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Assessment of the Load on Steel Structures of Heavy Cranes

L. Martovytskyi[1], V. Glushko[2], Z. Shanina[3], R. Frolov[4], D. Kozak[5], O. Syvachuk[6], N. Bashova[7]
[1,2,3,4,5,6]*National University Zaporizhzhia Polytechnic, Zhukovskogo str. 64, 69000 Zaporizhzhia, Ukraine*
[7] *Poznan University of Technology, 5 M. Skłodowska-Curie Square, 60-965 Poznan, Poland, Institute of Mathematics*

Abstract: Carried out were real studies of actual loads on the span structures of the ore bridge loading cranes. Combining the load histograms with the influence lines made it possible to obtain spectrograms of changes in internal strength factors for the rods of the grate and travelling girders of box steel structures of iron ore bridge loading cranes in A7-A8 operating modes. A probabilistic approach to assessing the load on steel structure elements of heavy cranes has been proposed.
Keywords: ore bridge loading cranes, load histograms.

1. Introduction

In modern production facilities, hoisting machines, especially unique ones, such as ore loading cranes, serve as the main equipment and as such provide a pretty significant share of the company's revenue. Given that the most expensive part of such a crane is its steel structure, which also has the longest service life, it is important to ensure that the equipment certificate performance characteristics, the safety of the design, and the operation of these cranes are maintained for the longest possible service life. Experience has shown that the service life of hoisting crane steel structures depends on many factors, the accuracy (precision) of design being the most important of which.

The transition to more accurate design computations of steel structures requires obtaining reliable information about the actual load and real conditions of the future operation of a new crane. In addition, an inaccurate assessment of the load on the steel structure can lead to a mismatch between the designed crane structure and the actual operation conditions, as well as an incorrect prediction of the remaining service life of the crane. This, in turn, can lead to significant premature failures and accidents over time. The increase in the accuracy (precision) of the design will ensure clear compliance of the newly created steel structure with the actual operation conditions.

A real experiment was conducted at Zaporizhstal plant on the example of bridge loading cranes (iron ore gantry cranes – PKK), which are used in the ore yard of the blast furnace shop to study the actual workload of steel structures of hoisting cranes. The cranes studied were as follows:

PKK-3 and PKK-4 are grate-type bridge-loading cranes (Fig. 1, a);

PKK-5 and PKK-6 are box-type bridge-loading cranes (Fig. 2, a).

All these cranes are classified as the main equipment of the enterprise with the A7-A8 operating mode, and their technical specifications are listed in Table 1.

Table 1**:** Technical specifications of bridge loading cranes

Indicators.	**Values**	
	PKK-3, 4	**PKK-5, 6**
Span, m	76,35 82,35	76,35
Flexible console length, m	21,0 46	23,75 47,5
Rigid console length, m	25,0	23,75
Load capacity (with grab), t	30	32
Efficiency, tonnes per hour	400	700
Lifting speed, m/s	1,08	1,33

Lowering speed, m/s	1,5	1,5
Trolley travel speed, m/s	3,46	3,33
Bridge travel speed, m/s	0,5	0,5
Grab capacity, m3	5,6	5,6
Grab lifting height, m	25,0	35,0

In order to generate load histograms of steel structures of the bridge loading crane spans, photographs of the actual load on each span were taken at the ore yard over the course of a month.

Throughout the real experiment, the following parameters were constantly recorded: the state of the grab (loaded, empty), the beginning, end, and direction of movement of the trolley, and the type of load being moved. The initial and final positions of the trolley at each movement were visually recorded relative to the metre marks placed along the spans, which, with the total length of the structures of 122.35 m and 123.85 m, provided practical convenience and sufficient measurement accuracy.

