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Residual resource of a one-storey steel frame industrial building constructed with bridge cranes

Остаточный ресурс стального каркаса одноэтажного промышленного здания с мостовыми кранами

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Ключевые слова: промышленное здание; остаточный ресурс; вероятностная модель; система коэффициентов надежности; напряженно-деформированное состояние; матрица жесткости

Abstract. The scheme of an integrated approach to the study of changes in the stress-strain state of the frame one-story industrial building constructed with bridge cranes, caused by accumulation of damage caused during the operation. The algorithm has been developed for estimating and predicting the residual resource of a production facility on the basis of processing the results of a series of surveys. It allows to obtain the values of reliability indicators in the correlation approximation using probabilistic models of disturbing influences. This approach is based on the assessment of the reserve strength of the framework structures, determined by the difference between their bearing capacity and the largest value of the generalized load. The article demonstrates the numerical implementation of the algorithm on the example of calculating the building of the shipbuilding shop of a marine shipbuilding plant. Consistent solution positive, negative and predictive tasks enabled by analyzing the dynamics of natural frequencies building frame under the action of the aggregate load estimate time reaches the maximum allowable state. The results allow to regulate the timing and direction of the actions of the repair work at lower 4...8 times the intensity of the survey.

Аннотация. Построена схема комплексного подхода к исследованию изменений напряженно-деформированного состояния каркаса одноэтажного промышленного здания с мостовыми кранами, вызванных накоплением повреждений, возникших в процессе эксплуатации. Разработан алгоритм оценки и прогнозирования остаточного ресурса производственного объекта на основе обработки результатов серии обследований. Он позволяет получить значения показателей надежности в корреляционном приближении с использованием вероятностных моделей возмущающих воздействий. Данный подход построен на оценке резерва прочности конструкций каркаса, определяемым разностью между их несущей способностью и наибольшим значением обобщенной нагрузки. Приведена демонстрация численной реализации предложенного алгоритма на примере расчета здания судокорпусного цеха морского судостроительного завода. Последовательное решение прямой, обратной и прогнозной задач позволило посредством анализа динамики частот собственных колебаний каркаса здания под действием совокупности нагрузок оценить период времени достижения им предельно допустимого состояния. Полученные результаты позволяют регламентировать сроки и направленность действия ремонтно-восстановительных работ при снижении в 4…8 раз интенсивности проведения обследований.

1. Introduction

Continuous growth of production capacity and introduction of modern technologies speaks about the need for technical re-equipment of industrial buildings already in operation. In this case, the problem of estimating and predicting their residual resource comes to the forefront. Special urgency its decision to

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acquire in the case of buildings, equipped with overhead cranes, because as the first option for Reconstruction acts replacing the existing crane equipment to increase its capacity. Such buildings are widely used in the organization of the technological process of machine-building, ship-repairing, metallurgical and ore-dressing plants.

The current practice of assessing the residual technical resource is mainly based on a deterministic approach, which is associated with the need for full-scale inspection of the building frame at a certain time [1–4]. The corresponding algorithm is reduced to an estimate of the safety factor based on the comparison of the results of the verification calculation of the actual characteristics of the stress-strain state obtained during the inspection of the building with the corresponding normative values.

The random character of the time variation of the stiffness characteristics of the structural elements, as well as the duration and direction of the disturbing effects, implies the determination of the time period for the safe operation of the building in a probabilistic setting. The analysis of the scientific literature made it possible to classify the problems of studying the changes in the behavior of the frame of a building into two types. The greatest interest is shown in the formulation of two types of problems. The first of these is the definition of the properties of the output parameters of the system with known probabilistic characteristics of the input combinations of loads [5-8]. The solution of the problem in this formulation is realized by finding the mathematical expectation and the standard of ordinates of the random function, and the search for the values of the required parameters reduces to an analysis of the correlation dependencies. This technique does not take into account the dynamics of changes in the physical parameters of materials and the static scheme as a result of force and non-force impacts on the object of investigation, corrosion of metal structures and destruction of bolted connections. The second type is aimed at solving a boundary value problem formalized through a system of nonlinear differential equations, the coefficients for unknowns and the load in which are random functions [9, 10]. The search for a solution is reduced to the implementation of a direct method for estimating the reliability of a building, the random character of which is determined by the spread of the properties of the geometric and rigidity parameters of the structure. This method has not yet found wide application in engineering practice, which is caused by the lack of a sufficient number of developed probabilistic calculation methods for spatial models of buildings and the complexity of computational nature.

