condition in which the risk of an accident is limited to an acceptable level is de-fined as the safety of the crane. The risk of crane is considered acceptable if its value is so insignificant that the benefits from the operation of this crane significantly outweigh this risk [1]. An accident is an event that leads to the destruction of load-bearing elements of metal structure, steel ropes, etc., or to the fall of a load.

The safety of the operating cranes is achieved through the implementation of a number of measures to prevent the accidents with cranes, and therefore reduce the risk of their operation. These measures should be taken into account at all stages of the crane's life-circle, starting from the design stage. But a special place is allotted to the operation stage and the decision to extend the service life.

The relevance of the research methods for extending the remaining resource is due to the steady increase in the proportion of equipment that has worked out the designated service life.

The task of assessing the remaining resource of an operated object belongs to the class of individual forecasting tasks and includes the solution of such tasks as assessing of the current state, predicting this state in the future, assessing of the probabilities of failures, the risk of emergency situations [1]. On the basis of this forecast, the maximum operational lifetime of the equipment is established or the period for the next monitoring of the state of the object under study is assigned.

Problem Statement

Metal structures of cranes operate in difficult operating conditions under the influence of variable loads and the external environment. As a result, the cracks and deformations appear in the elements of metal structures. In addition to mechanical loads, the crane is exposed to air, which causes corrosion damage to the metal structures.

Currently, when diagnosing (examining) the state of metal structures, a technique is used, the purpose of which is visual inspection, determination of the size of defects, instrumental control of cracks and metal thickness, static and dynamic tests of metal structures.

The purpose of this work is to reduce the subjective factor when making decisions about the possibility of further operation of the crane during the next inspection. The latter is achieved by ranking the damage factors and dividing them into three classes:

- damage from the duration of operation;
- manifestation of damage in the form of cracks and deformations;
- damage from corrosion.

Along with this, a subjective assessment of the state of metal structures is considered.

Calculation of the Reliability of Metal Structures of the Lifting Cranes

The damage caused by the duration of operation is determined analytically, taking into account the following factors: duration of operation, span length, passport mode of operation, real mode of operation, period of operation in real mode, the ratio of the maximum lifted load to the passport capacity, and the influence of the environment.

Below is a Table 1 for assessing the damage of the metal structures of the crane, where some medium duty crane is taken as an example.

Damage Calculation Due to the Service life

The damage due to the service life (DSL) will be defined as the ratio of the operating period — P_o to the possible service life of the м/s — P. Let us call such damage "pure", since it is necessary to take in to account other factors affecting the DSL. These factors include the length of the span, the maximum load to be lifted, the type of lifting device. Then "pure" damage due to the service life is

$$D_0 = \frac{P_o - P_{real}}{P} + \frac{P_{real} \cdot R_{real}}{P \cdot R_{pass}}, \tag{1}$$

where P_o — is the period of full operation, R_{real} — is the real operating mode, R_{pass} is the passport operating mode.

Note that the value of P is corrected depending on the environment by the formula $P_{est} = P \cdot (1 - 0{,}1 \cdot S)$, but it can be taken subjectively, as in the example of Table 1.

Span factor value

$$K_l = \begin{cases} \left(\frac{L}{10}\right)^{0,1}, & L > 10 \text{ m} \\ 1, & L \le 10 \text{ m} \end{cases}. \tag{2}$$

This factor considers the risk of missing damages with increasing span.

Load factor (see Table 1)

$$K_2 = Q_{\max} / Q\ . \tag{3}$$

Load gripper type factor

$$K_3 = 1 + \frac{T}{10}\ . \tag{4}$$

Considering (1) – (4), the DSL can be written as

$$X_1 = D_0 \cdot K_1 \cdot K_2 \cdot K_3\ . \tag{5}$$

The authors used several variants of formulas (1) – (5) and settled on the above, since due to them, the best multiple correlation factor was obtained.

Table 1 shows how the damage from cracks and deformations — X_2 and the damage from corrosion — X_3 are calculated.

Calculations are made according to the amount of damages and their weight (signifi-cance) [3]. Such calculations are easily done using an Excel macro.

To determine the regression factors, the state of 11 cranes and the results of their further operation over the past 10 years were considered.

The estimated resource was set in percentage from the standard period to the first survey (12 ...