The statistical samples of the experimental data were quite representative. After studying the results of the experiment, typical technological cycles for each experimental crane were determined:

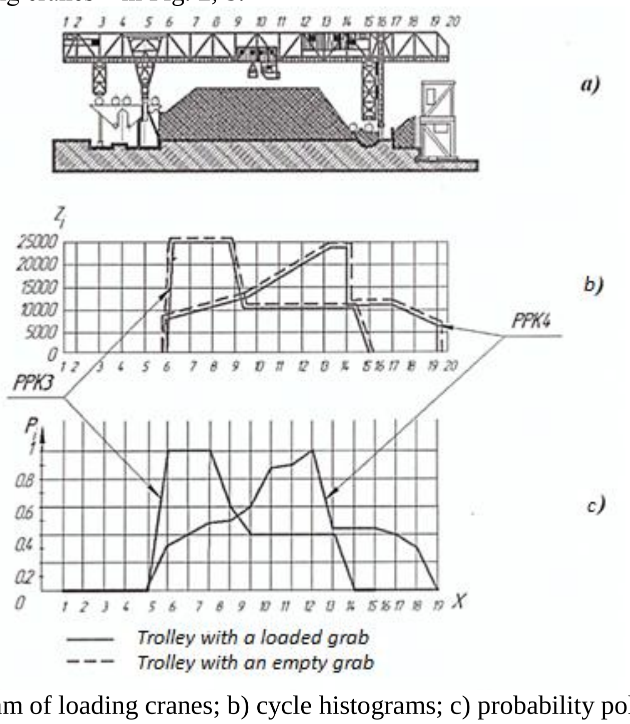
PKK-3 – overloading of dolomite from the overpass to the intermediate trench, preparation of a mixed stack of dolomite and limestone;

PKK-4 – overloading of limestone from a wagon dumper to the intermediate trench, overloading of iron ore pellets from the overpass to a stack and from the stack to skips, preparation of a burden mixture of limestone and concentrate in a ratio of 1:6, overloading of the mixture from the stack to transfer cars;

PKK-5 – overloading of limestone from the wagon dumper to the intermediate trench, overloading of iron ore from the wagon dumper to the stack and from the stack to the cars, preparation of a burden mixture of limestone and concentrate, overloading of the prepared mixture from the stack to the transfer cars;

PKK-6 – overloading of limestone from the wagon dumper to the intermediate trench, formation of stacks from a mixture of limestone and concentrate, overloading of the mixture from the stack to the transfer cars, overloading of iron ore, salt manganese, and coke from the wagon dumper to the appropriate stack and from the stack to the hoppers.

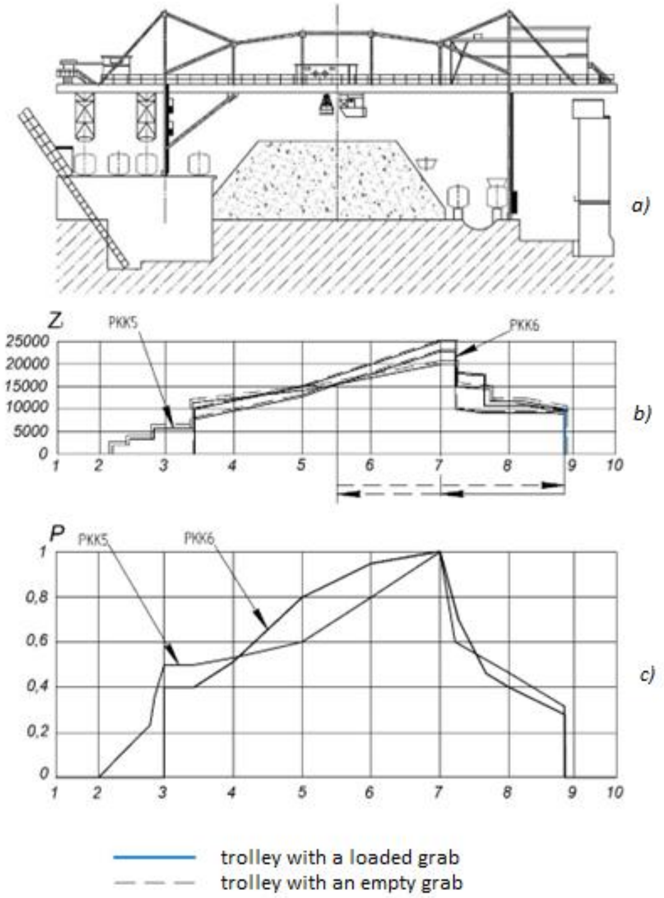
The obtained experimental cyclograms of the actual load for grate-type loading cranes are shown in Fig. 1, b, and for box-type loading cranes – in Fig. 2, b.



