Forecast Intensity of Manifestations of Defects and Damage to Steel Structures Operating under Extreme Conditions of the External and Internal Environment

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Abstract. All articles must contain an abstract. The article is devoted to the investigation of issues related to ensuring the reliability of the functioning of steel structures of production buildings (concentrating mills) in the extreme natural climatic and soil-geological conditions of the Republic of Sakha (Yakutia). System analysis and structural processing of the results of numerous in-situ studies of the technical state of capital construction objects carried out over a period of time have been carried out: from 1969 to 1991. The results of the processing of full-scale studies are considered as a verified source of data for practical and prospective studies. A new calculation technique (a mathematical forecast model) for the service life of steel bearing structures of concentrating mills is proposed. The results obtained with the help of mathematical models allow us to optimize design decisions and reliability indicators at the design stage of structural elements of production facilities.

1. Introduction

The functioning of the vast majority of buildings and structures of industrial (production) purpose is associated with ensuring a variety of technological processes in accordance with established regulations, taking into account the peculiarities of a particular industry. Formation of conditions for efficient and reliable operation is a priority task for capital construction objects intended to ensure the production of technological processes and functioning under conditions of extreme impact of natural-climatic and engineering-geological factors of the external environment.

Practical implementation of measures aimed at solving this problem is consistently carried out at all major stages of the life cycle of the industrial construction project (Figure 1).

![Figure 1. Life cycle of a production construction object.](image-url)
The effectiveness of the practical implementation of design (space-planning and constructive) solutions of the production facility is characterized by a system of indices of the complex reliability property. One of the most important indicators of the reliability of a construction object (constructive and construction system) is: «durability» [1,2]:

«The ability of a construction object to maintain strength, physical and other properties that are established during design and ensure its normal operation during the estimated service life».

«The structure shall be designed such that deterioration over its design working life does not impair the performance of the structure below that intended, having due regard to its environment and the anticipated level of maintenance».

The quantitative characteristic of the «service life» of the longevity index of the complex property of the reliability of a structural system (separate structural elements or building structures) of a production facility determines the time aspect or duration of the process of gradual deterioration of the technical state of the design functional characteristics (parameters of operational suitability).

The index of reliability of construction objects to production appointment in the format of durability (more precisely, the characteristics of «service life») remains the subject of attention of normative documents and recommendations about design, as an important technical and economic factor that determines the functional efficiency of structural solutions construction objects.

2. Relevance

Extraction of minerals and mining-processing production in the Republic of Sakha (Yakutia) is considered as a strategic priority of economic activity [3,4].

Buildings (industrial facilities) of concentrating factories are the largest construction objects of the mining branch located on the territory, natural-climatic and engineering-geological conditions of the Republic of Sakha (Yakutia). The features of technological processes and equipment, the required (project) capacity of enterprises, as well as the conditions of placement at specific construction sites, did not allow the implementation of uniform constructive formats. Space-planning solutions of concentrating factories are characterized by individual, complex configurations of plans, the presence of numerous high-altitude differences and technological galleries between parts of buildings.

Figures 2 to 7 present images of the general view of concentrating factories 3,8,12,14,15,16 of the joint stock company «ALROSA».

The main feature of the constructive systems of the construction objects under consideration is the use of steel structural elements. The wide spread of constructive solutions of concentrating factories with the use of steel bearing elements is explained by the following factors:

- features of geographical location (low level of transport accessibility);
- the level of development of the local construction industry (remoteness from the construction industry bases);
- features of the natural-climatic and hydrogeological conditions of the region (the presence of long-lasting and low values of negative temperatures, the spread of permafrost soils, difficult relief terrain);
- the need to use space-planning solutions, oriented to significant sizes (in plan and in height) and a complex architectural form;
- intensity of technological loads;
- directive requirements for reducing the term of commissioning.

Concentrating factories mining industry (regardless of the time of construction, operation period and regional location) in accordance with the current legislation in the field of technical regulation are classified as dangerous production facilities, and their industrial safety is subject to increased requirements [5,6,7].

