英文原文：

Fatigue life prediction of the metalwork of a travelling gantry crane

V.A. Kopnov
P.O.Box 64,Eknteriuburg 620107,Russian
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Abstract

Intrinsic fatigue curves are applied to a fatigue life prediction problem of the metalwork of a traveling gantry crane. A crane, used in the forest industry, was studied in working conditions at a log yard, an strain measurements were made. For the calculations of the number of loading cycles, the rain flow cycle counting technique is used. The operations of a sample of such cranes were observed for a year for the average number of operation cycles to be obtained. The fatigue failure analysis has shown that failures some elements are systematic in nature and cannot be explained by random causes.

Key words: Cranes; Fatigue assessment; Strain gauging

1. Introduction

Fatigue failures of elements of the metalwork of traveling gantry cranes LT62B are observed frequently in operation. Failures as fatigue cracks initiate and propagate in welded joints of the crane bridge and supports in three-four years. Such cranes are used in the forest industry at log yards for transferring full-length and sawn logs to road trains, having a load-fitting capacity of 32 tons. More than 1000 cranes of this type work at the enterprises of the Russian forest industry. The problem was stated to find the weakest elements limiting the cranes' fives, predict their fatigue behavior, and give recommendations to the manufacturers for enhancing the fives of the cranes.

2. Analysis of the crane operation

For the analysis, a traveling gantry crane LT62B installed at log yard in the Yekaterinburg region was chosen. The crane serves two saw mills, creates a log store, and transfers logs to or out of road trains. A road passes along the log store. The saw mills are installed so that the reception sites are under the crane span. A schematic view of the crane is shown in Fig. 1.

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A series of assumptions may be made after examining the work of cranes:

·if the monthly removal of logs from the forest exceeds the processing rate, i.e. there is a creation of a log store, the crane expects work, being above the centre of a formed pile with the grab lowered on the pile stack;

·when processing exceeds the log removal from the forest, the crane expects work above an operational pile close to the saw mill with the grab lowered on the pile;

·the store of logs varies; the height of the piles is considered to be a maximum;

·the store variation takes place from the side opposite to the saw mill;

·the total volume of a processed load is on the average k=1.4 times more than the total volume of removal because of additional transfers.

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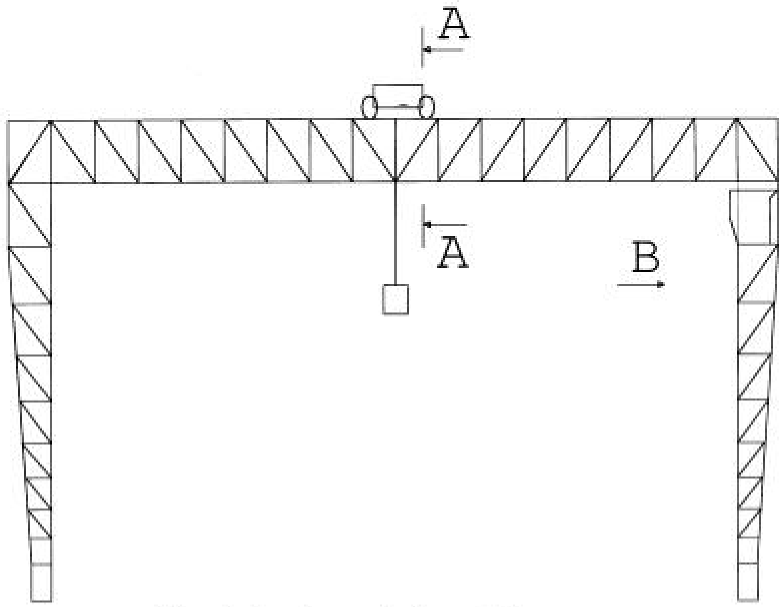

Fig. 1. A schematic view of the crane.