In this situation, the problem of estimating the residual resource becomes particularly urgent, since its solution allows us to predict the kinetics of the change in the stress-strain state with allowance for damages arising during the operation of the technical system and determine the time of its repair ability outcome. The timeliness of the work required to restore the identified structural elements with a high degree of accumulated deformation can lead to a significant extension of the further operation of the facility as a whole.

In the course of work on the topic, the results of numerous theoretical and applied studies of domestic and foreign scientists that have made a significant contribution to the development and improvement of methods of the theory of the reliability of building structures are studied [9, 11–15]. Methods for assessing changes in the stress-strain state of steel structures as components of the frame of an industrial building are considered when they perceive beyond design-fire [16], impact [17] and crane [18] effects. Based on the analysis of the sources studied, issues that require substantial refinement for the possibility of constructing a generalized method for probabilistic estimation and forecasting the resource of an industrial building in operation are identified. At the same time, proposals for the construction and implementation of algorithms for the complex optimal design of structural elements of the framework with a view to making the most effective decisions [19–22] are taken into account. The accents of the strategic line of further studies of the kinetics of the change in the stiffness characteristics of the framework of the production facility are placed with the random nature of the impacts and the numerical realization of their results in application to engineering practice.

The approach proposed by the authors of the article is radically different from the ones currently used in conducting the examination. It is based on an estimate of the strength reserve of carcass structures [23], determined by the difference between their bearing capacity and the largest value of the generalized load.

As an objective of the research implementing this approach, it is an increase in the service life of buildings and structures by carrying out repair and restoration works at the sites of the construction complex during the estimated periods of their operation. For achieve this goal, the authors resolved the following questions:

- development of an analytical apparatus for predicting the stress-strain state of the frame of an industrial building, taking into account random factors of impacts and adjusting the stiffness matrix, depending on the change in the displacements at fixed points of the design scheme;
- definition of functions of fictitious loading and working capacity of the building, taking into account the dynamics of changes in stresses in the individual structural elements of the framework, arising under the influence of a combination of factors;
- development of a methodology for assessing the residual life of an operational condition of industrial building structures, relying on a system of reliability coefficients;
- carrying out numerical studies and comparative analysis of the calculated results with experimental data and known computational solutions presented in the scientific and regulatory literature.

2. Methods

Analyzing the advantages and disadvantages of existing methods, the most suitable for ensuring the required reliability of the obtained numerical estimation results is a method based on the correlation of the levels of time series of stress values at individual points in the design scheme of the object. For the possibility of its implementation, it is required to develop an integrated approach to the study of changes in the rigidity characteristics of the framework under the action of a load factor aimed at solving the general problem of estimating the resource of an industrial building at any fixed time of its operation. As a defining criterion, a 10 % reduction in the frequency of the first forms of natural oscillations appears.

In the construction of the space frame design scheme research facility are taken into account such factors as:

– a variant of a layout of plates and quality of an embedding of seams in a covering;

– the effect of longitudinal vertical bonds on the torsional stiffness;

– split braking structures;

– way of representing the overhead crane.

The general form of spatial computational schemes storey industrial buildings with equal height spans equipped constructed with bridge cranes, is shown in Figure 1.

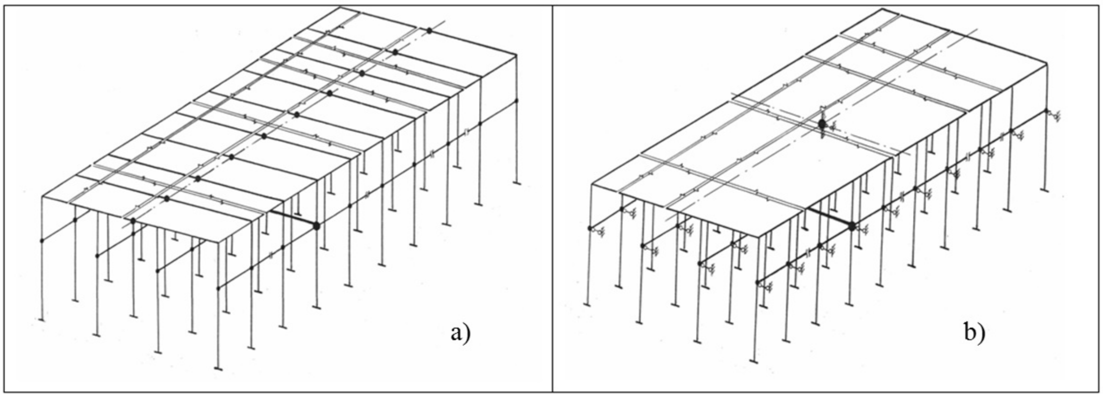

Figure 1. Generalized calculation scheme of a single-storey industrial building: a) with a compliant coating in its plane, b) with a rigid coating in its plane.