The analysis of the technical condition and industrial safety of buildings and facilities of concentrating factories (carried out in the period of time: from 1966 to 2016) indicates the presence in steel structural components defects and damage, characterized by different categories of danger [7,8,9,10,11,12,13].
3. Formulation of the problem

The main purpose of the work is to develop a technique for estimating the service life and parameters of the technical condition of load-bearing steel structures of industrial buildings by
examples of accounting for operational factors and natural-climatic conditions of the Republic of Sakha (Yakutia). Achieving the research goal is accomplished by the successive solution of the following tasks:

- justification, development and implementation of the concept of management of reliability indicators for the main stages of the life cycle of a construction object;
- formation of the structure of signs and characteristics of the construction object, justification and characterization of local conditions necessary for the analysis of accumulation of defects and damages;
- review and characteristics of the provisions of regulatory documents in the design, construction and operation of modern constructive and building systems of industrial buildings and structures;
- overview and characteristics of methods for determining the technical condition of load-bearing steel structures;
- analysis and systematization of types of defects and damages of load-bearing steel structures arising at the main stages of the life cycle of a construction object;
- actualization of the results of field surveys of constructive systems and elements of steel structures of construction objects located on the territory of the Republic of Sakha (Yakutia);
- systematization and analysis of the danger of defects and damages of constructive systems and constructive elements of construction objects located on the territory of the Republic of Sakha (Yakutia);
- the formation of a structure of parameters for assessing the technical condition and reliability indicators of load-bearing steel structures of construction objects, taking into account the peculiarities of their operation and location on the territory of the Republic of Sakha (Yakutia);
- development of a technique for estimating the service life of load-bearing steel structures, taking into account the quantitative indicators of the formation of defects and damages.

In the basis of the technique of estimation (forecast) of service life provides for the use of effective statistical, settlement-analytical and probabilistic research methods using the methods of reliability theory, mathematical modeling and automated means of research and design [14,15].

4. Theoretical part
The developed technique allows to use the mathematical apparatus of the forecasting estimation of the technical condition parameters of steel load-bearing structures for the design of reliability indicators in the format of the service life of construction objects, taking into account the local conditions of the Republic of Sakha (Yakutia) and for factors affecting operating conditions.

Load-bearing steel constructive elements of production purpose (concentrating factories) are exposed to a significant number of negative factors that contribute to the reduction of established indicators of reliability and functional efficiency due to the manifestation consequence of the effects of structural changes in materials, the accumulations of defects and damages [8,9,10,11,12,13]:

- defect – deviation of indicators of reliability and functional efficiency of the constructive element from design values, allowed at the design and/or production and/or construction (mounting);
- damage – deviation of the quality indicators of the research object from the design values that arose in the course of operating conditions;

Figure 8 shows the structure of groups of negative factors that lead to the formation and development of defects and damages of load-bearing steel constructive elements of concentrating factories.

The total number of separate types of negative factors in each of the above groups is quite large. Obviously, with time, the number of factors will only increase. When analyzing the quantitative indicators of reliability (lifespan), individual factors of one of the groups or complex combinations of simultaneous and/or successive actions of different groups that cause formation and/or development of defects and damages of load-bearing steel structures [16,17].
The forecast mathematical model is intended to determine the service life of load-bearing steel structures of industrial buildings (concentrating factories) using the calculated (analytical) method, taking into account the formation and/or development of defects and damages of the load-bearing steel structures for different stages of the life cycle of the accepted research objects.

The predictive format of the model is oriented, first of all, to the stage of design of constructive solutions of concentrating factories. It is at this period of the life cycle that the justification of the service life of the constructive system of the production building is made taking into account the following main factors [1,2]:

- functional purpose of the building object;
- characteristics of the material (steel);
- ways of organization of separate elements in the constructions, and of the constructions in constructive systems;
- local climatic conditions and external factors;
- combinations of loadings and impacts;
- the possibility of forming and develop defects and damages;
- conditions for the formation of the construction system (technology and organization of production of the relevant construction processes);
- operating conditions, including aggressiveness of the internal environment.

