Assessment of the influence of variable loads on the strength of welded joints of metal structures of bridge cranes

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Abstract. The article considers the assessment of the influence of dynamic effects on the calculation of welded joints of metal structures of bridge cranes operating under the influence of variable loads. Requirements for the dynamic characteristics of load-bearing elements of cranes are determined by the specifics of operation, design features and operating conditions of cranes operating under variable loads. Thus, it is proposed to perform calculations of welded joints of bridge cranes for endurance, operating under non-stationary variable load, based on the principle of linear summation of damages, which allows calculating in terms of load equivalent to the entire range of operational loads.

1. Introduction
Currently, [1-5] ensuring the reliability, safety of machines and efficiency at all stages of the life cycle, from the choice of a design solution to the decision on decommissioning or extending the service life is one of the main goals of studying the dynamic impact, stress state and strength of load-lifting machines. In works [3-8], we consider the influence of dynamic processes on the elements of metal structures and mechanisms of lifting cranes during their non-stationary operation: starting, braking, hitting the crane on the stops, etc.

Thus, the main directions in studying the dynamics of cranes are studies to ensure the strength and reliability of load-bearing structures, which are traditionally given great importance, primarily due to the potential danger in operation, the uniqueness of design solutions and the complexity of operating modes in conditions of intensive technological processes of various industries. Such works are designed to perform the task of finding ways and measures to reduce accidents. Based on the analysis of materials of investigation of causes of accidents [9, 10], three main groups of causes of accidents cranes: first, the inadequate security of the state structure of the valves; secondly, the mismatch of the requirements for the installation and dismantling; third, violation of safe operation conditions. As shown by the materials given in [9-12], crane structures are usually destroyed in the most loaded nodes, in which cracks are formed during operation. The results of long-term operation of various types of cranes allow us to conclude that the least reliable nodes are complex welded structures with places of significant stress concentration, which makes it difficult to calculate the stress state. In this regard, it is important to extend the service life, improve safety and develop new, effective methods for diagnosing cranes in General, as well as its mechanisms and metal structures. Another important
direction in the study of the dynamic characteristics of cranes is the diagnosis, testing and methods of automated monitoring of metal structures, steel ropes and other components and aggregates of cranes. Another important area of research is aimed at ensuring the safety [13-16] of lifting cranes, taking into account structural and technological methods.

2. Formulation of the problem
The most important task at present is the introduction of CAD systems [17-20] in the production [19], construction [18] and repair of cranes, the use of the finite element method [17, 20] for calculating the spatial strength of crane metal structures. These measures allow you to achieve the required technical level of creating lifting machines in General, protection systems and control of the crane by providing a degree of automation of the crane control, which allows you to effectively use the power and speed capabilities of the crane design. For designers of crane equipment, the following ways of development can be formulated: unification of crane equipment [7, 12], modular structure of the crane [4]. The most relevant research tasks at the moment based on the above can be formulated as follows:

- development of ways to reduce the impact of vibrations and vibrations that occur during the operation of the crane, which will extend the standard period of operation of the crane;
- taking into account the observed trend of automated control of the operation of cranes, it is advisable to analyze the impact of automatic speed control of working movements, with an increase in the load or different values of the departure of the lifting body in order to reduce the maximum load on the crane in dynamic modes of its operation;
- development of a methodology for organizing strict, multi-stage input control and testing of parts, components, units entering repair or mass production in order to meet the required characteristics;
- development of a comprehensive diagnostic method performed after major repairs or upgrades of lifting machines to check the effectiveness of the repair, which will make it possible to instantly assess the quality of work performed and will minimize the number of unjustified failures during the post-repair run-in; search for design solutions for crane structures and control systems that will ensure the performance, safety and reliability of lifting cranes.

3. Theory
For the calculation of metal structures and their elements by the method of permissible stresses, certain combinations of loads are set [11, 13, 21].

The cycle asymmetry coefficient is determined [6] based on the stress \( \sigma_{\text{min}} \) when the cart is unloaded one quarter of the span from the bridge support; based on the stress \( \sigma_{\text{max}} \) when the cart is loaded, corresponding to the maximum moment for the beams.

In the design calculation of crane beams of metal structures, the required values of the moments of resistance of their dangerous cross-sections relative to the vertical and horizontal axes are determined [7, 12]. Since it is possible to provide values of resistance moments for many sizes of belts and walls, the design usually takes a ratio of sizes that reflect the experience of designing, manufacturing and operating cranes.