2.1. Removal intensity

It is known that the removal intensity for one year is irregular and cannot be considered as a stationary process. The study of the character of non-stationary flow of road trains at 23 enterprises Sverdlesprom for five years has shown that the monthly removal intensity even for one enterprise essentially varies from year to year. This is explained by the complex of various systematic and random effects which exert an influence on removal: weather conditions, conditions of roads and lorry fleet, etc. All wood brought to the log store should, however, be processed within one year.

Therefore, the less possibility of removing wood in the season between spring and autumn, the more intensively the wood removal should be performed in winter. While in winter the removal intensity exceeds the processing considerably, in summer, in most cases, the more full-length logs are processed than are taken out.

From the analysis of 118 realizations of removal values observed for one year, it is possible to evaluate the relative removal intensity g(t) as percentages of the annual load turnover. The removal data fisted in Table 1 is considered as expected values for any crane, which can be applied to the estimation of fatigue life, and, particularly, for an inspected crane with which strain measurement was carried out (see later). It would be possible for each crane to take advantage of its load turnover per one month, but to establish these data without special statistical investigation is difficult. Besides, to solve the problem of life prediction a knowledge of future loads is required, which we take as expected values on cranes with similar operation conditions.

Table 1
Removal intensity (%)

Month	1	2	3	4	5	6	7	8	9	10	11	12
$q(t)$	0.25	0.24	0.32	−0.08	−0.17	−0.14	−0.13	−0.12	−0.15	−0.15	−0.06	0.19

Table 2
The amount of transferred load (1000 m^3)

Month	1	2	3	4	5	6	7	8	9	10	11	12
$Q(t)$	60.6	60.1	64.2	42.2	37.1	38.8	39.4	39.9	38.2	38.2	44.5	55.0

The distribution of removal value Q(t) per month performed by the relative intensity q(t) is written as

$$Q(t) = Q(Aq(t)+8.33)/100(\mathrm{m}^3), \tag{1}$$

where Q is the annual load turnover of a log store, A is the maximal designed store of logs in percent of Q. Substituting the value Q, which for the inspected crane equals 400,000 m3 per year, and A=10%, the volumes of loads transferred by the crane are obtained, which are listed in Table 2, with the total volume being 560,000 m3 for one year using K,.

2.2. Number of loading blocks

The set of operations such as clamping, hoisting, transferring, lowering, and getting rid of a load can be considered as one operation cycle (loading block) of the crane. As a result to investigations, the operation time of a cycle can be modeled by the normal variable with mean equal to 11.5 min and standard deviation to 1.5 min. unfortunately, this characteristic cannot be simply used for the definition of the number of operation cycles for any work period as the local processing is extremely irregular. Using a total operation time of the crane and evaluations of cycle durations, it is easy to make large errors and increase the number of cycles compared with the real one. Therefore, it is preferred to act as follows.

The volume of a unit load can be modeled by a random variable with a distribution function(t) having mean22 m3 and standard deviation 6;一3 m3, with the nominal volume of one pack being 25 m3. Then, knowing the total volume of a processed load for a month or year, it is possible to determine distribution parameters of the number of operation cycles for these periods to take advantage of the methods of renewal theory [1].

According to these methods, a random renewal process as shown in Fig. 2 is considered, where the random volume of loads forms a flow of renewals:

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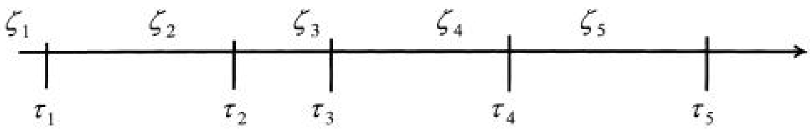

Fig. 2. Random renewal process of loads.

$$0 < \tau_1 < \tau_2 < \dots < \tau_n < \dots \tag{2}$$

In renewal theory, realizations of random:,,, having a distribution function F-(t), are understood as moments of recovery of failed units or request receipts. The value of a processed load:,, after }th operation is adopted here as the renewal moment.