The design scheme in general form defines the geometry of an industrial facility, including n longitudinal rows of columns and p transverse frames. In the cross-sections of the transverse frames there are constructed with bridge cranes. The masses of crane and brake structures, constructed with bridge cranes, parts of columns and wall fences are concentrated in the level of crane structures. The masses in the level of crane structures are determined by the weight of the structures and the time load. They are concentrated between two horizontal planes, passing in the middle of the heights of the crane and crane parts of the columns. Points of intersection of the frames and the longitudinal axis of the coating, columns and brake structures are taken for the calculated points. Each calculated point of the beam-column system receives one degree of freedom – horizontal displacement in the plane of the transverse frame [24], and on the cover two degrees – the horizontal displacement in the same plane and the angle of rotation in the plane of the coating.

Taking as a basis presented generalized calculation schemes, considered various options for building and ways to influence the implementation of such structural elements of the framework, such as: brake system designs; transverse end diaphragm; links imposed on the disk cover. The results of the research on the influence of crane equipment to the building frame work [25] made valid conclusions that the crane bridge is a component of the lateral frame. Redistributing the loads between opposite rows of columns, the bridge crane is taken into account as an absolutely rigid link in the level of the upper belt of the crane beams in the cross-section of the transverse frame.

According to the results to identify the most significant factors determining the calculation model of an industrial building equipped with overhead cranes, built a conceptual study scheme of its stress-strain state (Figure 2). It regulates the sequence of actions of the performer, starting with the organization of the collection of data on the object of the survey, until the deadlines for reaching the limit states in the work of its structural elements are established.