In the predictive mathematical model establishes the connection between the quantitative index of reliability (in the format of characteristic of the longevity – the service life) and the quantitative characteristic of the technical state in the presence of defects and damages – in a wearout indicator format (accumulation of defects and damages) of the load-bearing steel structure (or the constructive systems concentrating factories, generally) [15,18,19]:

$$I_t = (e^{\lambda(t - t_0)} - 1) \cdot 100\%.$$  
(1)

gде: $I_t$ – wearout indicator of the research object (percentage);
$e$ – natural number;
$\lambda$ – function (intensity) of wearout (accumulation of defects and damages);
$t_0$ – the amount of time needed to "breaking-in" the load-bearing steel structure (years);
$t_i$ – service life (years).

Quantitative evaluation of manifestations of defects and damages (wearout intensity, $\lambda$) of load-bearing steel constructive elements of concentrating factories is carried out with the help of absolute and relative statistical indicators:

- the intensity of manifestation of defects and damages falling on the total (summary) number of steel constructive elements:

$$\lambda_{stl} = \frac{n_d}{N_{\Sigma}}.$$  
(2)

gде: $n_d$ – number of defects and damages, pieces;
$N_{\Sigma}$ – total (summary) number of steel constructive elements of one type (appointment) taken for consideration, pieces.
– the intensity of manifestation of defects and damages falling on the total (summary) weight of steel constructive elements:

\[ \lambda_{A2} = \frac{n_A}{M_\Sigma}. \]  

(3)

gде: \( n_A \) – number of defects and damages, pieces;
\( M_\Sigma \) – total (summary) weight of steel constructive elements of one type (appointment) taken for consideration, pieces.

Figure 9 shows a structural scheme of the analysis of the possibilities for the development of a degradation process caused by a possible manifestation of emergency environment factor (in the format of defects and damages of a load-bearing steel constructive elements) that can lead to a reduction in reliability to an emergency state: both the element itself and the corresponding constructive system [16,20].

![Figure 9. Structural diagram of the analysis of the process of formation and development of the degradation process (formation and accumulation of defects and damages)](image)

The formation of defects and damages is the reason for the release of parameters (conditions) of maintenance and/or indicators of functional quality beyond the boundary of the field of permissible operating conditions, and the operational suitability of the load-bearing constructive element is characterized by a deviation from the initial (project) parameters in the direction of reducing the indicators of technical condition.

For statistical analysis is accepted the doctrine of a pessimistic and optimistic estimate at the forecast of emergence and accumulation (parrying) of defects in constructive elements of concentrating factories:

– pessimistic assessment: the intensity of occurrence and accumulation of defects will be not less, than the fixed number of defects for the corresponding period of observations;
– optimistic assessment: the intensity of parrying defects will be not less, than the fixed number of defects for the corresponding period of observations.

This approach allows to carry out assessment: of intensity of the occurrences of defects, due to the manifestation of the relevant emergency factors, as well as of intensity of accumulation (not parrying) of defects. The values of wearout indicators of metal (steel) constructive elements are considered in the context of quantitative values of the parameter \( \lambda \) – of intensity of wearout \( \lambda \) of the mathematical model of the forecast of service life (2).

5. **Practical importance**
All considered defects and damages of load-bearing steel constructive elements are systematized by types, possible cause of occurrence and probable consequences. Analysis of studies of defects and damages (by the nature of their formation) of steel structures leads to the conclusion that the main reasons for their occurrence are:

- errors and deviations from design positions when construction (mounting);
- full or partial dismantling elements of structural during the repair or reconstruction of process equipment;
- high degree of aggressiveness of the environment and violation of the terms of restoration of corrosion protection;
- negative impact of process equipment and production processes.