Let F(t)=P｛ τ_n <t｝. The function F-(t) is defined recurrently,

$$F_n(t) = \int_0^t F_{n-1}(t-x)\,\mathrm{d}F(x), F_1(t) = F(t) = P\{\zeta < t\}. \tag{3}$$

Let v(t) be the number of operation cycles for a transferred volume t. In practice, the total volume of a transferred load t is essentially greater than a unit load, and it is useful therefore totake advantage of asymptotic properties of the renewal process. As follows from an appropriate

limit renewal theorem, the random number of cycles v required to transfer the large volume t has

the normal distribution asymptotically with mean and variance.

$$m_v \approx t/m_\zeta, \sigma_v^2 \approx \sigma_\zeta^2 t/m_\zeta^3 \tag{4}$$

without dependence on the form of the distribution function 月t) of a unit load (the restriction is imposed only on nonlattice of the distribution).

Equation (4) using Table 2 for each averaged operation month,function of number of load cycles with parameters m,. and 6,., which normal distribution in Table 3. Figure 3 shows the average numbers of cycles with 95 % confidence intervals. The values of these parameters

for a year are accordingly 12,719 and 420 cycles.

Table 3
Parameters of the normal distribution of number of operation cycles

Month	1	2	3	4	5	6	7	8	9	10	11	12
Average	1378	1366	1467	958	844	882	895	907	869	869	1035	1251
Standard	46	45	49	32	28	29	30	30	29	29	34	41

3. Strain measurements

In order to reveal the most loaded elements of the metalwork and to determine a range of stresses, static strain measurements were carried out beforehand. Vertical loading was applied by hoisting measured loads, and skew loading was formed with a tractor winch equipped with a dynamometer. The allocation schemes of the bonded strain gauges are shown in Figs 4 and 5. As was expected, the largest tension stresses in the bridge take place in the bottom chord of the truss (gauge 11-45 MPa). The top chord of the truss is subjected to the largest compression stresses.The local bending stresses caused by the pressure of wheels of the crane trolleys are added to the stresses of the bridge and the load weights. These stresses result in the bottom chord of the I 一beam

being less compressed than the top one (gauge 17-75 and 10-20 MPa). The other elements of the bridge are less loaded with stresses not exceeding the absolute value 45 MPa. The elements connecting the support with the bridge of the crane are loaded also irregularly. The largest compression stresses take place in the carrying angles of the interior panel; the maximum stresses reach h0 MPa (gauges 8 and 9). The largest tension stresses in the diaphragms and angles of the exterior panel reach 45 MPa (causes 1 and hl.