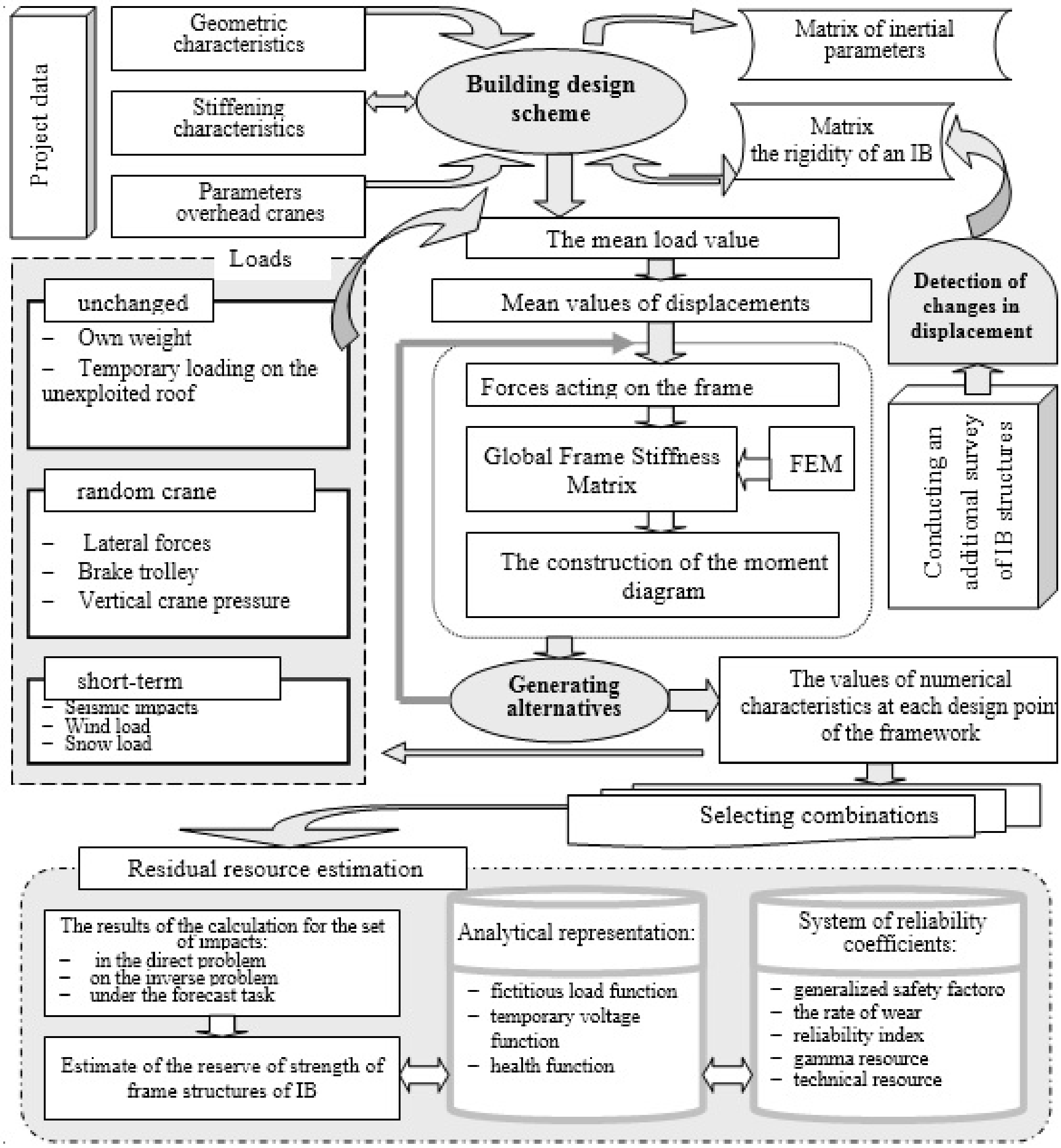

Figure 2. Scheme of an integrated approach to the study of the stress-strain state of an industrial building.

The presented scheme assumes on the part of the performer the wide variation in the formation of the loading of the design scheme of the object of investigation. However, as the most unfavorable combination of disturbing influences on the frame of a building, the authors justified accept a combined, including:

– constant loads from the own weight of the enclosing and load-bearing frame structures;

– vertical pressure from two closely spaced constructed with bridge cranes;

– lateral force when moving with a skew of one overhead crane, the highest carrying capacity;

– snow load;

– wind load.

This combination is formed both with the participation and absence of a short-term component of the generalized load presented in the form of a seismic action [15, 26–28].

Carrying out calculations for assessing the reliability and durability of the structure of the building frame is made possible through the use of the limit state method. The algorithm for processing the information obtained is based on an estimate of the strength reserve for the structure of the building frame $\tilde{S}$, determined by the difference between their bearing capacity $\tilde{R}_S$ and the highest value of the generalized load $\tilde{F}$, the mathematical expectation of which is found by the formula:

$$m_{\tilde{S}} = m_{\tilde{R}_S} - m_{\tilde{F}}. \quad (1)$$

Value $m_{\tilde{R}_S}$ is represented in the form of the average value of the standard resistance of the frame by the known maximum permissible value of the standard resistance $\overline{R}_{Sn}$ at a given level of significance α

$$m_{\tilde{R}_S} = \frac{\overline{R}_{Sn}}{1 - t_\alpha f_s}, \quad (2)$$

where f_S – coefficient of variation of the strength properties of the material of the structure.

The mathematical expectation of the random value of the load factor $m_{\tilde{F}}$ is represented as a sum of all stresses from the action of both static and dynamic loads considered in various combinations.

At repeated carrying out of inspection of constructive elements of a building by the electric measuring devices shifting's in concrete points of the accepted settlement scheme are fixed. The dynamics of changes in the obtained displacements characterizes the changes in the rigidity characteristics of the structure as a whole [29–32]. The stiffness matrix of the building from known displacements in the design points of the framework is determined by solving the inverse problem of structural mechanics using software and hardware [33, 34].

Having a corrected stiffness matrix taking into account the wear of the structures, and knowing the direction and magnitude of the acting load, the numerical characteristics of the bending moments and stresses are determined. The accumulated results obtained during the processing of the data of the conducted building surveys allow the generation of time series of stress dynamics at individual points in the calculation scheme. Correlating the levels of each of them, it is possible to construct the corresponding regression. The normalization of the analytical dependence of the generalized load on the time factor makes it possible to construct the function of a fictitious load $g(t)$. Then the time functions of the mathematical expectation of the generalized load at the individual points of the design scheme for a known value $m_{\tilde{F}}$ at the initial time t_0 take the form:

$$m_F(t) = m_{\tilde{F}(t_0)}\, g(t), \quad (3)$$

The values of the generalized safety factor, which assesses the risk factor for further exploitation of building structures at different times, are described by the function:

$$\xi(t) = \frac{m_{\tilde{R}_S}}{m_F(t)} \quad (4)$$

Taking into account the values of mathematical expectations of the bearing capacity of an industrial building (2) and the generalized load $m_F(t)$ (3), determine the rate of wear:

