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On the Control of Metal Strength of Structural Elements of Floating Cranes

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Introduction. The article is devoted to the issues of non-destructive testing of mechanical characteristics of metal structural elements of cranes. The reliability of cranes largely determines their safety. The main manifestations of operational failures of floating cranes are analyzed on the example of the UMK-2 crane. It is noted that 27% of failures occur due to the loss of metal strength of their structural elements. Determination of the causes of such failures is possible by conducting non-destructive testing of the mechanical characteristics of the failing structural elements metal. The paper provides the principle of one of the methods of non-destructive strength control based on the impact insertion of a conical indenter into the metal under study with the subsequent analysis of the intermediate parameters of this insertion. The results of measurements of the mechanical characteristics of the metal deformed during the operation of the boom strut of a floating crane are given. The current measured values of the mechanical characteristics of the metal obtained at various points of the strut are processed for compliance with the three-parameter Weibull law to obtain the minimum values of these characteristics. As a result of such processing, it is stated that the minimum values of yield strength, strength and elongation are lower than those claimed by the design documentation for the crane. This may be one of the reasons for the deformation of the structural element during operation.

Problem Statement. The application of the method of non-destructive testing of the metal of the boom strut is considered in order to assess the mechanical characteristics and establish possible causes of its deformation when analyzing the operational reliability of the crane.

Theoretical Part. When identifying possible causes of deformation or destruction of steel elements of crane structures, it is proposed to apply a method of non-destructive testing of mechanical characteristics based on the impact insertion of a conical indenter into the test surface. Further, it is proposed to process the obtained sample of values of the measured characteristic for compliance with the three-parameter Weibull law to estimate the shift parameter or the minimum value of this characteristic.

Conclusions. The minimum values of the tensile strength, yield strength and relative elongation of the metal of the deformed boom strut of the UMK-2 crane were obtained on the basis of the application of the method of non-destructive testing with subsequent approximation of statistical information by the Weibull distribution law. A conclusion was made about the reduced strength characteristics of the metal relative to those stated in the technical documentation, which could cause deformation of the crane boom element.

Keywords: reliability, mechanical characteristics, lifting cranes, non-destructive testing.

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Introduction. Lifting cranes are high-risk industrial objects, as a result of which particularly high requirements are imposed on their safety, largely determined by operational reliability. From the analysis of works devoted to the reliability of floating cranes [1-3], it follows that 22% of failures are caused by violation of rules of operation, 27% of failures are associated with a leak in the hydraulic system and 51% — the share of failures due to the physical and mechanical properties of the metal of structural elements, of which: 24 % — failures due to wear (rope, support rollers, bearing assemblies, elements of the rope-and-pulley system, brakes, etc.) and 27% of failures are because of the loss of metal strength (destruction of the base metal and welds, as well as excessive deformation of the elements of the boom metal structure, contact deformation of support rollers and hooks, etc.).

At the end of 2021, the staff of the Department of "Operation of Transport Systems and Logistics" of the Don State Technical University conducted a survey of the technical condition of the UMK-2 floating crane, which was used during the dismantling of the old and the construction of the new Voroshilov Bridge over the Don River in Rostov-on-Don, as well as on other water bodies where the work could be performed by a floating crane. When examining deformed metal structures, according to [4], it is necessary to pay attention to defects that lead to a decrease in the load-bearing capacity of the structure, namely: deviation from the straightness of the struts of truss elements, twisting of structures, misalignment of the joints of boom sections, towers, the presence of residual deflections of span beams, etc.

As a result of the survey, it was revealed that the main failures that occurred with the crane occurred on the boom, namely for the following reasons: deformation of the metal of the boom strut, cracks in the middle part of the boom root section, cracks in the welds of the boom root section, cracks in the boom hook pulley block, defects in the boom strut part that were deformed, as a result, the crane was decommissioned.

Problem Statement. The task was to investigate the cause of damage to the metal elements of the boom structure. In general, there are three possible reasons: insufficiently accurate calculation of the boom design, non-compliance of the strength characteristics of the steel grade used with the required ones, in accordance with the design documentation, and overloads during operation of the machine. The first reason is unlikely, since the UMK-2 crane was designed in the mid-70s in Soviet times and, as a rule, with a sufficient material reliability coefficient. In order to establish the second and third reasons, it was necessary to determine the strength capabilities of the applied metal of the damaged boom element. Determination of the mechanical characteristics of the metal of the operating machine is possible only by non-destructive testing.

Theoretical Part. Most methods of non-destructive testing — ultrasonic, radiation, magnetic, eddy-current, acoustic emission, etc. provide an opportunity for qualitative, rather than quantitative assessment of the condition of the object under study. Therefore, it was decided to apply the method of non-destructive testing of metal developed at the Don State Technical University to obtain quantitative values of its mechanical characteristics. The method is implemented in the "Durability" system [5–8], consisting of an electronic unit including an analog-to-digital converter L-CARDE 14-440, an impact mechanism and a laptop with a software [9].