Each of the known (fixed) types of defects and damages is characterized by: the cause of manifestation (occurrence), quantitative indicators of dimensions (defects and damages) and possible emergency consequences reducing the indicators of functional efficiency [7,21,22].

The estimation of the forecasted value of the technical condition is made using quantitative indicators of the occurrence and accumulation of defects of load-bearing steel constructive elements of concentrating factories (grouped according to their functional purpose, Table 1), noted during practical observations for the period from 1966 to 2016.

**Table 1.** Structure and composition of load-bearing steel constructive elements of concentrating factories (CF)

| Type of construction | Building object | CF №3 | CF №8 | CF №12 | CF №14 | CF №15 | CF №16 |
|----------------------|----------------|-------|-------|--------|--------|--------|--------|
| Elements of the carcass: |                |       |       |        |        |        |        |
| - columns of solid section |               | -     | +     | +      | -      | +      | +      |
| - columns of through section |             | +     | +     | -      | +      | +      | +      |
| - columns (pillar) fachwerk |               | +     | +     | +      | -      | +      | +      |
| - ties |               | +     | +     | +      | +      | +      | +      |
| Overlapping: |                |       |       |        |        |        |        |
| - beams secondary, from rolling profiles |             | +     | +     | +      | +      | +      | +      |
| - beams secondary, from welded profiles |             | +     | -     | -      | +      | -      | -      |
| - beams main, from rolling profiles |             | +     | +     | +      | +      | +      | +      |
| - beams main, from welded profiles |             | +     | +     | -      | +      | -      | -      |
| - floor slabs, monolithic reinforced concrete |             | +     | +     | +      | -      | +      | +      |
| Elements for the device of the process equipment: |                |       |       |        |        |        |        |
| - columns (pillar) for process equipment |             | +     | +     | +      | +      | +      | +      |
| - beams for process equipment |             | +     | +     | +      | +      | +      | +      |
| - technological platforms |             | +     | +     | +      | +      | +      | +      |
| Cranes and crane equipment: rails, brake elements: |                |       |       |        |        |        |        |
| - crane beams |             | +     | +     | +      | +      | +      | +      |
| - crane track rails |             | +     | +     | +      | +      | +      | +      |
| - brake constructions |             | +     | +     | +      | +      | +      | +      |
| Coatings: |                |       |       |        |        |        |        |
| - boundary constructions |             | -     | +     | -      | +      | -      | +      |
| - rafter beams, from rolling profiles |             | -     | +     | +      | -      | +      | +      |
| - rafter beams, from welded profiles |             | +     | -     | -      | -      | -      | -      |
| - rafter farms |             | +     | +     | +      | +      | +      | +      |
| - purlins, from rolling profiles |             | +     | +     | +      | +      | +      | +      |
| - purlins, from welded profiles |             | -     | -     | +      | -      | -      | -      |
| - coating ties, horizontal |             | +     | +     | +      | +      | +      | +      |
| - coating ties, vertical |             | +     | +     | +      | +      | +      | +      |
| - coating ties, cross-shaped |             | +     | +     | +      | +      | +      | +      |
Metal (steel) main beams of overlappings from rolling and welded profiles and severaling standard sizes have found application practically in all constructive systems of considered concentrating factories.

The technique of determining the quantitative indicators of the intensities of occurrence and accumulation of defects and damages to determine the service life of steel constructive elements using analytical dependence (2) is represented by the example of the main beams of overlappings (as a constructive element characterized by a significant number of defects and damages identified during the observation period: from 1966 to 2016).

Table 2 provides information (total number and weight) on the dynamics of operation of the metal (steel) main beams of overlappings of concentrating factories.

