Methods of determining the margin of cyclic crack resistance of metal structures for hoisting machinery

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Abstract. In the course of manufacturing and operation, there can appear cracks in load-carrying metal structures which are hard to be detected till a definite moment. That is why in the course of designing metal structures, it is necessary to ensure their durability during possible existence of cracks up to the next routine inspection of a structure. For the prognostication of the durability of a structure with a crack, a research of coefficients of stress intensity on end-element models with crack-like defects of different length is carried out. As a result of this, a procedure for the definition of crack-resistance resource allowing the supposition of safe operation of a metal structure with a crack within the limits of recurrent routine works is developed.

1. Introduction

Both technological and fatigue cracks can appear in parts of load carrying metal structures in hoisting machines during production or operation processes. The resistance of metal to structure crack propagation is called fracture toughness.

The known concept of secure damage is based on the assumption that in any metal structure, even in new, there are always defects that may remain long undetected. Dimensions of detected defects are determined by resolution of applicable testing aids. All defects which are beyond the scope of testing aids remain undetected and, when present in the metal structure, they are potentially dangerous for metal structure operation.

To assess the vitality and the remaining life of metal structures, as well as to assess the impact of technological and operational defects on their load-bearing capacity, we must have a calculation device to predict behavior of metal structures with cracks under operational loads, which includes methods of fracture mechanics using the stress intensity factor (SIF) as the main characteristics of the stress and strain state of the material near the crack tip. The value of SIF may be found, for example, by reference data [1, 2] or by numerical methods. However, SIF guides do not contain practically any solutions to the cracks in the spatial objects of box-section typical for parts of metal structures of hoisting machines. In the paper presented this problem is solved on the basis of the end-element modeling of structures with crack defects with the purpose of the assessment of metal structure durability at the stage of designing.

2. Simulation of the stress and strain state at the tip of the fatigue crack

Many scientists were engaged in the solution of problems concerning cracking and fracture of load carrying metal structures of machinery, with the use of the finite element method as well [3-7]. In this study, finite element models of metal structures with box-section design were built to calculate the stresses in the vicinity of the crack tip and SIF in the automated design system and in the analysis of automated workstations WinMachine. These constructions are typical for the type of bridge cranes, which are the most common means of mechanization of cargo handling, transport and warehousing operations during various types of production and warehouse complexes [8]. In the bearing section models, simulated crack-like defects of different lengths were simulated.

When constructing models and studying the stress and strain state, some measures were foreseen. They allowed one to improve the accuracy of the solution, namely, small discretization was carried out during the crack tip partition into small elements; at points located at different distances r from the crack tip, the values of stress intensity coefficient K_I were determined by calculation; diagrams of K_I dependence on r were built. Required value K_I corresponding to the considered crack is defined as a result of extrapolation when $r \rightarrow 0$. When carrying out extrapolation, we exclude values K_I, corresponding to the points which are most closely located to a crack.

In the current study, the values of SIF were found for normal separation cracks by extrapolating the graph of function $K_I(r) = \sigma(r)\sqrt{2\pi r}$ at point $r = 0$, where $\sigma(r)$ is stress at distance r from the crack tip. The linear extrapolation is carried out within the zone of accumulation of elastic-plastic fractures [9], where the stress partially exceeds yield stress σ_T.

As a result of numerical experiment, stress values and SIF have been determined under rated stresses in the considered section of the metal structure equal to 50, 75 and 100 MPa, respectively.

The obtained SIF values were approximated by polynomial functional dependencies $K_I(\alpha)$ (figure 1):

- at 50 MPa: $K_I(\alpha) = 4.1908 + 181.1681 \cdot \alpha - 136.3966 \cdot \alpha^2$;

- at 75 MPa: $K_I(\alpha) = 10.4058 + 122.5162 \cdot \alpha + 442.216 \cdot \alpha^2$;

- at 100 MPa: $K_I(\alpha) = 12.0978 + 210.3875 \cdot \alpha + 225.2415 \cdot \alpha^2$,
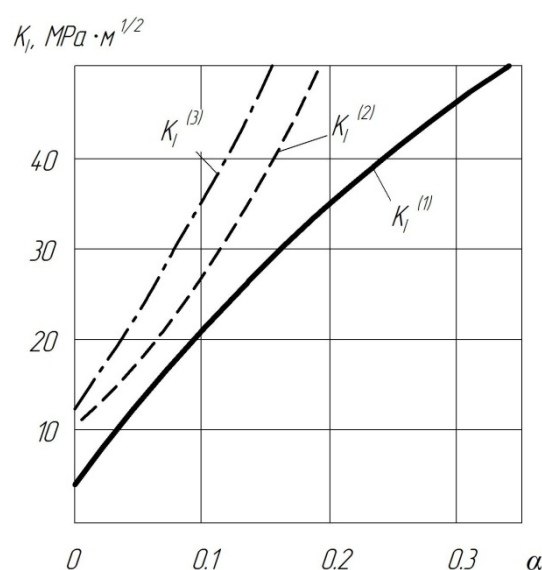
where α – incremental dimension of the crack.

