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Influence of Structural Damping on the Durability of a Crane Metal Construction

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Abstract. The durability of the metal structure of a clamshell crane is predicted in two ways: by the hypothesis of linear summation of damage and using the model of cyclic degradation of the static properties of the material. In the second case, a conservative estimate of longevity is obtained for a quasi-random stress spectrum at the dangerous point of the span beam. A significant influence of structural damping on the service life of the crane has been revealed. Calculations by the developed algorithm are performed on an ordinary personal computer with a small expenditure of computer time.

INTRODUCTION

Previously, free damped vibrations of the span beam of a bridge crane were studied with a given logarithmic decrement [1]. This loading takes place during the starting braking modes of the travel mechanism. The calculation of the life of the beam according to the linear hypothesis of summation of fatigue damage was compared with the calculation using the model of cyclic degradation [2]. In [3], a significant effect of structural damping of a beam with a filler made of light foam on its durability was predicted. This study develops the approach to the evaluation of longevity discussed in [1, 3].

The results obtained make it possible to pass to the practically important case of loading with the amplitude and the asymmetry coefficient varying from cycle to cycle. For example, if the grab volume is accidentally filled with a bulk load, the stresses at a dangerous point of the bridge structure will also be a random variable. In addition, with each cargo lift, there are also free damped vibrations caused by acceleration and braking of the lifting mechanism. The number and amplitude of these vibrations and, consequently, the durability of the beam depend on the degree of structural damping. The method of deterministic estimation of the durability of the span beam of a grab crane is discussed in the paper in view of the joint action of a random spectrum of stresses from external loading and free damped vibrations.

CONSTRUCTING THE RHEOLOGICAL EQUATION OF HIGH-CYCLE FATIGUE

The phenomenological approach to the construction of the rheological equation of a degradation process is based on the experimentally established change in the static deformation diagram. The parameters of the diagram change when the change in the material properties occurs throughout the volume of the test sample. The theories of creep, long-term strength, hydrogen embrittlement, etc. are based on this principle [4-6]. In the tensile tests of cyclically trained standard samples there is no noticeable change in the diagram, therefore, it is impossible to establish a relationship between the static and cyclic properties [7, 8]. The reason for this is an exceptionally high localization of fatigue damage [9].

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In the theory of fatigue, in one way or another, a measure of fatigue damage is introduced ω and the equation of its change is written. As a rule, damage is determined formally, according to the linear hypothesis, as the ratio of the current number of cycles to the limit one,

$$\omega = \sum \frac{n}{N}, \tag{1}$$

the equality ω=1 being a criterion for fatigue fracture.

It is possible to calculate damage only in the simpliest cases. In [3], the cyclic damage ω_C of the model sample was considered from the position of the structural-phenomenological approach and estimated by the relative number of structural elements destroyed by fatigue. A formula is obtained that relates structural damage ω_C to a macroscopic parameter, namely, to ultimate strength,

$$S_B(\sigma_M, \mathrm{n}) = (1-\omega_C)S_{B0}, \tag{2}$$

where σ_M =const is the maximum stress of a steady-state cycle.

It is extremely difficult to calculate the damage ω_C of a real structural material. It is proposed to determine it from the results of fatigue tests of small thin-walled samples with the construction of a complete static diagram with a branch descending to zero [3]. It is shown that, in the case of regular loading, tensile strength becomes a function of maximum cycle stress and the number of loading cycles, and it is approximated by the exponential function

$$S_B(\sigma_M; n) = S_{B0} - \frac{S_{B0} - \sigma_M}{N_R^m} n^m, \tag{3}$$

where the S_{B0} is the ultimate strength of the untrained material, *m* is the experimental constant, which is close to two for the materials under study. The coefficient k_S is found from the condition of fatigue failure of the sample when the strength is reduced to the level of the maximum cycle stress,

$$S_B(\sigma_M; N_R) = \sigma_M, \tag{4}$$

where N_R is the durability of the fatigue curve constructed by the condition of crack initiation with the asymmetry coefficient *R*.

Substituting function (3) into formula (2), we obtain the expression for cyclic damage in the Corten–Dolan form

$$\omega_C = \frac{S_{B0} - \sigma_M}{S_{B0}} \left(\frac{n}{N(\sigma_M)} \right)^m. \tag{5}$$

Formula (3) defines a family of kinetic curves parametrized by the value of the maximum cycle stress. In the case of nonstationary loading, the stress change is treated as a transition from one kinetic curve to another with the condition that the damages are equal.

In the calculation of welded structures, the basic endurance limit σ_{-1KB} is set depending on the material of the welded joint, the type of the weld and the combination of loads [10], the endurance limit for a symmetric cycle based on N_0=2·10^6 being calculated by the formula

$$\sigma_{-1K} = \sigma_{-1KB} \left(\frac{t_B}{t} \right)^{0,2}, \tag{6}$$

where *t* is the thickness of the element, t_B= 20 mm.