Table 2. Dynamics of commissioning of metal (steel) main beams of overlappings of concentrating factories (CF)

| Building object | Years of operation | 1966÷1970 | 1971÷1975 | 1976÷1991 | 1992÷1999 | 2000÷2002 | 2003÷2016 |
|-----------------|--------------------|-----------|-----------|-----------|-----------|-----------|-----------|
| CF №3           |                    | 36        | 63        | 36        | 36        | 36        | 36        |
|                 |                    | 26        | 26        | 26        | 26        | 26        | 26        |
| CF №8           |                    | –         | 50        | 50        | 50        | 50        | 50        |
|                 |                    |           | 35        | 35        | 35        | 35        | 35        |
| CF №12          |                    | –         | –         | 32        | 32        | 32        | 32        |
|                 |                    |           |           | 22        | 22        | 22        | 22        |
| CF №14          |                    | –         | –         | –         | 49        | 49        | 49        |
|                 |                    |           |           |           | 49        | 49        | 49        |
| CF №15          |                    | –         | –         | –         | –         | –         | –         |
| CF №16          |                    | –         | –         | –         | –         | –         | –         |
|                 |                    | –         | –         | –         | –         | 65        | 46        |
| Total           |                    | 36        | 86        | 118       | 167       | 167       | 232       |
|                 |                    | 26        | 61        | 83        | 115       | 115       | 161       |

Notes on Table 2:
1. In the numerator indicates the total number of standard sizes of constructive elements of the type considered.
2. In the denominator indicates the total weight of the constructive elements of the type considered.

Analysis of indicators of technical condition of the main beams of overlappings for all concentrating factories (total number: 232 standard sizes, total weight: 161 tons) for the period of operation 1966 - 2016 are presented on Figures 10÷13.

Figure 10. Absolute indices of emergence, elimination (parrying) and accumulation of defects and damages in the main beams of overlappings
Figure 11. Dynamics of emergence, elimination (parrying) and accumulation of defects and damages in the main beams of overlappings

Figure 12. Dynamics of the intensity of emergence, elimination (parrying) and accumulation of defects and damages in the main beams of overlappings - by the total number of elements

Figure 13. Dynamics of the intensity of emergence, elimination (parrying) and accumulation of defects and damages in the main beams of overlappings - by total weight of elements

Table 3 presents the quantitative values of the wearout intensity (of defects and damages) of the main beams of overlappings of the constructive systems of concentrating factories (CF) commissioned for the period from 1966 to 2016, grouped taking into account the doctrine of the optimistic and pessimistic assessment of the possibility of manifestation, accumulating and parrying defects and damages.
Table 3. Quantitative values of the intensity of wearout (defects and damages) of the main beams of overlappings of concentrating factories (CF)

| № i.o. | Name of concentrating factory | Characteristic of constructive elements | Function (intensity) of wearout (refusal) of constructive elements by quantity | Function (intensity) of wearout (refusal) of constructive elements by weight |
|--------|-------------------------------|----------------------------------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| 1      | CF №3                         | 36 pieces, 26 weight, tons             | 30/(50·36)=0.0167 7/(50·36)=0.0039                                          | 30/(50·26)=0.0231 7/(50·26)=0.0054                                               |
| 2      | CF №8                         | 50 pieces, 35 weight, tons             | 31/(45·50)=0.0137 7/(45·50)=0.0031                                          | 31/(45·35)=0.0196 7/(45·35)=0.0044                                               |
| 3      | CF №12                        | 32 pieces, 22 weight, tons             | 28/(40·32)=0.0219 8/(40·32)=0.0063                                          | 28/(40·22)=0.0318 8/(40·22)=0.0091                                               |
| 4      | CF №14                        | 49 pieces, 32 weight, tons             | 11/(24·49)=0.0094 3/(24·49)=0.0026                                          | 11/(24·32)=0.0143 3/(24·32)=0.0039                                               |
| 5      | CF №15                        | -                                       | -                                                                          | -                                                                            |
| 6      | CF №16                        | 65 pieces, 46 weight, tons             | 7/(13·65)=0.0083 6/(13·65)=0.0071                                          | 7/(13·46)=0.0117 6/(13·46)=0.0100                                               |
| All factories: | 232 pieces, 161 weight, tons | 0.0140 0.0046                         | 0.0201 0.0066                                                                 |

On figure 14 and in Table 4 show the results of determining the service life of the main beams of overlappings, calculated taking into account the doctrine of optimistic and pessimistic estimates of the formation, parrying and accumulation of defects and damages.

