DEFINITION OF RELIABILITY PARAMETERS OF THE SPACER PLATE OF A JAW CRUSHER DEPENDING ON THE CHARACTERISTICS OF THE WORKING ENVIRONMENT AND THE MATERIAL OF MANUFACTURE

The object of the study is the spacer plate of a Jaw crusher. The Jaw crusher is the main machine in the crushing and sorting scheme. An unexpected failure of one of the crusher parts leads to a stoppage of the entire scheme. One of the important parts of the crusher is the spacer plate, which is in a complex, alternating stress state.

The paper investigates the reliability parameters of the spacer plate of a jaw crusher in the processes of crushing crushed stone, which is an aggregate in the manufacture of concrete. The calculation of the strength of the spacer plate in existing methods is carried out using empirical formulas. A number of functional methods are also used. However, most functional methods have inherent shortcomings that are built on statistical approaches, which can lead to inaccurate reproduction of the picture of the failure of machine elements. In the work, the problem is solved by using a combined model, namely the linear damage accumulation algorithm in combination with a finite element model to which the Weibull distribution is added, which is the most universal method of functional distribution for determining the limit states of parts and machine assemblies. Such a solution allows to determine the reliability parameters and establish a real picture of the process. A solid-state model of a jaw crusher has been developed and the loads applied to the spacer plate have been calculated.

Using the nCode EN Constant and nCode EN TimeSeries presets, which are built into the ncode DesignLife product of Hottinger Baldwin Messtechnik GmbH (Germany), the parameters of the failure life and fatigue strength of the crusher spacer plate were determined. In the nCode EN TimeSeries preset, the WeibullAnalysis glyph was used for data analysis. The results of the study can be used in studies of a wide range of machines to determine the limit states of machine parts and assemblies

Keywords: jaw crusher, spacer plate, model, Weibull distribution, parameters, failure, reliability

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1. Introduction

A wide range of machines are used in the production of building materials. The most energy-intensive process is the crushing process, for which appropriate crushing machines are used. The main types of crushing machines intended for the production and processing of building materials are jaw, cone, roller and impact crushers. Jaw crushers are used mainly at the first and second stages of crushing. The costs of material resources for the process of manufacturing building materials by a crushing machine can generally be divided into two categories, namely for the destruction of the material to the required size and the operation of the machine. Operating costs include machine maintenance, the purpose of which is to maintain the machines in good condition by repairing or replacing worn parts. The destruction of the crusher structural elements can occur due to fatigue wear after some operation or suddenly due to defects in the

manufacturing process of the part. The reliability of the crushing machine structural parts depends on a number of factors, as a result of which the solution of such a problem is significantly difficult. Unplanned failure of a part or component of a crushing machine can lead to a decrease in plant productivity, unwanted equipment downtime, which will ultimately lead to significant material costs. The most loaded components of a jaw crusher include crushing plates, bearings, spacer plate, belt, eccentric shaft.

It should be noted that traditional approaches based on rigidly regulated rates of write-off of resources (for example, planned preventive maintenance according to the calendar) are gradually being replaced by Condition-Based Maintenance and Predictive Maintenance strategies. In this context, the "classic triad" of operational indicators – operating hours, energy consumption and load – takes on a new meaning, turning into a stream of digital data that requires complex analytical processing.

A number of functional methods are used to solve reliability problems and determine the optimal values of durability and fatigue strength parameters in accordance with the tasks set [1]. However, most functional methods have the following disadvantages:

1) are built on statistical approaches, which may lead to inaccurate reproduction of the picture of the failure of machine structural elements;

2) have significant difficulties in taking into account the interaction of machine design elements;

3) the complexity of describing reliability parameters under operating conditions of machine elements under variable load.

Therefore, to take into account the real picture of the operation of a construction machine, it is necessary to combine the functional method with other models or approaches. Such models include operating condition coefficients, physical load models, limit state models, degradation models, accelerated test models, Markov models, etc.

Thus, research devoted to determining the reliability parameters of the structural elements of a crushing machine is relevant.

2. Analysis of literary data and problem statement

In [2] an approach for assessing the reliability is proposed. systems when failure data is missing. Research primarily aimed at an industry such as aviation technology. The main disadvantage of the work is that only one functional Weibull method was used to determine the reliability parameters, this can lead to inaccuracy of the model, while the shape parameter is assumed to be known in advance. In addition, the constructed model [2] takes into account only failure-free observations and is tested only for a satellite sensor. In another work [3], the authors performed an analysis of the reliability of machine tools with numerical program control, where the data between the failure times of the machines are described by a two-parameter Weibull distribution. The disadvantage of the work is the limitation of the data to machines with numerical program control of full models and lack of analysis of operational factors. In [4], the authors combine the Bayesian approach with the Weibull distribution to model the distribution of time to failure and assess the reliability of the system based on a data set. The disadvantages of the study are that when using the Bayesian method, the result strongly depends on the selected distribution, limited analysis of tech-