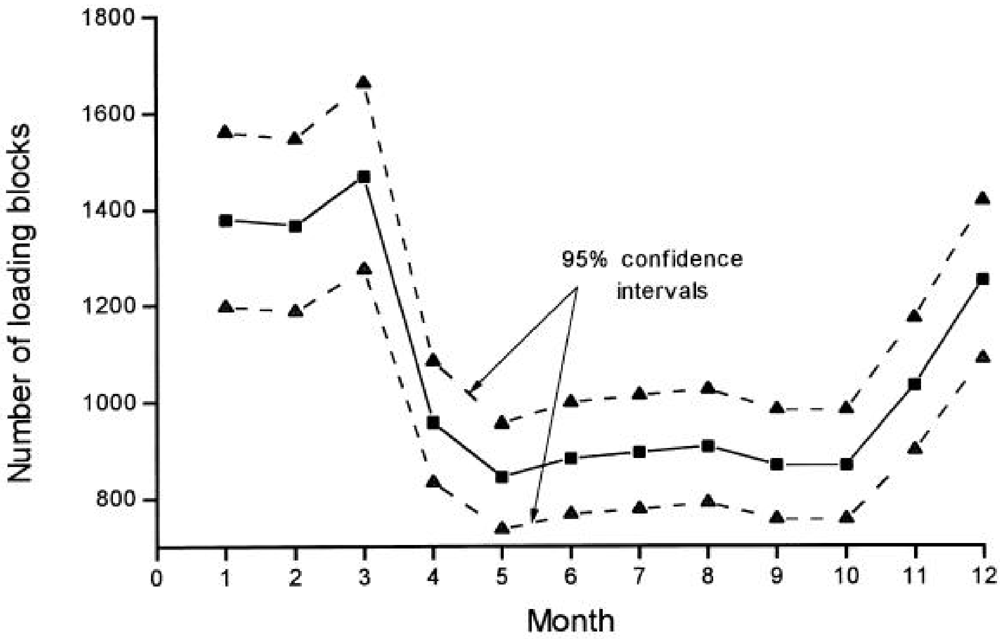

Fig. 3. Average numbers of operation cycles with 95% confidence intervals.

The elements of the crane bridge are subjected, in genera maximum stresses and respond weakly to skew loads. The suhand, are subjected mainly to skew loads.1, to vertical loads pports of the crane gmmg rise to on the other

The loading of the metalwork of such a crane, transferring full-length logs, differs from that of a crane used for general purposes. At first, it involves the load compliance of log packs because of progressive detachment from the base. Therefore, the loading increases rather slowly and smoothly.The second characteristic property is the low probability of hoisting with picking up. This is conditioned by the presence of the grab, which means that the fall of the rope from the spreader block is not permitted; the load should always be balanced. The possibility of slack being sufficient to accelerate an electric drive to nominal revolutions is therefore minimal. Thus, the forest traveling gantry cranes are subjected to smaller dynamic stresses than in analogous cranes for general purposes with the same hoisting speed. Usually, when acceleration is smooth, the detachment of a load from the base occurs in 3.5-4.5 s after switching on an electric drive. Significant oscillations of the metalwork are not observed in this case, and stresses smoothly reach maximum values.

When a high acceleration with the greatest possible clearance in the joint between spreader andgrab takes place, the tension of the ropes happens 1 s after switching the electric drive on, the clearance in the joint taking up. The revolutions of the electric motors reach the nominal value in

O.}r0.7 s. The detachment of a load from the base, from the moment of switching electric motors on to the moment of full pull in the ropes takes 3-3.5 s, the tensions in ropes increasing smoothly to maximum. The stresses in the metalwork of the bridge and supports grow up to maximum values in 1-2 s and oscillate about an average within 3.5%.

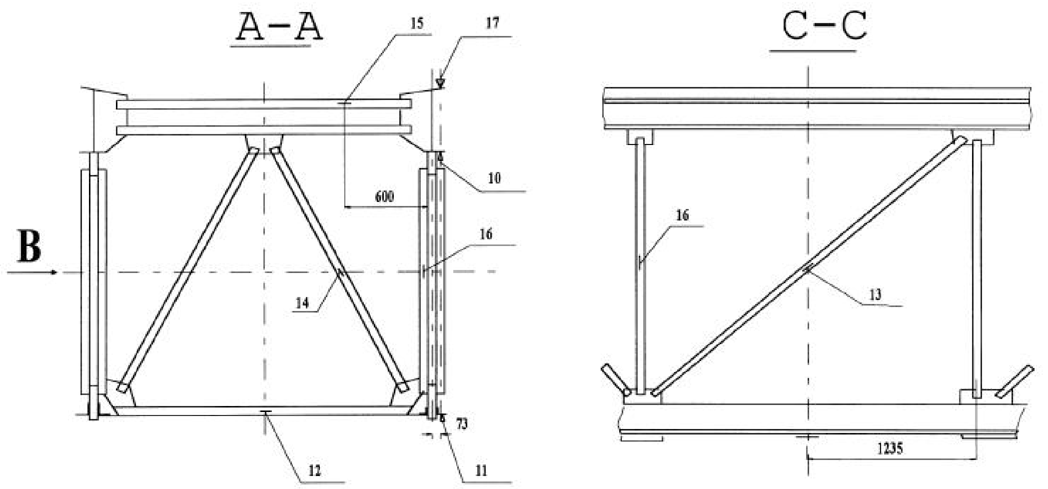

Fig. 4. Allocation schemes of gauges in the bridge.