Figure 14. Determination of the service life and indicator of wearout of the main beams of overlappings at various assessments of the intensity of wearout (of defects and damages)
Table 4. The service life of the main beams of overlappings of the concentrating factories (CF) at various assessments of the intensity of wearout (of defects and damages)

| Name of indicator                        | Indicators of reliability and technical condition |
|------------------------------------------|--------------------------------------------------|
|                                          | Service life, years | Indicator of wearout, % |
| The intensity of wearout by the number of elements - a pessimistic estimate \((\lambda = 0.0140)\) | 34 | 60.96 |
| The intensity of wearout by the number of elements - an optimistic estimate \((\lambda = 0.0046)\) | 103 | 60.61 |
| The intensity of wearout by the weight of the elements - a pessimistic estimate \((\lambda = 0.0201)\) | 24 | 62.00 |
| The intensity of wearout by the weight of the elements - an optimistic estimate \((\lambda = 0.0066)\) | 72 | 60.83 |

Similarly, are defined quantitative values of function of the intensity of wearout of all constructive elements (grouped according to the functional purpose, see Table 1) of concentrating factories.

In Table 5 presents the results of calculations of the intensity of wearout (defects and damages) of all load-bearing steel structures of concentrating factories.

Table 5. Quantitative values of the intensity of wearout (defects and damages) of steel load-bearing elements of concentrating factories (CF)

| № i.o. | Name of constructive elements                          | Function (intensity) of wearout (refusal) of constructive elements |
|--------|-------------------------------------------------------|---------------------------------------------------------------|
|        |                                                       | by quantity    | by weight    |                                                       |
|        |                                                       | pessimistic assessment | optimistic assessment | pessimistic assessment | optimistic assessment |
| 1      | Columns and fachwerk of carcass                      | 0.0059         | 0.0027       | 0.0080         | 0.0036       |
| 2      | Ties of carcass                                     | 0.0042         | 0.0015       | 0.0175         | 0.0089       |
| 3      | Main beams of overlappings                           | 0.0140         | 0.0046       | 0.0201         | 0.0066       |
| 4      | Secondary beams of overlappings                       | 0.0136         | 0.0063       | 0.0454         | 0.0209       |
| 5      | Elements for the device of the process equipment     | 0.0046         | 0.0027       | 0.0170         | 0.0102       |
| 6      | Cranes and crane equipment                           | 0.0070         | 0.0012       | 0.0171         | 0.0030       |
| 7      | Rafter beams (coatings)                              | 0.0082         | 0.0026       | 0.0129         | 0.0052       |
| 8      | Rafter farms (coatings)                              | 0.0071         | 0.0021       | 0.0206         | 0.0057       |
| 9      | The purlins and ties of coating                      | 0.0038         | 0.0013       | 0.0251         | 0.0086       |

The mathematical model (in the format of analytical dependence (2)) allows to analyze the development of the process in space and in time, in exact accordance with the specific conditions, in which it is supposed operation of the designed building construction. The method of mathematical modeling appears to be much more (in comparison with physical modeling) an effective way to predict the degradatsonn phenomena and processes associated with the formation and development of wearout (defects and damages) of load-bearing steel structures.

6. Conclusions

The results of investigations into the service life and technical condition of the constructive elements of the concentrating factories are characterized by significant perspective and prognostic significance for appointment of reliability indicators (service life) of constructive solutions of the designed construction objects of similar designation (objects of new construction).

The obtained results are available for carrying out researches and evaluation of other reliability indicators (including quantitative characteristics indicators of failure-free) associated with the service life and intensity of wearout (formation of defects and damages) of load-bearing steel structures.

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