$$\overline{V}_S(t)=\frac{d}{dt}m_{\tilde{S}}(t), \tag{5}$$

Then, the health functions $S(t)$ and reliability index $\beta_S(t)$ taking into account the wear become:

$$S(t)=m_{\tilde{S}(t_0)}-t\,\overline{V}_S(t), \tag{6}$$

$$\beta_S(t)=\frac{m_{\tilde{S}(t_0)}-t\,\overline{V}_S(t)}{\sqrt{\sigma_{\tilde{R}_S}{}^2-t^2\sigma_{V_S}{}^2}}\ , \tag{7}$$

where $m_{\tilde{S}(t_0)}$ is the mathematical expectation of the reserve strength at the first inspection,

$\sigma_{\tilde{R}_S} = m_{\tilde{R}_S}\ f_S$ is standard carrier capacity of construct,

$\sigma_{V_S} = \overline{V}_S\ f_{V_S}$ is standard wear rate, f_{V_S} is wear rate coefficient of variation.

Reliability index, which allows to evaluate the durability of a building and the maintenance of its operability before the onset of the limit state since the last survey, is a gamma resource. For a given confidence level of results, it is defined as:

$$T_\gamma(t_n)=\frac{2m_{\tilde{S}(t_0)}\overline{V}_S(t_n)-\sqrt{4m^2_{\tilde{S}(t_0)}\overline{V}_S^2(t_n)-4\left(\overline{V}_S^2-\beta_S^2(t_n)\sigma^2_{V_S}\right)\left(m^2_{\tilde{S}(t_0)}-\beta_S^2(t_n)\sigma^2_{m_{\tilde{S}}}\right)}}{2\left(\overline{V}_S^2(t_n)-\beta_S^2(t_n)\sigma^2_{V_S}\right)}. \tag{8}$$

where t_n is the time interval from the commissioning of the facility until the last survey.

As a final indicator of the assessment of the total period of operation of the facility from the moment of construction to reaching the limit state, a technical resource is adopted:

$$T=t_n+T_\gamma(t_n). \tag{9}$$

A practice in which, based on the results of only one field test, conclusions are drawn about the magnitude of the wear rate, should be considered erroneous. In this case, the obtained calculated values of the strength reserve, corresponding to the stress-strain state at the time of the survey, are compared with similar design indicators. With such a formulation of the problem, the researcher initially comes to unreliable results, since the actual values of the displacements at fixed points of the frame under the action of a generalized load when the building is started may differ significantly from the calculated ones. It should be concluded that it is necessary to conduct at least two full field tests of the object being examined. Moreover, for greater reliability of the results obtained, the first of them should take place at the initial stage when the industrial building is commissioned.

3. Results and Discussion

The reliability of the results of the numerical implementation of the developed algorithm is ensured by good convergence with the experimental data obtained during surveys of industrial buildings of the “Red Barricades” ship hull and naval shipbuilding plant, the diesel ceremonial workshop of the Lenin shipbuilding and shiprepair plant, the main building of the “Promstroimaterialy” plant of reinforced concrete structures operating on the territory of the Astrakhan region of the Russian Federation.

As an example, we present an analysis of the results of calculating the building of the shipbuilding shop of the Astrakhan Marine Shipbuilding Plant. Its spatial design scheme corresponds to that presented in Figure 1(b), and is refined taking into account the factors that significantly affect the work of the framework [25, 35].

In the course of implementing the algorithm, three problems were solved successively: direct, inverse and predictive (Figure 3). Based on the results of measuring dynamic parameters during the first survey at the initial stage of building operation in 1986, the direct task of assessing the technical state of the facility was solved. Its formulation is aimed at determining the stress-strain state of an object at a particular time, starting from the initial data and the known patterns of its behavior. For determine them in the level of the crane beam and the cover, movements from the loads acting on the frame of the building are fixed. The initial data for solving direct problems: the geometric dimensions of buildings and its main load-bearing structures, complete information on the cranes used, external and internal loads, stiffness matrix and mass matrix. In 1996 the movements in the same control points were re-determined, which made it possible to implement the inverse problem algorithm. It boils down to the search for new values of stiffness characteristics when establishing the design points of the framework, in which there was a change in the displacements associated with a decrease in rigidity of the carcass after several years of operation. The received corrected matrix is used in further studies in solving problems of assessing the performance of structures under the influence of external influences. The forecast task is aimed at finding a time point when the frequency of the building's fluctuation will decrease by 10 % relative to the initial one. Algorithm for its solution allows to determine the time period for the object to reach a state that requires an unscheduled survey.