Table 1. **Expert assessment of the damage to metal structures of cranes**

1	Span (m)			L= 28,5
2	Carrying capacity (t)			Q=10
3	Passport mode of operation (1 ... 8)			R_{pass}=5
4	Real operation mode (1 ... 8)			R_{real}=4
5	Period of work in real operation mode (years)			P_{real}=8
6	Maximum lifted load (t)			Q_{max}=8,5
7	Type of lifting device (0 – hook, 1 – grab, 2 – magnet)			T=2
8	Environment (0 – normal, 1 – wet, 2 – aggressive, 3 – very aggressive)			S=1
9	Possible service life (70-L (ight), 55-A (verage), 45-H (ard), 40-V (ery) H (ard))			P=50
10	Estimated damage due to the service life (DSL)			X_1=0,697
* Cracks considering repairs m/s		Quantity	Weight	Damage
11		0	0,5	0
12		1	0,15	0,15
13		2	0,03	0,06
** Curves, dents, etc.		Quantity	Weight	Damage
14		5	0,01	0,05
15	Calculated damage for cracks and deformations X_2=0,26			
16	Main beams (bottom chord, bottom walls)	5	0,03	0,15
17	Junction markers of supports and main beams	5	0,02	0,1
18	Global corrosion	3	0,01	0,03
19	Junction markers of supports and main beams X_3=0,28			
20	*** Subjective assessment of damage in points (1...10) X_4=5			

Notes:

* with a crack length up to 150 mm, count it as one, other wise count as two; if the crack zone is strengthen ed, then consider it as half;

** dents up to three thick nesses are counted as one, other wise as two;

*** no damages or the yare not dangerous (1–2 points), minor damages (3–4), medium and not dangerous damages (4–5), medium damages (6–7), significant damages (8–9), dangerous damages (9–10).

20 years). The following equation was obtained for resource prediction:

$$Y = 1{,}154 - 0{,}4X_1 - 0{,}202X_2 - \\ - 0{,}212X_3 - 0{,}049X_4, \qquad (6)$$

all coefficients are significant, the multiple correlation factor of 0,966 is quite large.

So, for example, for X_1=0,697; X_2=0,26; X_3=0,28; X_4=5,0 the result Y= 0,518 was obtained, which for the average operating mode gives the residual resource of $R_{res} = 0{,}518 \cdot 16 = 8{,}29$ year. However, this does not mean that in 3 years, when the next survey takes place, the residual resource will be 5,29 years. It may be 5 or 6 years, or less than 5 years.

If the estimated residual resource obtained is less than the period until the next survey, then additional research and calculations need to be made.

Table 2. **Results of calculating the probability of crack occurrence**

t*, *gr	**3**	**6**	**9**	**12**	**15**
Q(*t*)	0,0011	0,0041	0,0128	0,0234	0,0330
t, *gr*	18	21	24	27	30
Q(*t*)	0,041	0,063	0,0891	0,114	0,132

Destruction Probability Estimate of the Crane Metal Structure

The case of multi-cycle fatigue is considered, while as the main indicator of the remaining life-circle the resource is taken, given by two values: the operating time and the probability expressed in percentage (or relative shares) that during this operating time the limiting state of the structure will not be reached.

Fig. shows a diagram for determining the residual resource of the crane metal structure, taking into account the survivability stage.

$Q(t)$ is the probability of a fatigue crack in the structure, l — is the length of a fatigue crack, we can take $Q(t) = 0{,}05$.

At the moment ta, an instrumental assessment of the technical state of the structure is carried out (technical diagnostics), t_e — is the time to reach the estimated design life.

Thus, according to the scheme (Fig.), the residual resource is the difference between te and ta. It is proposed to calculate the function of durability (curve 1 in Fig.) in the time interval t_e-t_a.

It is necessary to take into account that in the considered cross-section, due to the action of stress amplitudes exceeding the initial fatigue limit, a gradual decrease in the initial fatigue limit of the structure durability occurs. And also, according to the results of non-destructive testing, it is now feasible to make adjustments in terms of reducing the area of the design cross-section and increasing the stress concentration due to a local effect as a consequence of corrosion of internal cavities of the crane metal structures.

In fact, the assessment of the residual resource for the indicated limiting state of the crane metal structure is based on predicting the degradation processes of the considered cross-section of the structure because of fatigue and corrosion damage. To make the final decision on the possibility of further operation of the crane metal struc-ture based on the residual resource calculation data, one can use a conservative decision-making scheme based on the relative resource indicator [7]:

$$N_r = N \;/\; N_c \,. \tag{7}$$

Here N_r — is the indicator of the relative resource; N_c — is the calculated number of loading cycles; N — is the actual operating time in loading cycles.

It is assumed that at N_r<0,8, the structure has a sufficient remaining life. If the condition 0,8<N_r<1 is satisfied, then the structure is located near the boundary of the safety area. For N_r > 1, the considered construction falls into the region of limited safety; in this case, it is necessary to perform an additional calculation of the structure resource at the stage of fatigue crack growth (graph 2 in Fig.).