a) diagram of loading cranes; b) cycle histograms; c) probability polygons

Figure 1: Cycle histograms and probability polygons of load on steel structures of ore gantry loading cranes

Bridge-loading cranes operate outdoors and are often exposed to wind, which contains sulphur compounds and other aggressive substances. These compounds, in combination with precipitation, form acidic solutions that accelerate the corrosion of steel structures.



a) diagram of loading cranes; b) cycle histograms; c) probability polygons

Figure 2: Cycle histograms and probability polygons of load on steel structures of box-type ore gantry loading cranes

It is well known that the internal strength factors in the steel structure elements of cranes depend on the position of the travelling load along the span structure in accordance with the influence lines.

Influence lines for the most loaded rods of grate-type bridges are shown in Figure 3, and for the tie rod and traveling girders of box-type bridges, as statically indeterminate structures, in Figure 4.

Using influence lines, the forces and their stop-arrestors for the rods and traveling girders were determined depending on the position of the trolley on the crane bridge. For each such position, the histogram considers the frequency of finding the trolley in a given place while performing technological operations by the loading crane. Joint consideration of the influence lines and actual load histograms made it possible to obtain spectra of internal strength factors in the bridge elements of ore-loading cranes. For example, the spectra of the actual load on the rods of the grate-type PKK-3 are shown in Figure 5, and in the tie rods and travelling girders of PKK-5 and PKK-6 – in Figure 6.

Using experimental histograms of the actual load on the span structures of specific loading cranes and applying influence lines for internal strength factors for each element of the steel structure, it is possible to perform accurate (precise) strength, rigidity, and fatigue computations.

In addition, the combination of actual histograms and influence lines makes it possible to determine the duty operating mode for each section and element of a particular loading crane steel structure. The validity of this conclusion can be observed from the histograms, which clearly show that some sections of the span are not loaded with a moving loaded trolley at all. It can also be seen that each crane performs its own technological hoisting operations, which determine the configuration of the load histogram specific to that crane. To ensure the equal-strength operation of the entire length of the steel structure and its elements, the loading cranes should swap places periodically, but this is impossible to realize in actual operation conditions.