Figure 1. Experimental functions

$K_I^{(1)}(\alpha)$ – at 50 MPa,

$K_I^{(2)}(\alpha)$ – at 75 MPa,

$K_I^{(3)}(\alpha)$ – at 100 MPa

The diagram of SIF changes for different lengths of crack-like defects at a nominal level of the current stresses of 50 MPa is presented in figure 2.
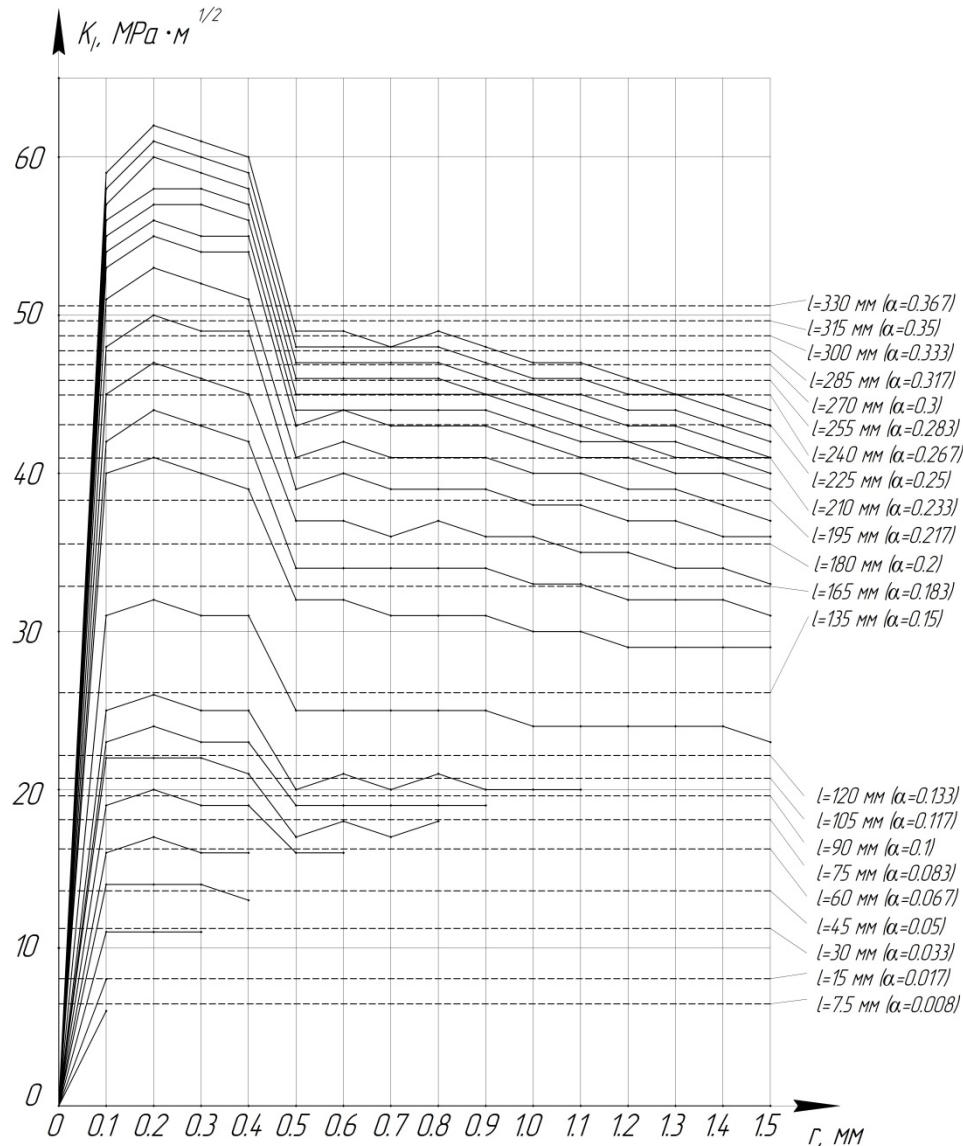

Figure 2. Charts changes of SIF: l – the cracks length, α – the relative size of the crack, r – the distance from the crack tip.

The margin of crack toughness of a metal structure under cyclic loading is characterized by the number of cycles required for the crack growth from initial size a_0 to critical a_c. If the cycle of stress changes in the crack location is of constant signs, then modeling and planning of the process, operational load of a metal structure are exercised by the method described in [10].

