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Design of Crane Steel Structures with Random Loads

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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 been most widely used in the design of steel structures for tower cranes and other construction machinery. It is important to extend probabilistic methods to the steel structures of heavy and large cranes, such as overhead cranes weighing 1000 tonnes or more. In addition, the large dimensions of the steel structure mean that every single element of the crane bridge operates in a specific operating mode throughout its entire service life.

In this case, it is advisable to know the actual load of each element of the metal structure, which is not always known. To accurately assess the load of the elements of the bridge of the loader it is best to have experimental histograms. This is not always possible to do, so we propose a probabilistic assessment of the load on the steel structures of heavy cranes.

There are a number of basic concepts in probability theory. One of the main concepts is an "event", which is defined as any fact that may or may not occur as a result of an experiment.

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

A. The location of the trolley on a specific section of the crane bridge;
B. The trolley is in the appropriate state (with a loaded grab, with an empty grab).

Considering these events, we understand that each of them has a certain degree of possibility, but in our case it is not possible 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 probability of an event is a numerical measure of the degree of objective possibility of this event.

When we introduce the concept of event probability, we associate a specific practical meaning with this concept, namely: judging from our experience, we consider the event that occurs more often to be more likely; an event that occurs rarely– 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.

To study the actual workload of metal structures of hoisting cranes, a full-scale experiment was conducted on the example of overhead loaders (ore gantry cranes–PKK) at Zaporizhstal, which are used in the ore yard of the blast furnace shop. The cranes that were studied are:

PKK-3 and PKK-4 are bridge reloaders of lattice design (Fig. 1, a);

PKK-5 and PKK-6 are box-type bridge loaders.

All the stipulated cranes are classified as the main equipment of the enterprise with the A7-A8 operating mode.

In order to generate load histograms of the metal structures of the bridge crane spans, photographs of the actual load on each span were taken at the ore yard during one month.

In the full-scale experiment, the following parameters were constantly recorded: the state of the grab (loaded, empty); the beginning, the stop and the direction of the trolley movement; 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, considering the total length of the spans 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 experimental results, typical technological cycles for each experimental crane were determined:

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

PKK-4 – transfer of limestone from a car tipper to an intermediate trench, transfer of iron ore pellets from the overpass to a stack and from the stack to skips, formation of a stack of a mixture of limestone and concentrate in a ratio of 1:6, transfer of the mixture from the stack to transfer cars;

PKK-5 – transfer of limestone from the tipper to the intermediate trench, transfer of iron ore from the tipper to the stack and from the stack to the transfer cars, stacking of a mixture of limestone and concentrate, transfer of the stacked mixture from the stack to the transfer cars;

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

The obtained experimental cyclograms of the actual load for the lattice-design reloaders are shown in Fig. 1, b.

Let's look at our experiment using load cycle histograms for cranes. Let's take the PKK-3 crane as an example (Fig. 1). The bridge of this crane is divided into 19 range 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 cycles per month. Given the histogram, it can be argued that the most likely appearance 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 appearance of the trolley in areas 9-10, 10-11, 11-12, 12-13, 13-14, 14-15, and the appearance of the trolley in areas 1-2, 2-3, 3-4, 4-5, 5-6, 15-16, 16-17, 17-18, 18-19, 19-20 is unlikely because under normal operating 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 perspective on 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 sure event, which is most likely not to occur at all. Its probability is 0. Thus, the range of measuring the probability of any event is from 0 to 1.

Let's return to our example withPKK-3 crane. Inarea7-8, the number of load cycles is 25000 out of 25000, i.e. the probability of the trolley appearing in this section is 1, and this event can be construed as certain. In area11-12, the number of loading cycles of the structure is 10000 out of 25000, that is the probability of the trolley arriving at this area is $p = \frac{10000}{25000} = 0{,}4$. Therefore, this event is probable, but to a lesser extent than the previous one. In section 3-4, the number of loading cycles is 0 out of 25000, i.e. the probability of the trolley hitting this section during the operation of the forklift is 0, and this event can be considered 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 the probabilities of all possible values of a random event is equal to one. This total probability is somehow distributed among the individual values. A random variable will be fully described from a probabilistic point of view if it is possible to specify this distribution, i.e. to specify exactly what probability each event has. This will be the given law of random variable distribution.