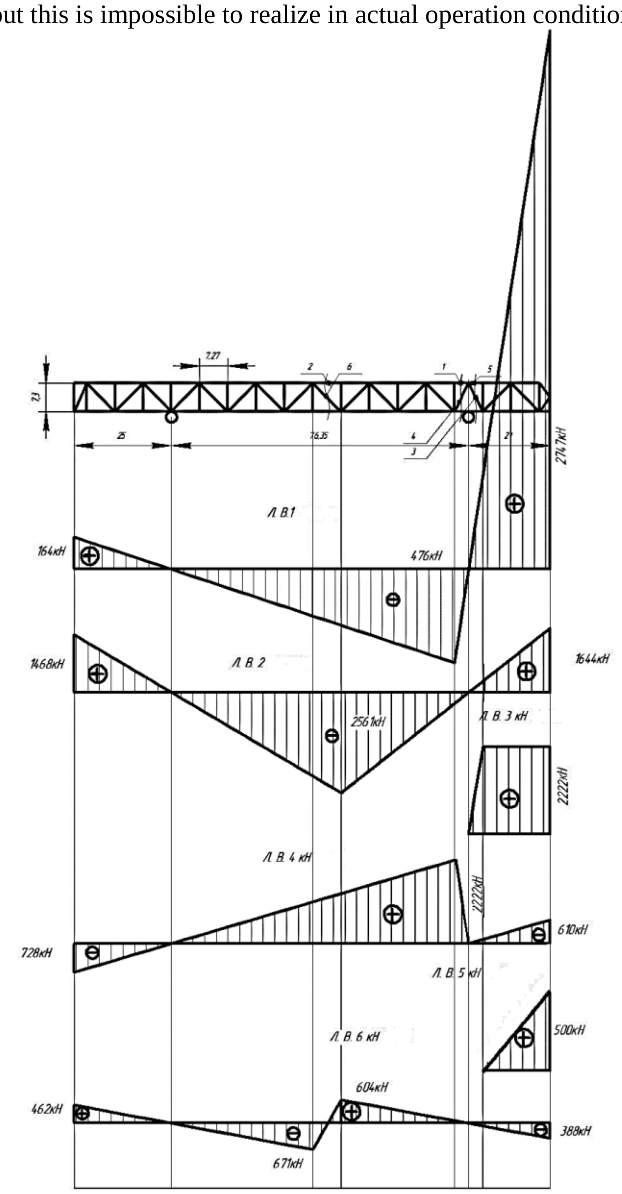


Figure 3: Influence lines for PKK-3 and PKK-4

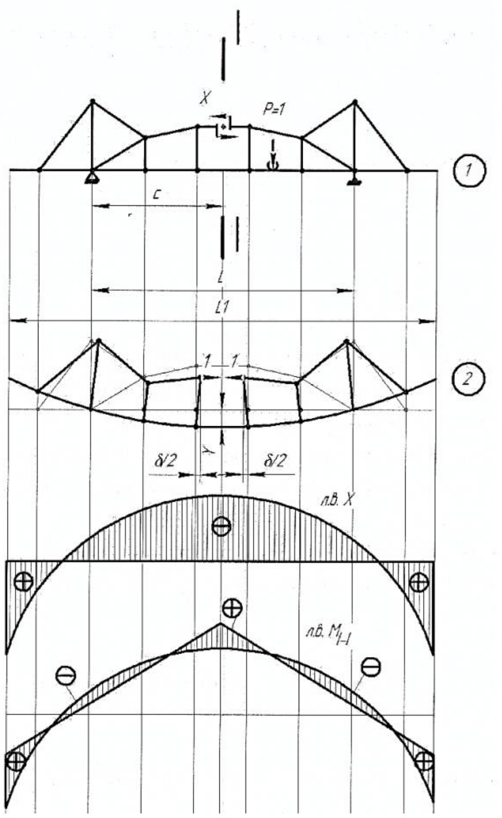


Figure 4: Influence lines for PKK-5 and PKK-6

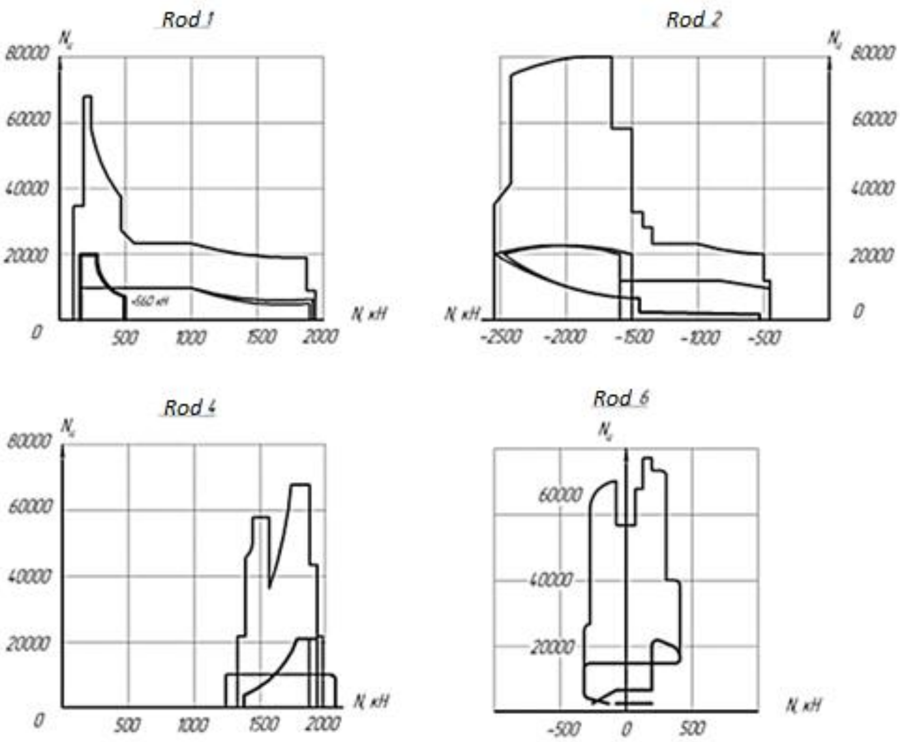


Figure 5: Spectra of actual strengths in PKK-3 rods

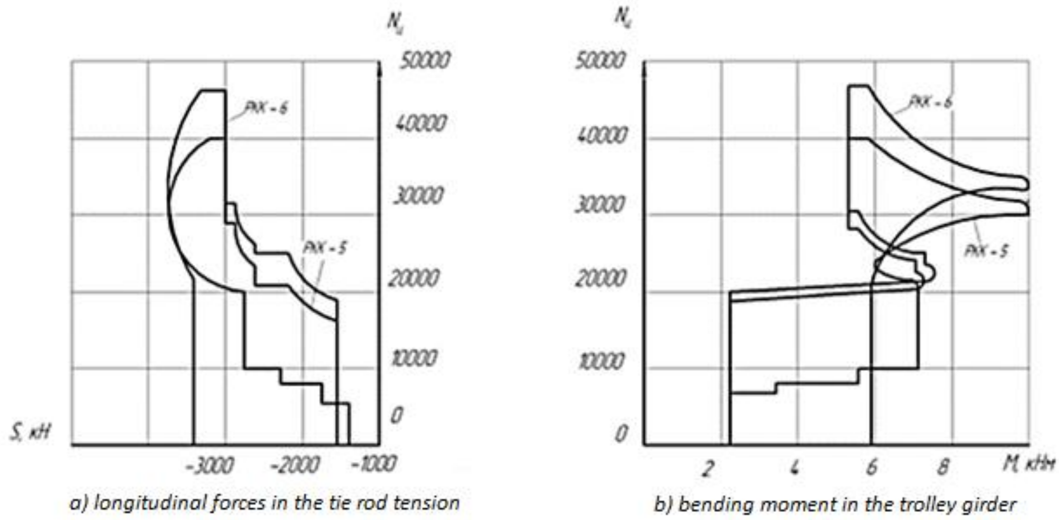


Figure 6: Spectra of actual internal strength factors acting on PKK-5 and PKK-6 steel structure elements

As can be noted, it is too costly and cumbersome to conduct real experimental studies of the actual load on each element of the steel structure of operating heavy cranes such as loading cranes, and in some cases, it is simply impossible. Given this, a probabilistic assessment of the load on steel structures of heavy cranes is proposed.

The random nature of the values describing the parameters of the loads acting on the steel structures of cranes during operation leads to the introduction of probabilistic methods in engineering strength calculations. The probabilistic calculation method has evolved the most when designing steel structures for tower cranes and other construction machinery. Extending probabilistic methods onto the steel structures of heavy and large cranes, such as overhead cranes weighing 1000 tonnes and more, is important. In addition, large dimensions of the steel structure mean that even every single element of the crane bridge operates under specific operation conditions throughout its entire service life.

The probability theory includes a number of basic concepts. One of the main concepts is "event", which is interpreted as any fact that may or may not occur due to an experiment.

Analysing the experimental studies conducted, the following events can be distinguished:

A – the trolley is located on a specific section of the crane bridge;

B – the trolley is in a specific state (with a loaded grab, with an empty grab).

Considering these events, we understand that each of them has a certain degree of possibility. Still, in our case, it is impossible to immediately determine which of the events is more likely. The concept of event probability is introduced to describe the possibility of an event occurring. The event probability is a numerical measure of the degree of an objective possibility of this event.

When we introduce the concept of event probability, we associate a specific practical meaning with this concept, namely, based on experience, we consider an event occurring more often to be more likely, an event that rarely occurs to be less likely, an event that almost never occurs to be unlikely.

Thus, the concept of event probability is closely related to event frequency.