Calculation of the Structure Resource at the Stage of Fatigue Crack Growth

To assess the relationship between the parameters of the loading mode and the rate of crack propagation in the structure section, we propose to use the well-known Peris-Elber equation:

$$V = \frac{dl}{dN} = A\left(\Delta K_{ef}\right)^n \tag{8}$$

where l — is the current value of the fatigue crack length; $\Delta K_{ef} = \left(\sigma_{i\max} - \sigma_i\right)\left(\pi \cdot l\right)Y$ — the range of the stress intensity factor; A and n — are constants of the construction material.

Based on the data of direct experiment, it is possible to calculate the rate of development of a fatigue crack in the considered section of the crane metal structure.

$$V_i = 7,899 \cdot 10^{-9} \cdot (\beta_i\, Y_i)^{2,4}\, l_i^{1,2}. \qquad (9)$$

By integrating expression (9) along the length, the fatigue crack growth function $l = f(N)$ is obtained.

Let's consider the calculation of the residual resource of the crane metal structure. The number of loading cycles n_i by stress σ_{ai}

$$N_i = t_i \times t v_\delta \qquad (10)$$

where v_δ — is the number of cycles in the load block (block size) within its accepted duration in units of durability (per year of operation).

Ratio showing the possibility of fatigue damage accumulation under the action of ai (X>1) or damage absence (X≤1):

$$X = \frac{\sigma_{ai}}{\sigma_{-1\,dam(i-1)}} = n_p \left(\frac{\sigma_{ai}}{\sigma_{a1}}\right) \cdot \left(\frac{\sigma_{-1Dor}}{\sigma_{-1\,dam(i-1)}}\right) \qquad (11)$$

The limiting loading coefficient is found by the method of successive approximations. Its initial value nll is taken in the interval [1...2]. The number of N_i loading cycles before failure under stress is — σ_{ai}: $N_i = N_r (1/X)^m$.

Endurance limit of the damaged part at the moment of action of the *i*-th stage of the load block

$$\sigma_{-1dam\ i} = \sigma_{-1dam\ i-1}\left[1 - (n_i / N_i)\ (X\ -1)K\right] \qquad (12)$$

where K — is a parameter characterizing the intensity of the decrease in the endurance limit due to the action of overloads $\sigma_{ai} > \sigma_{-1dam\ i-1}$.

Fatigue damage from the action of the *i*-th stress amplitude, expressed by the cyclic ratio: $Y = \frac{n_i}{N_i}$.

If for a given durability *t* at some *i*-th stage of stress X>1 and Y>1, then it means that the destruction for the accepted value of n_l occurs before the durability *t*, (to find the limiting loading coefficient n_l, its initial *nll* value needs to be reduced). If at some *i*-th stage of stress X<1, then this means that the accumulation of damages at this stage stops, there is no fracture during a given durability *t* (to find the limiting loading coefficient n_l, its initial value n_{ll} should be increased).

The quantile of the normal distribution, corresponding to the probability of destruction Q,

$$U_Q = \frac{(1-\tilde{n})}{\sqrt{\tilde{n}^2 v^2_{\sigma_{-1D}} + v^2_\varepsilon}}, \qquad (13)$$

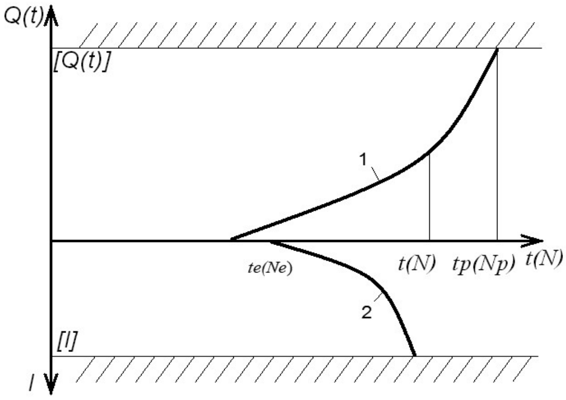

Fig. Diagram for determining the residual resource of the crane metal structure

where $\tilde{n} = n_p\, n, n\ = \sigma_{ai} / \sigma_{-1Dor}$ — is the average loading factor.

In a complex stress state with components σ (normal stress) and τ (shear stress), the reliability function can be estimated by the formula:

$$P(t) = P(t_\sigma) P(t_\tau), \qquad (14)$$

where $P(t_\sigma), P(t_\tau)$ — are the probabilities of non-destruction under the action of only normal and only shear stresses, respectively.

For the assessment, it is required to perform the calculation twice with the corresponding initial data for normal and shear stresses.