For beams used in metal structures [19] (Figure 1, a), the thickness of the belts (horizontal shelves),
and especially the thickness of the vertical walls, are small in comparison with the cross-section of the beam-height and width. Therefore, such beams are usually considered thin-walled [15].

The highest beam height is limited by optimization conditions, and the lowest - by the deflection or damping time of the bridge vibrations. The thickness of the vertical wall \( \delta_2 \) (Fig. 1, a) is determined from the conditions of its stability and strength. The minimum wall thickness is 6 mm, while the crane is operated under conditions of increased corrosion - 8 mm.

Optimal designs should be considered those that have a minimum amount of manufacturing and operation costs when working reliably.

Since the cost of a structure is determined mainly by its mass (the cost of material is approximately 70% of the total cost of a metal structure), the main criterion of optimality for cranes can be taken as the mass of the structure.

The paper shows that the minimum weight of a crane bridge can be taken as the working criterion of optimality. thus, the lowest costs are incurred in the manufacture of a beam according to the variant (Fig. 1, b), which has a mass of 24%, and the labor intensity is 10% less [].

The effective stress concentration coefficient \( k \) is taken depending on the type of metal structure element, the characteristics of the design section and the element material.

Calculation of metal structures by the method of limit States is performed in order to prevent the occurrence of limit States during the operation of the crane during the entire service life.

The calculation determines the standard loads, which are the maximum forces of the working state, determined in accordance with the technical conditions or based on experience in the design and operation of cranes.

The calculated forces are usually considered when determining the first limit state for the following load combinations:

- the main combinations of loads that are constantly active and regularly occur during the operation of the crane;
- additional combinations, which are combinations of main loads with additional, irregular loads (wind, installation, etc.).
- special combinations, which are combinations of basic loads with additional loads; the latter include loads that are characterized by special effects and occur in exceptional cases (shock, emergency, seismic).

To allow for a lower probability of matching design loads with more complex combinations, the combination coefficient \( \psi<1 \) is usually entered.

Due to the fact that the design loads and coefficients of working conditions accepted for endurance calculations using the method of limit States cannot be definitively established, the verification calculation of the main beams for endurance and strength is performed using the method of allowable stresses.
At the end beams, sections located at the junction with the main beams are calculated, as well as sections near the attachment points of the boxes.

When calculating the main beams of bridge cranes for vertical loads, the beam is considered as a two-support freely supported, loaded with concentrated forces in the middle part of the span and evenly distributed load. In this case, only the average cross-section of the beam should be calculated for bending (more precisely, the cross-section in which the maximum bending moment occurs), replacing the calculated beam with two equivalent half-length beams.

When calculating a two-girder bridge for the effect of horizontal inertial loads, each main beam is considered as a two-support beam with the ends of the final stiffness sealed. This takes into account the action of concentrated and distributed loads, and two sections are calculated for bending: located in the middle of the span and located near the end beam. In this case, the main beam is replaced by four equivalent beams: two internal ones (i.e. located near the middle of the span and having a common seal in the middle section of the main beam) and two external ones located near the end beams and sealed in the end beams.

Since the calculated lengths of equivalent beams reflect the diagrams of bending moments and, consequently, their equations, it is most convenient to determine these lengths in the form of moment ratios based on linear (when taking into account concentrated forces) or quadratic (when taking into account distributed loads) dependencies.

When calculating bridge cranes, the main beams are usually checked for static and dynamic stiffness. The static stiffness calculation consists of checking the relative static deflection, and the dynamic stiffness calculation consists of checking the vibration damping time. For the second limit state for the development of excessive deformations or vibrations, the limit conditions of static and dynamic stiffness have the same form as when calculating by the method of allowable stresses.

4. Results

The distribution of stress in a point connections. The stress concentration in point connections increases with the growth of the $t/d$ ratio, where $t$ is the distance between points in the direction perpendicular to the action of the force, and $d$ is the diameter of the point.

The concentration coefficient is within the range of $0.62 t/d < a < t/d$, where $a = 0.38 + 0.62 t/d$.

The forces at individual points of connection located in a longitudinal row, when they work in the elastic region, are not the same. The extreme points are much more heavily loaded, and as the number of points in the longitudinal row increases, the disparity increases. Beyond the limits of elasticity, there is an equalization of forces. However, under variable loads, point connections have low strength, since local stresses are much greater than the calculated ones within elastic deformations.

You should be careful and allow such loads only in full confidence that the material is not capable of delamination, and the mechanical properties in the direction of thickness correspond to the level stipulated by the technical requirements.