Let us consider our experiment using load cycle histograms for loading cranes. PKK-3 crane will serve as an example (Fig. 1). The bridge of this crane is divided into 19 polygonal areas, the boundaries of which are limited by the vertical truss posts. The total number of cycles of loading the bridge with a loaded or empty trolley is 25,000 in one month. Based on the histogram, it can be argued that the most likely location of the trolley is in areas 6-7, 7-8, 8-9 because the trolley appears in these areas most often (the largest number of load cycles is concentrated in these areas), less likely is the placement of the trolley in areas 9-10, 10-11, 11-12, 12-13, 13-14, 14-15, and it is unlikely to find the trolley in areas 1-2, 2-3, 3-4, 4-5, 5-6, 15-16, 16-17, 17-18, 18-19, 19-20, because under normal operation conditions, the trolley does not appear in these areas. The histogram of load cycles for PKK-4, PKK-5, and PKK-6 steel structures should be considered using the same method.

From this point of view at events, we get such concepts as a certain event and an impossible event. A certain event is an event that will happen in any case. Its probability can be taken as one. In this case, events that are probable but not certain will be characterised by a probability of less than one. An impossible event is the opposite of a certain one, which most likely will not to occur at all. Its probability is 0. Thus, the range of measuring the probability of any event is from 0 to 1.

Back to our example with PKK-3 crane. In area 7-8, the number of load cycles is 25,000 out of 25,000, i.e., the probability of the trolley hitting this section is 1, and this event can be considered certain. In area 11-12, the number of loading cycles on the structure is 10,000 out of 25,000, which means the probability of the trolley hitting this section is $\rho = 10000/25000 = 0{,}4$. Therefore, this event is probable, but to a lesser extent than the previous one. In area 3-4, the number of loading cycles is 0 out of 25,000, i.e., the probability of the trolley hitting this section during the operation of the loading crane is 0, and this event can be considered as impossible.

In our experiment, the total number of crane loading cycles is a discrete value rather than a continuous one, i.e., each section has its own specific load value.

The sum of probabilities of all possible values of a random event is one. This total probability is somehow distributed among individual values. A random variable will be fully described from the probabilistic point of view if it is possible to specify this distribution, i.e. to specify exactly what probability each event has. The distribution law of the random variable will stipulate this.

Let us consider the distribution law of a random variable for PKK-3 ore gantry loading crane. Let us denote the event of the trolley hitting the first section of the bridge as 1, the second as 2, the third as 3, and so on. Then, calculate the probability of the trolley hitting these sections. The number of bridge loading cycles in the first five and last five bridge sections is 0, i.e., for event values 1, 2, 3, 4, 5, 15, 16, 17, 18, and 19; their probability is zero. For events 6, 7, 8 (for areas 6-7, 7-8), the number of cycles is 25,000 out of 25,000, i.e. the probability of these events is 1. In area 9, there is a decrease in the number of cycles; the average number of cycles for this section is 15,000, which means the probability of event 9 is $\rho = 15000/25000 = 0{,}6$. For event values of 10, 11, 12, 13, the number of cycles is 10,000, thus their probability is $\rho = 10000/25000 = 0{,}4$. For an event value of 14, the number of cycles is 5,000 on average, so the probability of this event is $\rho = 5000/25000 = 0{,}2$.

Using the same approach, we set the distribution law for PKK-4, PKK-5, and PKK-6 loading cranes.

Tables 2 and 3, which specify the laws of probability distribution, are called series of random variables distribution. In order to make the series more evident, it should be represented graphically: on the abscissa axis, we plot the possible values of a random event, and on the ordinate axis – the probability of this event. For clarity, connect the points with lines. The resulting graphs are polygons of probability distribution.