3. Forecasting methods of structure durability with a crack
Engineering assessment of the crack toughness margin is performed in the framework of the settlement system at the ultimate limit states, so we must enter the relevant factors that will ensure the reliability of this assessment. The number of crane working cycles up to failure Z_a when the crack growth occurs to a critical size is defined by the formula:

$$Z_a = \frac{\gamma_{dN}\left(\gamma_n\gamma_m\Delta K_0\right)^q \cdot P}{\zeta_{ea}V_0 \cdot K_I\left(\alpha\right)^q}\int\limits_{a_0}^{a_c}\frac{d\alpha}{K_I\left(\alpha\right)^q \cdot \alpha^{q/2}} \qquad (1)$$

where γ_{dN} is the coefficient of reliability of calculation methods; γ_m is safety factors as an intended design or a part of the structure; γ_m is safety factors according to characteristics of the material; ΔK_0, q, V_0 are parameters of the Paris's equation (ΔK_0 – amplitude of the stress intensity factor (SIF); $\Delta K_0 = 0,005\sigma_B - 9$; q, V_0 are empirical constants ($q = 3$, $V_0 = 10^{-7}$ м); P is a sectional perimeter with a crack; ζ_{ea} is a cyclic loading rate; $K_I\left(\alpha\right)$ is a function of SIF changes from the relative crack length; a_0, a_c is the initial and relative size of the crack.

By results of modeling and calculation, dependence graphs of durability of a metal design from a relative length of a crack are constructed (figure 3).
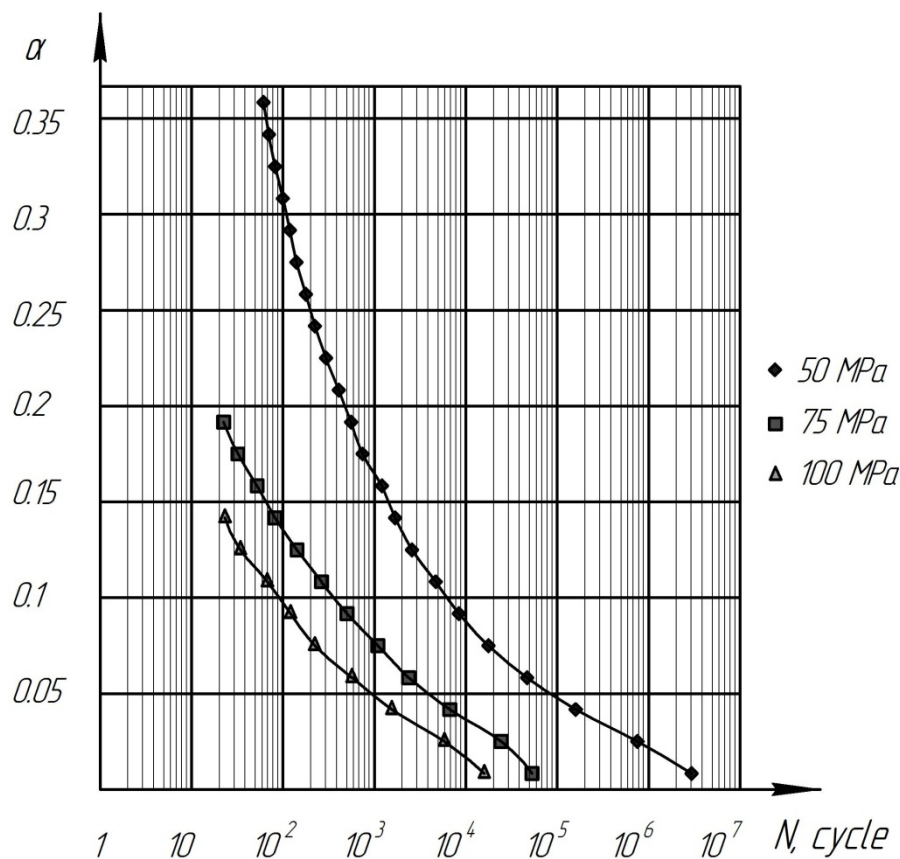

Figure 3. The dependence graphs of durability of the relative crack length.

The condition of safe operation of the crane for the period between its complete engineering certification (CEC), met once per every three years within the limits of standard service life, looks like:

$$Z_a \geq Z_d = n_c n_s n_d N , \qquad (2)$$

where Z_d – number of loading cycles for the period between complete technical examinations; n_c – number of cycles per shift; n_s – number of shifts per day; n_d – number of working days a year; $N = 3$ years – the period of operation of the crane between complete technical examinations.

4. Conclusion

According to the study results, the following method of forecasting of the crane safe operation can be offered for a period of up to the next full technical inspection:

1. Current stresses at different load levels are computed.

2. Depending on the level of nominal stress in the most dangerous section, this or another dependence $K_I(\alpha)$ is accepted

3. According to formula (1), the value of the crack toughness margin is calculated, Z_a.

4. The margin of crack toughness Z_a is compared with the permitted number of cycles Z_d (the interval between the crane complete engineering certification (CEC)). If $Z_a \geq Z_d$, so the crack toughness condition is met, which means that even by an undetected crack at the technical inspections of metal structure of the bridge crane will serve Z_a cycles. And if $Z_a < Z_d$, then we need to make structural changes into the metal structure to ensure the fulfilment of condition (2).

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