Strength of the base metal of welded joints under variable loads. The calculation of the fatigue produced under the action of vibration or variable loads, is characterized by a large frequency of occurrence of not less than 10-3 times. In this case, the calculation of endurance is reduced to determining the strength of structures under the action of such variable loads. To perform an endurance calculation, you need to know the appropriate value of the endurance limit. The endurance limit of the structural element-$\sigma_r$, $k$ depends on the characteristics of the load cycle, on the properties of the material and on the shape of the element itself. The value of the endurance limit is determined experimentally. Let's consider some General concepts on the example of the action of vibration load on various structures of machine-building type. In this case, the change in the load value that occurs from the impact of rotating machine parts is characterized by a certain regularity (Figure 2, 3).
When a variable load is applied, structural elements can be destroyed under loads that are less than the yield point. In this case, the highest value of the stress of the variable load that causes destruction $\sigma_{\text{max}}$ will depend on the number of load cycles. The dependence of the amount of destructive stress on the number of cycles is expressed by a curve called the Weller curve, shown in the figure on the right. This relationship shows that at a certain stress limit, failure will not occur even with a very large number of cycles. This stress, defined for a given number of cycles (called the test base), is called the endurance limit (or fatigue limit).

For steel samples, the test base is assumed to be $N = 10^7$. For aluminum samples, it is much larger and equal to $N = 5 \times 10^7$. Such a large value of the test base is appropriate for parts of machine-building structures, which in the course of their work can be exposed to a very large number of variable load cycles. For metal structures in many other industries and construction, the number of variable load cycles can be significantly smaller. For example, it is assumed that for hull structures, the number of cycles of variable load for the entire period of their service does not exceed $N = 10^6$; for bridge structures, $N = 2 \times 10^6$. The same value is typical for crane metal structures. In this regard, for such structures, the conditional limit of endurance is determined at a much smaller base. Usually in these cases, the base $N = 2 \times 10^6$ is accepted.

Depending on the characteristic of the cycle $r$, which is the ratio of the minimum value of stresses from the vibration load to their maximum value, the value of the endurance limit $\sigma_{\text{max}}$ changes (Fig. 3 b).

Usually, when the temperature increases, the values of the endurance limits of steels decrease. In aggressive environments, the limit of endurance is significantly reduced. The strength of structural parts under variable loads depends on the stress concentration.

The effective coefficient of stress concentration $CE$ is the ratio of the endurance limit of a smooth sample to the endurance limit of the sample in the presence of a pressure concentrator; $CE \geq 1$; and, the closer the CE is to one, the better the product works. For brittle materials, the effective coefficient of CE concentration is close to the theoretical value, while for plastic materials it is much less.

5. Summary and conclusions
Thus, it can be concluded that the quality of the technological process has a decisive influence on the fatigue strength. In the presence of technological defects (slag inclusions, pores, oxides, cracks, non-welding, etc.), the strength of welded joints under variable loads decreases sharply. Even a small non-
welding of the root of the seam forms an incision and stress concentration, which can significantly reduce the strength of butt joints under variable loads. In addition, the effect of non-welding on reducing fatigue strength depends on the type of material. Welded joints made of austenitic steels and titanium alloys are very sensitive to non-welding. In addition to stress concentrators caused by non-vapors, the presence of pores and slag inclusions affects the reduction of fatigue strength. The shape of the seam surface has a great influence on the endurance limit: it is much smaller for convex butt joints compared to smooth ones; very good results are obtained when removing the butt joint reinforcements or when processing them, providing a smooth transition from the seam to the base metal. you can Get connections with good strength not only when welding rolled elements, but also when welding cast parts or rolled with cast ones.

The strength under variable loads of t-joints depends largely on the preparation of the edges. It is experimentally proved that the endurance limit of a t-joint welded with edge preparation is higher than that of the same joint without edge preparation. The reason for this is the stress concentration due to non-welding of the edges. When welding t-joints on submerged arc machines, the penetration depth is greater than for other types of welding. This circumstance improves the performance of connections subjected to variable loads.

It should be noted that residual stresses can be not only harmful, but also useful. If compressive residual stresses are created in the zone of the greatest tensile stresses from external loads, the latter will contribute to increasing the fatigue strength of welded joints. Favorable residual compression stresses can be created by local plastic deformation. For this purpose, welded joints are sometimes subjected to surface machining: rolling with rollers or, which is more simple and convenient, blowing with a shot, processing with a pneumatic hammer or a bundle of wires by impact methods. At the same time, plastic deformation occurs in the surface layers of the metal, which causes the metal to incline, accompanied by an increase in σ and, in addition, residual compression stresses are formed. The higher the stress concentration coefficient in the weld joint, the more effective the application of surface treatment of seams.