The endurance limit for an arbitrary asymmetry coefficient is calculated by the formula

$$\sigma_{RK} = \frac{2\sigma_{-1K}}{1 - R + \psi_K(1+R)}. \tag{7}$$

Since the kinetic curve (3) was constructed for a pulsating stress cycle, all the cycles of the spectrum are reduced to the same from,

$$\sigma_{ri} = \sigma_i \frac{\sigma_{-1K}}{\sigma_{RKi}}. \tag{8}$$

The fatigue curve is assumed to have the conventional from

$$\sigma_{RK}^{\alpha} N_0 = \sigma_i^{\alpha} N_i. \tag{9}$$

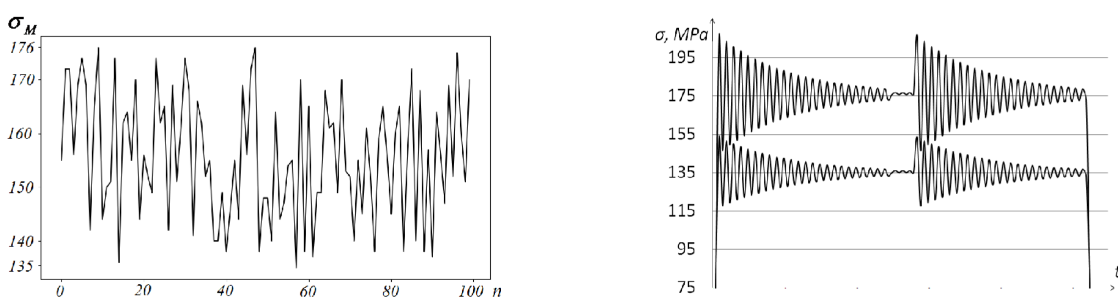
Thus, in the methodology for calculating the longevity with allowance for cyclic degradation, along with the original part, the experimental data accumulated in the long-term studies of the phenomenon of fatigue are also involved.

A PROCEDURE FOR CALCULATING THE DURABILITY OF THE SPAN BEAM OF A BRIDGE CRANE

The random nature of loading is due mainly to the random value of the weight of the bulk load in the grab, and the free vibrations are caused by the acceleration of the start-brake modes.

The first stage of the calculation consists in determining the stress-strain state of the span beam by the finite element method and hot points with stress concentrators. In the example, a point is chosen in the lower girdle of the beam near the diaphragm near the dangerous section, where the welds intersect. In engineering calculations of the durability of cranes, only normal stresses are taken into account [10]. The calculated stresses at the dangerous point of the flying beam were 74 MPa for an empty crane, 176 MPa for a complete filling of the grab, and 135 MPa for a minimum filling. The initial amplitude of free oscillations is calculated from the dynamic coefficient, which is equal to 1.3 [10]

The second stage is related to the random character of the maximum stresses on the interval of their variation $\sigma_M \in [135,176] MPa$ (Fig. 1a).



(a) (b)

FIGURE 1. The maximum stress spectrum σ_M obtained using the function of random numbers (a); a global cycle with two random stress values σ_M (b)

The higher the stress, the higher the initial amplitude of free vibrations.

The third stage reflects the essence of the procedure, and it consists in a sequence of the following actions: for the first cycle of random stresses with a given value σ_M, the asymmetry coefficient *R* and the initial amplitude σ_0 of free vibrations are found; a tabular value of the endurance limit σ_{-1K} is set and a correction for the scale effect is introduced using formula (6); a limited endurance limit σ_{RK} is found by formula (7); the cycle is reduced to symmetric (8); durability *N* is found by formula (9) at a given value of *α*; damage is determined by the linear hypothesis $\omega_L = 1/N$; defects are determined by formula (5); the current value of tensile strength is found by formula (3), adapted to nonstationary loading; a new value of ultimate strength after the completion of free vibrations is found by the built-in algorithm; if the current tensile strength is higher than the maximum stress of the next cycle, a transition to a new kinetic curve is made based on the equality of cyclic damage.

NUMERICAL EXPERIMENT RESULTS

The fourth stage of the technique consists in plotting cumulative damage curves ω for different values of the logarithmic decrement, with comparing the sought-for durabilities N_G expressed in global cycles or cargo lifts (Fig. 2). The graphs indicated by primed digits are plotted according to formula (1), and the graphs marked by digits without primes are plotted by formula (5).

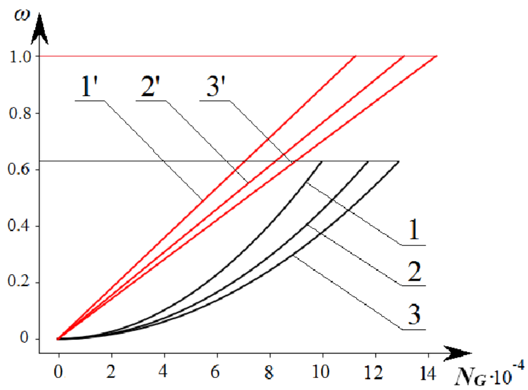


FIGURE 2. Damage for different values of the decrement: 1 – δ = 0.05; 2 – δ = 0.1; 3 – δ = 0.2

Structural damping increases the predicted life cycle of the crane by 30 thousand lifts (curves 1 and 3 in Fig. 2). The model of cyclic degradation gives a conservative prediction of durability in comparison with the linear hypothesis, this being associated with the introduction of the criterion of fatigue destruction in the form of Eq. (4).

CONCLUSION

A relatively simple mathematical formalization in the description of the degradation process makes it possible to carry out a cycle-by-cycle calculation of beam damage on an ordinary personal computer and to provide a deterministic estimate of longevity. The increase in the safe number of cargo lifts by 30,000 when the beam is damped with foam, when the decrement increases from 0.05 to 0.2, should be considered significant. The predicted number of lifts according to the cyclic degradation model is 10% lower than according to the rule of linear summation of fatigue damages. With a decrease in the thickness of the beam cross-section stack, this effect is enhanced.

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