When a rigid load is lifted, the accelerated velocity of loading in the rope hanger and metalwork is practically the same as in case of fast hoisting of a log pack. The metalwork oscillations are characterized by two harmonic processes with periods 0.6 and 2 s, which have been obtained from spectral analysis. The worst case of loading ensues from summation of loading amplitudes so that the maximum excess of dynamic loading above static can be 13-14%.Braking a load, when it is lowered, induces significant oscillation of stress in the metalwork, which can be }r7% of static loading. Moving over rail joints of 3} mm height misalignment induces only insignificant stresses. In operation, there are possible cases when loads originating from various types of loading combine. The greatest load is the case when the maximum loads from braking of a load when lowering coincide with braking of the trolley with poorly adjusted brakes.

4. Fatigue loading analysis

Strain measurement at test points, disposed as shown in Figs 4 and 5, was carried out during the work of the crane and a representative number of stress oscillograms was obtained. Since a common operation cycle duration of the crane has a sufficient scatter with average value } 11.5min, to reduce these oscillograms uniformly a filtration was implemented to these signals, and all repeated values, i.e. while the construction was not subjected to dynamic loading and only static loading occurred, were rejected. Three characteristic stress oscillograms (gauge 11) are shown in

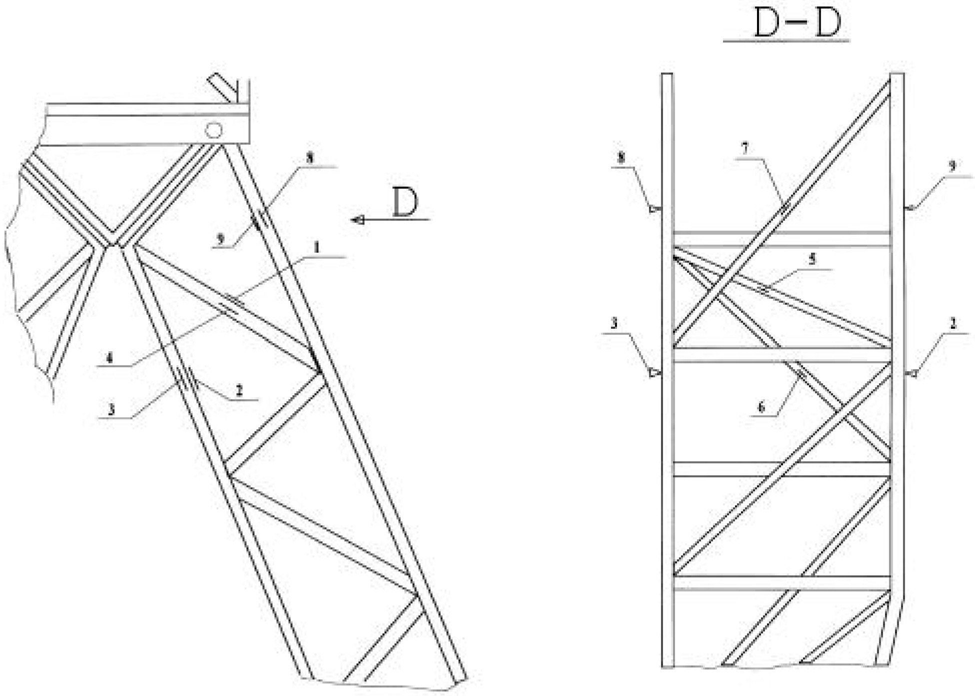

Fig. 5. Allocation schemes of gauges in the support.

Fig. 6 where the interior sequence of loading for an operation cycle is visible. At first, stresses increase to maximum values when a load is hoisted. After that a load is transferred to the necessary location and stresses oscillate due to the irregular crane movement on rails and over rail joints resulting mostly in skew loads. The lowering of the load causes the decrease of loading and forms half of a basic loading cycle.