The effect of increasing the endurance limit of welded point joints is achieved by compressing them with forging pressure when cooling. Forging increases the resistance to fatigue destruction by 1.4...2.0 times, and when processing with a special tool and high-speed forging-to a greater extent.

Thus, the endurance of welded joints can be increased when pre-loaded while eliminating harmful tensile residual stresses in the concentrator zone. Sometimes it is considered useful to create pre-stresses in thin-walled structures and their susceptibility to vibration. In this case, the residual tensile stresses are reduced by several tens of percent, and the resistance to fatigue loads increases.

References
[1] Gokhberg M M 1969 Metal structures of lifting and transport machines (Moscow: Mashinostroenie).
[2] Vershinsky A V Gokhberg M M and Semenov V P 1984 Construction mechanics and metal (Leningrad: Mashinostroenie)
[3] Maizel V S and Navrotsky D L 1965 Welded structures (Moscow: Mashinostroenie)
[4] Sokolov S A 2012 Metal structures of lifting and transport machines (Saint-Petersburg: Politehnika)
[5] Elyash N N 2015 Metal Structures of lifting and transport machines (Yekaterinburg: UNTA, 2015)
[6] Lagerev A V et al. 2020 Lifting and transport machines: calculation of metal structures by finite element method (Moscow: YURAIT)
[7] Shestopalov K. K. 2012 Lifting and transport construction and road machinery and equipment: textbook (Moscow: Academy)
[8] Kudryavtsev E M 2012 Construction machines and equipment (with examples of calculations, including on the computer) (Moscow: Publishing house of the DIA)
[9] Beletsky B F 2012 Construction machines and equipment / B. F. Beletsky, I. G. Bulgakova. - Saint Petersburg: LAN publishing House, 2012. - 608 p.
[10] G. A. Nikolaev, S. A. Kurkin, V. A. Vinokurov Welded structures. Strength of welded joints and deformations of structures: in 2 books / G. A. Nikolaev, S. A. Kurkin, V. A. Vinokurov. Moscow: Higher school, 1982, 272 p.

[11] Kopelman, L. A. Fundamentals of the theory of strength of welded structures (Saint Petersburg: LAN Publishing House)

[12] Daniltsev N N 2014 Design of welded structures (Omsk: OmSTU Publishing House)

[13] Akhtulov A L, Kirasirov O M and Kirasirov M O 2019 Features of calculation of steel structures of bridge cranes at variable loads S. Bratan (Ed.) International Conference on Modern Trends in Manufacturing Technologies and Equipment: Mechanical Engineering and Materials Science ICMTMTE 2019 MATEC Web of Conferences 298 pp. 1-6 (doi: 10.1051/matecconf/201929800032)

[14] Akhtulov A L, Ivanova L A, Kirasirov O M and Kirasirov M O 2020 Application of the Substructure Method to Assess the Vibration State of the Bridge Crane Ronzhin A., Shishlakov V. (eds) Proceedings of 14th International Conference on Electromechanics and Robotics “Zavalishin’s Readings” Smart Innovation, Systems and Technologies 154 (Springer, Singapore), pp. 741-751 (doi: 10.1007/978-981-13-9267-2_62)

[15] Akhtulov A L, Kirasirov O M and Kirasirov M O 2017 Optimization of choice of parameters for beams for formata of a data Bank in automating the design of bridge cranes Basic research 8 (1) pp 21-26

[16] Akhtulov A L 2018 The algorithm of numerical calculation of constraints reactions in a dynamic system of transport machine AMD: IOP Publishing: Journal of Physics: Conference Series 944 012002. pp. 1-12 (doi: 10.1088/1742-6596/944/1/012002, EID: 2-s2.0-85042282003)

[17] N V Druzhinin N V and Khokhov:V M 1982 Design and calculation of welded structures (Moscow: Akademiya)

[18] Ovchinnikov V I 2010 Calculation and design of welded structures (Moscow: Akademiya)

[19] Nasonov S B 2019 Guide to the design and calculation of building structures. Reference edition (Moscow: DIA Publishing House)

[20] Panasenko N N and Sinelschikov A V 2020 Finite element analysis and design of lifting structures in earthquake-resistant design. Monograph ()

[21] Kirasirov O M and Akhtulov A L 2009 Calculation of details of crane mechanisms by equivalent loads Omsk scientific Bulletin 3 (83) pp. 121-123