	1	2	3	4	5	6	7	8	9	10
Direct problem	4.13	4.39	24.57	25.4	25.55	25.67	25.71	25.92	26.11	27.78
Inverse problem	3.9	4.06	22.96	24.05	24.29	25.41	25.55	25.82	25.85	27.8
Forecasting task	3.714	3.941	22.25	23.28	23.56	25.41	25.55	25.81	25.85	27.8
Deviation, %	10.07%	10.23%	9.44%	8.35%	7.79%	1.01%	0.62%	0.42%	1.00%	0.07%

Figure 3. Dynamics of frequency distribution for the first 10 forms of vibration.

At the initial stage, the oscillation frequency in the first form was 4.15 sek^{-1}, and after 10 years of operation 3.90 sek^{-1}. The change in the dynamic characteristic was 5.5 %, which does not exceed 10 %, established by standards. With a 10% change in the initial frequency, its value in the first waveform will be 3.714 sek^{-1}.

The performed calculations in the probabilistic setting, taking into account the lower stiffness characteristics, can be used to assess the hazard of the action of the established loads after a specific service life of the object. During the analysis of the calculation results, the largest stress values were recorded at the monitored points of the most loaded transverse frame, in which the bridge crane functions. Realizing the proposed algorithm for assessing the reliability and durability of the object (1)–(9), it becomes possible to construct correlation dependencies of the considered indicators. The basis of the dependencies put the wear rate of the structural element and the planned number of t years of operation of the research object.

The values of the numerical characteristics of the generalized load, voltage, reserve, operability and reliability obtained during the processing of the results of the two surveys made it possible to establish a compliance with the time factor (Figures 4–8). The graphs are plotted for the worst values of the indices calculated for each of the monitored points of the model of the object with and without taking into account the seismic component. Rationing the analytical representation of the value of the generalized load made it possible to perform the construction of the corresponding function (Figure 4).

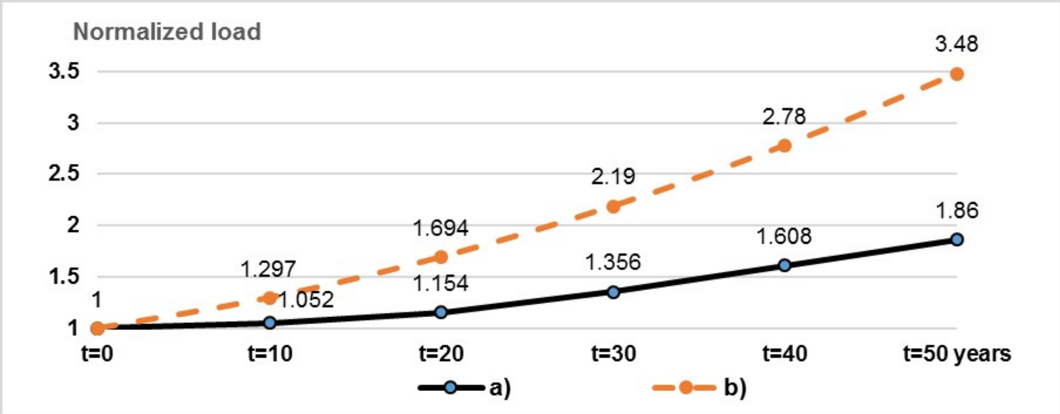

Figure 4. Fictitious load function: a) without seismic actions, b) taking into account seismic actions.

Fictitiousness lies in the fact that, in accordance with the statement of the problem, the load factor remains unchanged. Therefore, this function displays the magnitude of the effects applied to the framework with the initial stiffness characteristics that would allow to achieve the displacements predicted after 10, 20, ... years of operation.

Then the dynamics of the change in the maximum stresses at the node points of the design scheme during long-term operation of the shipbuilding shop can be traced by analyzing the behavior of the corresponding time function (Figure 5).