4.1. Analysis of loading process amplitudes

Two terms now should be separated: loading cycle and loading block. The first denotes one distinct oscillation of stresses (closed loop), and the second is for the set of loading cycles during an operation cycle. The rain flow cycle counting method given in Ref. [2] was taken advantage of to carry out the fatigue hysteretic loop analysis for the three weakest elements: (1) angle of the bottom chord(gauge 11), (2) I-beam of the top chord (gauge 17), (3) angle of the support (gauge 8). Statistical evaluation of sample cycle amplitudes by means of the Waybill distribution for these elements has given estimated parameters fisted in Table 4. It should be noted that the histograms of cycle amplitude with nonzero averages were reduced afterwards to equivalent histograms with zero averages.

4.2. Numbers of loading cycles

During the rain flow cycle counting procedure, the calculation of number of loading cycles for the loading block was also carried out. While processing the oscillograms of one type, a sample number of loading cycles for one block is obtained consisting of integers with minimum and maximum observed values: 24 and 46. The random number of loading cycles vibe can be described

by the Poisson distribution with parameter λ =34.

Table 4
Parameters of Weibull distribution for loading amplitudes

	Weibull distribution parameters	
Name	Scale c, MPa	Form b
1. Angle of the bottom chord	23.4	5
2. I-beam of the top chord	40.4	4
3. Angle of the support	29.5	4

Average numbers of loading blocks via months were obtained earlier, so it is possible to find the appropriate characteristics not only for loading blocks per month, but also for the total number of loading cycles per month or year if the central limit theorem is taken advantage of. Firstly, it is known from probability theory that the addition of k independent Poisson variables gives also a random variable with the Poisson distribution with parameter k},. On the other hand, the Poisson distribution can be well approximated by the normal distribution with average}, and variation },. Secondly, the central limit theorem, roughly speaking, states that the distribution of a large number of terms, independent of the initial distribution asymptotically tends to normal. If the initial distribution of each independent term has a normal distribution, then the average and standard deviation of the total number of loading cycles for one year are equal to 423,096 and 650 accordingly. The values of k are taken as constant averages from Table 3.

5. Stress concentration factors and element endurance

The elements of the crane are jointed by semi-automatic gas welding without preliminary edge preparation and consequent machining. For the inspected elements 1 and 3 having circumferential and edge welds of angles with gusset plates, the effective stress concentration factor for fatigue is given by calculation methods [3], kf=2.}r2.9, coinciding with estimates given in the current Russian norm for fatigue of welded elements [4], kf=2.9.

The elements of the crane metalwork are made of alloyed steel 09G2S having an endurance limit of 120 MPa and a yield strength of 350 MPa. Then the average values of the endurance limits of the inspected elements 1 and 3 are ES 一l=41 MPa. The variation coefficient is taken as 0.1, and the corresponding standard deviation is 6S-、一4.1 MPa.

The inspected element 2 is an I-beam pierced by holes for attaching rails to the top flange. The rather large local stresses caused by local bending also promote fatigue damage accumulation. According to tables from [4], the effective stress concentration factor is accepted as kf=1.8, which gives an average value of the endurance limit as ES 一l=h7 Map. Using the same variation coiffing dent th e stand arid d emit ion is σ_{s-1}=6.7 MPa.

An average S-N curve, recommended in [4], has the form:

Table 5
Parameters of lognormal distribution

Name	Life distribution parameters	
	Mean (blocks)	Standard (blocks)
1. Angle of the bottom chord	106,800	58,200
2. *I*-beam of the top chord	143,200	79,000
3. Angle of the support	74,620	32,300

$$N(S) = N_0(S_{-1}/S)^m \tag{5}$$

with the inflexion point No=5・106 and the slope m=4.5 for elements 1 and 3 and m=5.5 for element 2.