It is based on a modified Rockwell hardness estimation method, while static indentation is replaced by dynamic indentation with impact energy of 0.16 J, and the angle at the top of the indenter is replaced from 120° to 90° for more informative measurement results. Impact indentation is carried out due to a spring mechanism in which the striker strikes the indenter holder. At the same time, the electronic unit records intermediate parameters: depth, maximum and minimum speeds, acceleration and deceleration of the indenter during its introduction into the material and transfers them into the mechanical properties of the material.

The creation of the system was preceded by long-term studies of the mechanical characteristics of a large number of steel grades of various strength classes. As a result, correlations of intermediate characteristics of the material image, standard yield strength and elongation strength and hardness were obtained.

After filling the electronic unit with these dependencies, it is enough to measure the newly studied material and the values of standard mechanical characteristics are displayed on the screen of a laptop with the developed software. The system has a total dispersion caused by the spread of properties in the metal and the measurement error. The limit values of the error of one measurement by the system are ± 4%.

Discussion. The metal of the deformed boom element was subjected to control. The surface was cleaned from paint and corrosion to pure metal, 10 to 15 measurements were made at various points of the element with a one-time registration of mechanical characteristics.

In accordance with [10, 11], the distribution of random values of mechanical characteristics obtained as a result of measurements is best described by the three-parameter Weibull law.

$$F(X) = 1 - \exp[-((X - C)/A)^{B}], \qquad C < X < \infty,$$

where X — the magnitude of the mechanical property; A, B, C — the scale, shape and shear parameters.

The most important parameter of this distribution is the shear parameter or the minimum value of the mechanical characteristic.

For this reason, the data obtained at different points of the element were combined into one array (Table 1) and then processed using a program for compliance with the three-parameter Weibull law.

Table 1

Array of data subject to processing

Measured current values of mechanical characteristics, ranked in ascending order of strength characteristics		
Values of yield strength $\sigma_т$, MPa	Values of tensile strength $\sigma_в$, MPa	Values of elongation δ_5, %
301	431	26
303	437	25
310	439	24
312	445	24
313	451	24
314	453	23
315	455	23
316	457	23
317	458	23
318	459	23
322	460	22
322	460	22
322	460	22
323	461	22
326	461	22
329	461	22
335	462	22
338	462	22

Measured current values of mechanical characteristics, ranked in ascending order of strength characteristics		
Values of yield strength $\sigma_т$, MPa	Values of tensile strength $\sigma_в$, MPa	Values of elongation δ_5, %
340	464	21
342	468	21
345	470	21
347	471	21
348	479	20
353	482	20
351	492	19
352	499	19

Approximation of the empirical values of yield strength $\sigma_т$, tensile strength σв and elongation δ_5 was carried out using the methods of moments and maximum likelihood with the fitting criterion ω^2 (Table 2).

Table 2

Approximation of empirical values of mechanical characteristics

Mechanical characteristics	Distribution parameter			Approximation method	Value of the fitting criterion ω^2
	Scale parameter "A"	Shape parameter "B"	Shear parameter (minimum characteristic value) "C"		
$\sigma_т$	47.29	2.89	285 (MPa)	Moments	0.49
	37.41	2.32	294 (MPa)	Maximum likelihood	0.51
σв	38.91	2.44	427 (MPa)	Moments	0.77
	43.22	2.76	423 (MPa)	Maximum likelihood	0.73
δ_5	5.45	3.17	17,3 (%)	Moments	0.51
	5.14	3.04	17,6 (%)	Maximum likelihood	0.52

According to the test results, the following was found. When assessing the yield strength, the criterion of the value ω^2 is slightly lower according to the method of moments, which corresponds to a minimum value of 285 MPa. When assessing the tensile strength, the value of the criterion ω^2 is lower according to the maximum likelihood method and this corresponds to a minimum value of 423 MPa. When assessing the relative elongation, the value of the criterion ω^2 is slightly lower according to the method of moments and this corresponds to a minimum value of 17.3%.

Let us note that in all cases the shape parameter "B" had a value exceeding 2, which also indicates the consistency of the distribution of the current measured values with the Weibull distribution.

Conclusions. The design documentation for the manufacture of the UMK-2 lifting crane specifies the material of the boom strut steel 09G2S. This steel must have mechanical characteristics values not lower than: $\sigma_т$ = 345 MPa; $\sigma_в$ = 490; δ_5 = 21%. That is, the minimum values of the mechanical characteristics of the tested material are inferior to the declared corresponding values for 09GS steel in yield strength by 17%, in tensile strength — by 14% and in elongation — by 18%, which may be one of the reasons for the plastic deformation of the boom strut.

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N. L. Vernesi — statement of the problem, development of the concept of the article; V. A. Rusakov — critical analysis of the literature, collection and processing of statistical data.