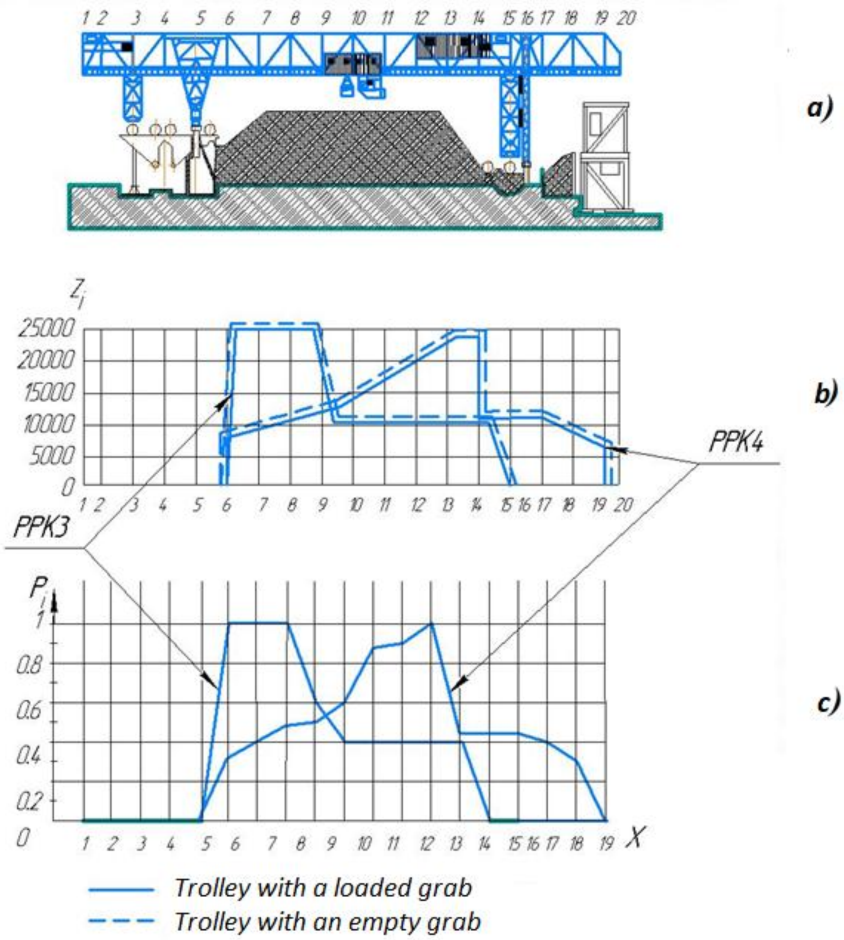
Let us consider the distribution law of a random event for PKK-3 ore gantry crane. Let us denote the event of the trolley getting to the first section of the bridge as 1, the second as 2, the third as 3, and so on. Then we calculate the probability of the trolley reaching these sections. The number of bridge loading cycles for the first five and last five sections of the bridge is 0, which means that for the values of events 1, 2, 3, 4, 5, 15, 16, 17, 18 and 19, their probability equals zero. For events 6, 7, 8 (for sections 6-7, 7-8) the number of cycles is 25000 out of 25000, i.e. the probability of these events is 1. At site 9 there is a decrease in the number of cycles, the average number of cycles for this site is 15000, that is the probability of event 9 is $p = \frac{15000}{25000} = 0{,}6$. For event values 10, 11, 12, 13, the number of cycles is 10000, then their probability is $p = \frac{10000}{25000} = 0{,}4$. For event value 14, the number of cycles is 5000 on average, so the probability of this event is $p = \frac{5000}{25000} = 0{,}2$.

Using the same method, we set the distribution law for PKK-4 hoisting crane.

The table that defines the law of probability distribution is called a series of distribution of random variables. In order to make the series more visual, it must be represented graphically: on the abscissa we plot the possible values of a random event, and on the ordinate – the probability of that event. For clarity, connect the points with lines. The resulting graph is a probability distribution polygon.

Table 1. Load probability distribution law for ore hoisting cranes.

Event number		1	2	3	4	5	6	7	8	9	10	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



a) Diagram of Hoisting Cranes; b) Histograms of Cycles; c) Probability Polygons
Figure 1 –Histograms of cycle and probability polygons of load on metal structures of ore gantry cranes

Probabilistic analysis is possible only for discrete random variables. In addition, in order to build a probability distribution series, it is necessary to know in advance the probabilities of each event value, which in our case would not have been possible without a preliminary experiment. As mentioned above, to accurately predict the service life of machines such as overhead cranes and hoisting cranes in general, it is necessary to know the actual load on their metal structures. And in this case, it is impossible to do without a load cycle diagram, which in practice can also be obtained through experimentation.

The problem is that it is not always possible to conduct an experiment. This is due to many factors, including material costs, problems with work organisation, etc. Besides, if it is possible to determine the actual load as early as at the design stage of the crane, then the operation time and service life of the 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 metal structure.

As a solution to this imperfection, we can replace the experiment with a probabilistic calculation. To do this, let us represent our experiment as two events A and B.

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

Let us consider the probability that a random variable X get to the range area from α to β. Let's assume that the leftmost value of α is included in the interval (α, β) while the rightmost value of β is not. Then the probability of a random variable X getting to the area (α, β) satisfies the inequality

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

The probability of this event is expressed as a distribution function of the variable X. For this purpose, we consider three events:
Event A, which means that x<β;
Event B, which means that x<α;
Event C, which means that $\alpha \le X < \beta$.

Given that A=B+C, according to the addition theorem on probability, 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 appearance of the trolley, which takes the value 1 for a loaded grab and 0 for an empty grab.

We have a complete group of incompatible hypotheses $H_{1,}$ H_2,...$H_{n.}$ The probability of these hypotheses is known before the experiment and is equal to $P(H)_{1,}$ $P(H_2)$,...$P(H_n$). 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 the occurrence of this event?

That is, it means that it is necessary to find the conditional probability $P(H_i|A)$ for each of the hypotheses.

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

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

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

Or discarding the left-hand side, we get

$$P(A)P(H_i \mid A) = P(H_i)P(A \mid H_i) \, . \tag{5}$$

It is followed by

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

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

In conclusion, for the accurate (precision) design of metal structures for overhead cranes, and ideally for each crane, it is necessary to specify the range of cargoes, the sequence and intensity of their handling, their location in the loading yard, a description of the handling 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 in the form of a mathematical model that would correspond closely enough to the actual state of loading of metal structures and their actual operating conditions. Probabilistic models (Bayes' formulas, rainfall method, Monte Carlo method, etc.) of the load on metal structures of overhead cranes when operating in a specific location of the ore yard and under specific operating conditions can be recommended.