Table 2: Load probability distribution law for PKK-3 and PKK-4 ore-loading cranes

Event number		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**1**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
Probability, P_i	**PKK-3**	0	0	0	0	0	1	1	1	0.6	0.4	0.4	0.4	0.4	0.2	0	0	0	0	0
	PKK-4	0	0	0	0	0	0.32	0.4	0.48	0.5	0.6	0.88	0.9	1	0.44	0.44	0.44	0.4	0.3	0

Table 3: Load probability distribution law for PKK-5 and PKK-6 ore-loading cranes

Event number		**1**	**2а**	**2б**	**2в**	**2г**	**3а**	**3б**	**4**	**5**	**6**	**7а**	**7б**	**7в**	**8**	**9**
Probability, P_i	**PKK-6**	0	0	0.08	0.16	0.24	0.5	0.24	0.56	0.6	0.7	1	0.6	0.48	0.44	0
	PKK-5	0	0	0	0	0	0.4	0.4	0.52	0.7	0.94	1	0.7	0.44	0.4	0

The conducted probabilistic analysis is possible only for discrete random variables. In addition, in order to generate a series of event probability distributions, it is necessary to know in advance the probabilities of each event value, which, in our case, would be impossible without a preliminary experiment. As was mentioned above, to accurately predict the service life of machines such as bridge-loading cranes and hoisting cranes in general, it is necessary to know the actual load on their steel structures. In this case, it is impossible to avoid having a diagram of load cycles, which, in reality, can also be obtained through an experiment.

The problem stems from the fact that it is not always possible to conduct an experiment. This is due to many factors, including material costs, work organisation issues, etc. In addition, if it is possible to determine the actual load at the design stage of the crane, then the service life and operation life of a crane will become more specific, as this makes it possible to set the load more accurately both for each crane individually and for each element of the steel structure.

To solve this imperfection, the experiment could be replaced with a probability calculation. To do this, let us represent our experiment as A, B, C events.

For the probability calculation of these events, it is proposed to determine the probability of a random variable hitting a given area.

Let us consider the probability that a random variable X gets to the area from α to β. Then, assume that the leftmost value of α is included in the (α, β) interval and the rightmost value of β is not. In this case, the probability of a random variable X getting to (α, β) interval is given by the inequality

$$\alpha \le X < \beta. \tag{1}$$

The probability of this event is expressed as a distribution function of X. For this purpose, three events will be considered:

event A, which means that $x < \beta$;
event B, which means that $x < \alpha$;
event C, which means that $\alpha \le X < \beta$.

Given that $A = B + C$, according to the addition rule for probabilities, we have:

$$P(X < \beta) = P(X < \alpha) + P(\alpha \le X < \beta), \tag{2}$$

followed by

$$P(\alpha \le X < \beta) = P(X < \beta) - P(X < \alpha). \tag{3}$$

In this calculation, X is a random variable for the trolley's appearance, which takes the value of 1 for a loaded grab and 0 for an empty grab.

We have a complete set of incompatible hypotheses $H1, H2, \ldots . Hn$. The probability of these hypotheses is known before the experiment and is equal to $P(H1), P(H2), \ldots . P(Hn)$. It is necessary to conduct an experiment that will result in some event A. How does the probability of the hypotheses change in connection with this event?

Thus, it means it is necessary to find the conditional probability $P(Hi|A)$ for each hypothesis.

From the multiplication rule of probability (Bayes' theorem), we have:

$$P(AH_i) = P(A)P(H_i|A) = P(H_i)P(A|H_i), \tag{4}$$

where $i = 1,2, \dots, n.$

Or if we discard the left-hand side, we get

$$P(A)P(H_i|A) = P(H_i)P(A|H_i) \tag{5}$$

It is followed b

$$P(H_i|A) = \frac{P(H_i)P(A|H_i)}{P(A)}. \tag{6}$$

In our case, the group of hypotheses is the hypotheses about the trolley's location on a specific section of the crane bridge, and event A is the trolley's appearance from the first launch, for example, in the second section.

In conclusion, for the accurate (precision) design of steel structures for bridge loading cranes, and ideally for any individual crane, it is necessary to specify the range of cargoes, the sequence and intensity of their overloading, their location in the loading yard, a description of the overloading process and other characteristics of cargo flows as an integral part of the technical assignment. If this is not possible, the specified information should be presented as a mathematical model that would correspond closely enough to the actual state of loading of steel structures and their real operation conditions. Recommended can be the probability models (Bayes' formulas, the theorem of rain, Monte Carlo method, etc.) of load on steel structures of bridge loading cranes when operating in a specific location of the ore yard and under specific operation conditions.

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