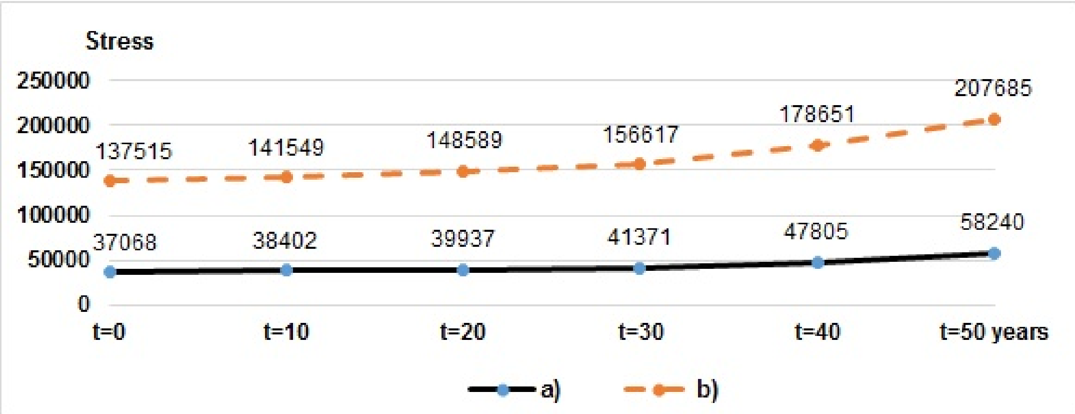

Figure 5. Time function of stress: a) without seismic actions, b) taking into account seismic actions.

The generalized safety factor, which assesses the risk factor for further exploitation of building structures at different times, is described by the function graphically presented in Figure 6.

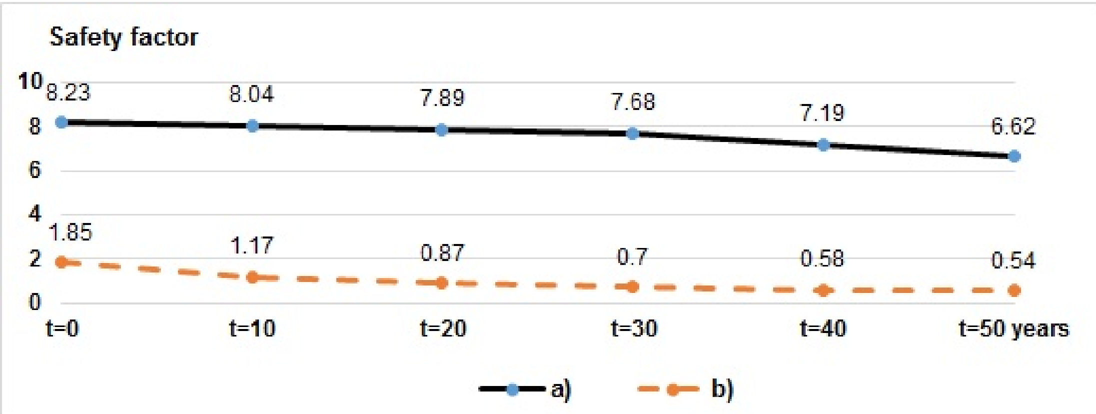

Figure 6. The function of the generalized safety factor: a) without seismic actions, b) taking into account seismic actions.

For the possibility of predicting the reliability indicators under consideration, proceeding from the difference in the sums of the mathematical expectations of all stresses from the action of the unchanged load factor based on the results of the two surveys, the average annual wear rate was determined. Taking into account this value, construction of operability functions (Figure 7) and reliability index (Figure 8), describing the reduction of the system's carrying capacity during the operation of the facility, was carried out.

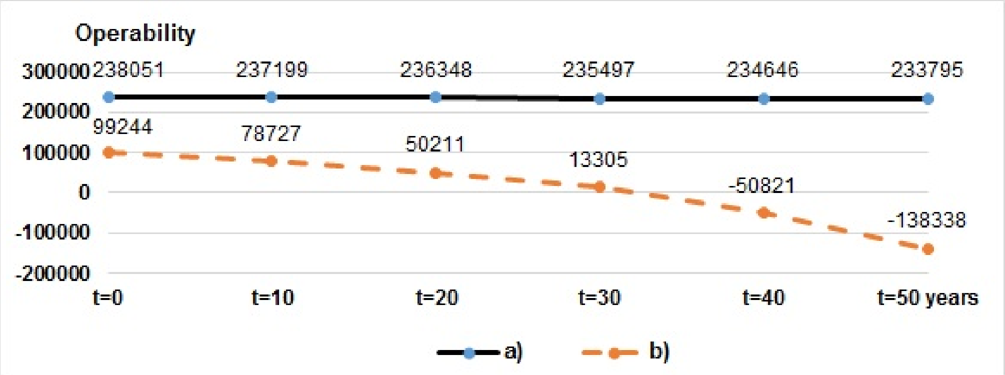

Figure 7. Operability function: a) without seismic actions, b) taking into account seismic actions.