The probability of structural failure is determined by the dependence

$$Q(t) = 1 - P(t). \qquad (15)$$

The reliability of the crane bridge beam was calculated (curve 1 in Fig. 1) [8, 9]. In this case, the standard service life of bridge-type cranes was taken equal to 25 years [5]. The intensity coefficient of the endurance limit decreasing is assumed to be K = 1,33 [6].

It can be said that after 12 years of operation, the probability of fatigue crack occurrence exceeds the permissible value, considering the actual dispersion of the fatigue limit of the crane beam. After this service life-circle it becomes necessary to conduct an industrial safety examina-tion, including instrumental analysis with the subsequent calculation of the resource at the stage of fatigue crack development.

Conclusions

A method for assessing the residual resource, which facilitates to predict the loss of strength of a metal structure as a result of fatigue and corrosion damage is considered. After analyzing the results of calculating the structure persistence (curve 2 in Fig.), a decision is made on its further operation. If the results of calculating *Q*(t), with the consideration of the change in σ_{-1D} in terms of the coefficient of variation, exceed the value of the 25 years durability, then it is impractical to calculate survivability.

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ОЦІНКА НАДІЙНОСТІ МЕТАЛОКОНСТРУКЦІЙ ВАНТАЖОПІДЙОМНИХ КРАНІВ

Вступ. Актуальність досліджень методів подовження залишкового ресурсу зумовлена неухильним зростанням частки обладнання, що відпрацювало призначений термін служби. Задача оцінки залишкового ресурсу експлуатованого об'єкта включає в себе оцінку поточного стану, прогнозування цього стану в майбутньому, оцінку ймовірностей настання відмов, оцінку ризику аварійних ситуацій. На основі цього прогнозу встановлюється гранично-допустимий термін експлуатації обладнання, або призначається термін чергового контролю стану досліджуваного об'єкта.

На цей час при діагностуванні стану металоконструкцій використовується методи-ка, призначенням якої є візуальний огляд, визначення розмірів дефектів, інструментальний контроль тріщин і товщини металу, проведення статичних і динамічних випробувань металоконструкцій.

Мета — зменшити суб'єктивний фактор при прийнятті рішень про можливість пода-льшої експлуатації крана при черговому обстеженні.

Методи. Зменшення суб'єктивного фактору досягається за рахунок ранжирування факторів пошкоджень і поділу їх на три класи: пошкоджуваність від тривалості експлуатації, прояв пошкодження у вигляді тріщин і деформацій, пошкоджуваність від корозії.

Пошкоджуваність від тривалості експлуатації визначається аналітично з урахуванням наступних факторів: тривалості експлуатації, довжини прольоту, паспортного режиму роботи, реального режиму роботи, періоду роботи в реальному режимі та ін.

Пошкоджуваність у вигляді тріщин і деформацій та пошкоджуваність від корозії визначається з урахуванням кількості пошкоджень та їхньої ваги (значущості).

Для оцінки взаємозв'язку між параметрами режиму навантаження і швидкістю розвитку тріщини використовується рівняння Періса-Елбера. Визначено ймовірність руйнування конструкції.

Результати. Для визначення коефіцієнтів регресії було розглянуто стан 11 вантажопідйомних кранів і результати їхньої подальшої експлуатації протягом останніх 10 років. Розрахунковий ресурс задавався в частках від нормативного терміну до першого обстеження (10...20 років). Отримано лінійне рівняння для прогнозу ресурсу, в якому всі коефіцієнти значущі, а коефіцієнт множинної кореляції 0,966 є достатньо великим.

Здійснено розрахунок надійності балки моста крана, при цьому нормативний термін служби кранів мостового типу приймався рівним 25 років. Коефіцієнт інтенсивності зниження межі витривалості прийнято $K = 1{,}33$.

За результатами розрахунків можна стверджувати, що, якщо отриманий залишковий ресурс менше терміну до наступного обстеження, то необхідно провести додаткові дослідження і розрахунки.

Висновок. Розглянуто метод оцінки залишкового ресурсу, що дає можливість прогнозу втрати міцності металоконструкцій в результаті втомного і корозійного пошкодження. Після аналізу результатів розрахунку живучості конструкції приймається рішення про подальшу її експлуатацію. Якщо результати розрахунку $Q(t)$ з урахуванням зміни σ_{-1D} за коефіцієнтом варіації перевищують значення довговічності 25 років, то розраховувати живучість недоцільно. Необхідно відзначити, що вже після 12 років експлуатації ймовірність появи втомної тріщини перевищує допустиме значення та виникає необхідність проведення експертизи.

Ключові слова: *металоконструкція, надійність, пошкоджуваність, втомна тріщина, корозія, термін експлуатації, залишковий ресурс.*