The possible values of the element endurance limits presented above overlap the ranges of load amplitude with nonzero probability, which means that these elements are subjected to fatigue damage accumulation. Then it is possible to conclude that fatigue calculations for the elements are necessary as well as fatigue fife prediction.

6. Life prediction

The study has that some elements of the metalwork are subject to fatigue damage accumulation.To predict fives we shall take advantage of intrinsic fatigue curves, which are detailed in [5]and [6].

Following the theory of intrinsic fatigue curves, we get lognormal life distribution densities for the inspected elements. The fife averages and standard deviations are fisted in Table 5. The lognormal fife distribution densities are shown in Fig. 7. It is seen from this table that the least fife is for element 3. Recollecting that an average number of load blocks for a year is equal to 12,719, it is clear that the average service fife of the crane before fatigue cracks appear in the welded elements is sufficient: the fife is 8.5 years for element 1, 11.5 years for element 2, and h years for element 3. However, the probability of failure of these elements within three-four years is not small and is in the range 0.09-0.22. These probabilities cannot be neglected, and services of design and maintenance should make efforts to extend the fife of the metalwork without permitting crack initiation and propagation.

7. Conclusions

The analysis of the crane loading has shown that some elements of the metalwork are subjectedto large dynamic loads, which causes fatigue damage accumulation followed by fatigue failures.The procedure of fatigue hfe prediction proposed in this paper involves tour parts:

(1) Analysis of the operation in practice and determination of the loading blocks for some period.

(2) Rainflow cycle counting techniques for the calculation of loading cycles for a period of standard operation.

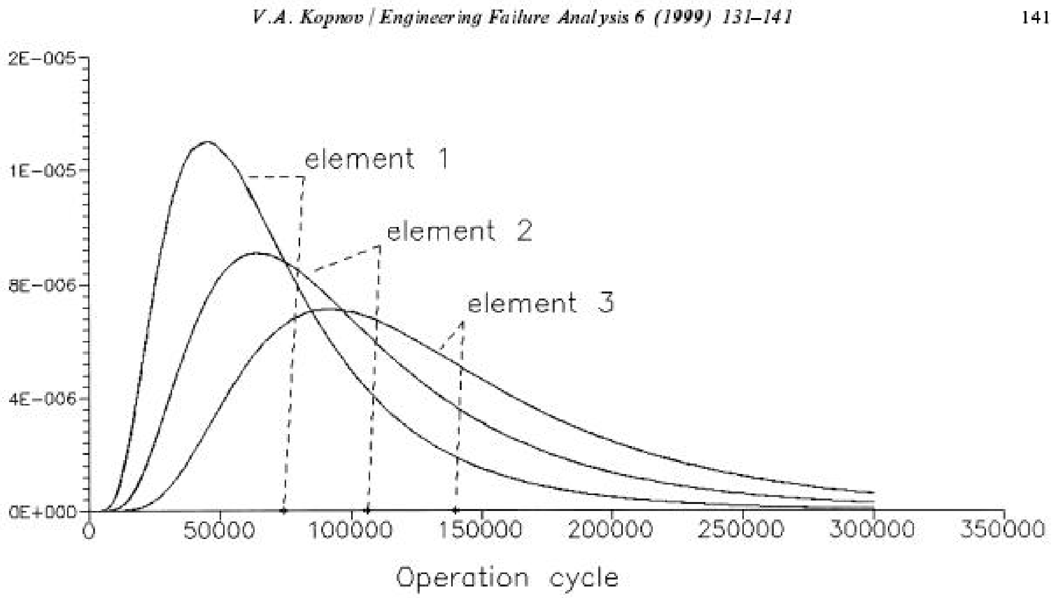

Fig. 7. Life distribution densities for the inspected elements.

(3) Selection of appropriate fatigue data for material.

(4) Fatigue fife calculations using the intrinsic fatigue curves approach.

The results of this investigation have been confirmed by the cases observed in practice, and the manufacturers have taken a decision about strengthening the fixed elements to extend their fatigue lives.

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