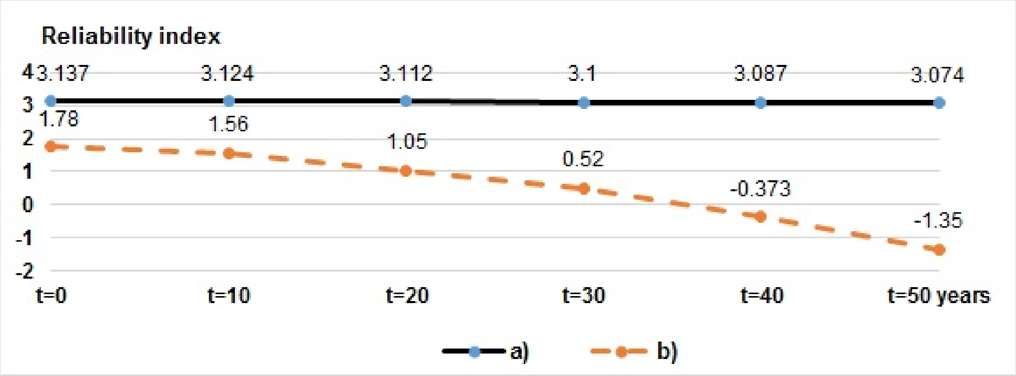

Figure 8. Reliability index function: a) without seismic actions, b) taking into account seismic actions.

Judging by the graphs of the functions shown in Figures 6, 7 and 8, the reliability of structural elements of the building frame is significantly reduced during operation. This fact is a consequence of a gradual decrease in horizontal rigidity and accumulation of damages in the mating interfaces of load-carrying structures of the frame.

Under the action of a combined combination of loads, taking into account seismic actions, significant increments in all the considered dynamic indices are fixed in the level of the completion of the columns, which is explained by the motions of the soil at the base of the frame. For the possibility of conducting a comparative analysis, Table 1 presents the average annual growth rates for each of them.

Table 1. Average annual growth rates of indicators.

Indicators	Fictitious load	Temporary voltage function	The generalized safety factor	Operability function	Reliability index
without seismic actions	1.76%	1.04%	-0.38%	-0.04%	-0.04%
taking into account seismic actions	4.96%	0.98%	-1.31%	-4.65%	-3.53%

Table 2 shows the results of an assessment of the safety of operation of the shop building according to the spectrum of the most unfavorable values of these indicators, determined for all nodes of the design scheme at the time of the second survey.

Table 2. Extreme values of indicators.

Combined combination of loads	The generalized coefficient of reserve	Reliability index	Wear rate (kPa/year)	Residual resource (years)
without seismic actions	8.04	3.12	97	17
taking into account seismic actions	1.17	1.56	4751	0.43

Analysis of the results of calculations for a specific research object allowed the following conclusions:

- the value of the reliability index is provided for all positions only under the action of the generalized load without taking into account seismic disturbances;
- the smallest generalized safety factor excluding the seismic action is 8.04, which is within the range of the recommended design practice [6; 9];
- the smallest generalized safety factor taking into account the action of seismic load drops to 1.17, due to the 50-fold increase in the wear rate structures;
- the predicted service life, after which the frequency of natural oscillations of the carcass structures will change by 10 %, decreases with taking into account the seismic load from 17 years to 0.43 years.

These parameters are the basis for deciding whether to implement structural measures to strengthen the framework.

4. Conclusions

Thus, the implementation of the developed mathematical apparatus allows not only to assess the technical condition of the building at the time of the survey, but also to predict the timing of the onset of a dangerous state on the basis of an analysis of changes in its dynamic characteristics. The forecasting of the dynamics of the stress-strain state changes allows planning the timing and direction of the repair of load-bearing structures in order to increase their service life.

The reliability of the obtained results is provided by taking into account the entire range of possible deviations of the input parameters of the calculation model and the loads with respect to the corresponding mathematical expectations.

The presented algorithm for estimating the residual life of an industrial building in operation allows:

1. to formalize the concept of a probabilistic approach to the study of changes in the stress-strain state of the framework of a production facility in the process of its operation, taking into account the variability of impacts through the sequential solution of direct, inverse and predictive problems;

2. to orient the formulation and search for the solution of the research tasks to assess the resource by analyzing the dynamics of the natural oscillation frequencies at the controlled points of the framework when constructing in the correlation approximation the functions of fictitious load and the performance of the building;

3. to carry out calculations to assess the reliability and durability of the steel frame structures of an industrial building using the limit state method, taking into account the random nature of the existing loads and the strength properties of building materials based on the results of surveys using a probabilistic model.

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