nical causes of failures and operating conditions, and a small amount of data sample. In [5], the authors use mixed Weibull models. However, this approach still does not increase the accuracy of the model, since it is built on a statistical distribution model and does not take into account the stress-strain state of the machine tool design. On the other hand, the use of the three-parameter Weibull distribution significantly complicates the calculation model, which can also affect the accuracy of the calculations. In [6], the authors build a reliability model for CNC machine tools based on a combination of a structural model in BlockSim and a statistical failure distribution in Weibull++. Here, the problem of taking into account the real stress state of parts or machine structure is still not solved. Although Weibull++ and BlockSim support various types of functional distribution methods and are powerful tools for reliability analysis, when solving problems of designing and creating machine structures, it is often necessary to display the stress and strain pattern. It should be noted separately that in [6] the assumption was made that the time between failures is subject only to the Weibull distribution. In [7], an analysis of the fatigue reliability of mechanical components subjected to random vibration loading was performed. The Weibull distribution model is combined with a fatigue damage accumulation model, which allows modeling the stochastic behavior of a mechanical component under dynamic loading and making reliability predictions. The disadvantages of the model are the possibility of using it only for the analysis of systems operating under vibration loading. The absence of a stress and strain pattern, as well as a dynamic analysis that determines the energy characteristics of the process. In [8], a study of the use of the Weibull distribution in the case when there is no data on failures, i.e., when the parts are made of durable materials and with high processing accuracy, is considered. It should be noted that the best option in this case is the use of the functional distribution method in combination with finite element analysis. In [9], the practical use of two statistical models for assessing the reliability of industrial systems is considered:

1) discrete inverse model Polya;

2) a discrete version of the Weibull distribution.

The disadvantages include a small data sample and discrete approximation. In [10], the authors consider the prediction of mechanical system failures using a mixed Weibull model in combination with a proportional hazard model. The disadvantages are the complexity of the model and the need for a large amount of data. In [11], the use of the Weibull distribution as a criterion for assessing equipment failure states based on the analysis of vibration parameters of machines is investigated. The disadvantages are the limited application of this approach to underground mining equipment, the dependence on data quality, and the simplified hazard function model.

In [12], the distribution of stresses and strains in the elements of vibrating machine structures was investigated. The disadvantage of the work is the lack of studies of reliability parameters. In [13], the equations of motion of the "machine-environment" system are investigated, in which the environment is represented by a discrete-continuous model, however, the time to failure is not given.

The efficiency of the work process of any construction or mining machine is determined by a set of parameters of the machine itself and the working environment and an assessment of their mutual influence. These parameters are closely related to each other and have a significant impact on the

energy efficiency of the machine as a whole. From the review of similar works presented above, it follows that the use of a separate functional method or their combination to determine the reliability parameters is still a common approach, which still cannot provide an accurate and detailed picture of the operation of the machine parts. Therefore, the study of the reliability parameters of the machine was carried out based on a combination of different models and algorithms, which as a result gives significant flexibility in the design and operation of such machines.

All of the above allows to state that it is advisable to conduct a study dedicated to determining the reliability parameters of structural elements of construction machines using combined methods, which will include a finite element model in combination with a linear damage accumulation algorithm, a functional distribution method, and physical and mechanical properties of the environment.

3. The aim and objectives of the study

The aim of the study is to determine the reliability parameters of the jaw crusher spacer plate depending on the characteristics of the working environment and the material of manufacture. This will make it possible to optimize the material costs of operating the crusher and, at the initial design stage, rationally select the parameters of the mechanical mode of the machines depending on the physical and mechanical properties of the material being crushed.

To achieve the aim, the following objectives were set:
– to investigate the influence of the parameters of the Weibull distribution method on the change in reliability parameters;
– to investigate the reliability of the spacer plate of the designed jaw crusher based on the use of the combined method and taking into account the characteristics of the working environment and the material of manufacture.

4. Materials and methods

The object of the study is the spacer plate of a jaw crusher. The hypothesis is accepted in the work that the application of the Weibull functional distribution method in combination with a finite element model of the part for research makes it possible to obtain parameters of the failure durability and fatigue strength of the spacer plate, which reflect the real picture of the process of its loading. It should be noted separately that the combined model, which is indicated above, is supplemented by a physical and mechanical model of the material, which is determined by the applied force to the spacer plate. In the theoretical modeling of the loads on the spacer plate, only the case of the force acting along the axis was considered, which is a corresponding simplification.

When modeling the experiment, a material with a compressive strength not exceeding 80 MPa was used. A special script written in the python programming language was used to construct a diagram of the real crusher operation process.

Thus, JupyterLab (Open) was used to calculate the optimal values of the Weibull distribution parameters and to construct the corresponding graphs. Source Project, International Community), which is due to the flexibility of this software and its wide practical using. Modeling of loads on the jaw crusher spacer plate and corresponding determi-

nation of stresses, deformations and safety factors was performed in Ansys 2024 R 1 (ANSYS, Inc., USA), as it is best suited for modeling the statics and dynamics of continuous and discrete media by the finite element method and allows parameterizing the created models and loading experimental data. In order to determine the reliability parameters, the corresponding nCode module was connected to Ansys 2024 R 1 (ANSYS, Inc., USA). DesignLife (HBK, Germany). nCode module DesignLife (HBK, Germany) is the best choice for studying the reliability parameters of machine design elements. Solid-state modeling of machines and parts was performed in Autodesk Inventor 2025 (Autodesk, Inc., USA), which is due to the availability of this software when solving scientific problems.

5. Results of the study of the reliability parameters of the jaw crusher spacer plate

5. 1. Study of the influence of Weibull distribution method parameters on the change in reliability

Statistical distributions are designed to model certain behavior. The mathematical function that describes the distribution is the probability density function. The Weibull distribution function can be of three types, according to the number of parameters. Thus, the three-parameter Weibull probability density function is determined based on the dependence

$$f(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}}, \tag{1}$$

where $f(t) \geq 0$, $t \geq \gamma$, η – the scale parameter or characteristic lifetime, $\eta > 0$; β – the shape parameter (or slope), $\beta > 0$; γ – the location parameter (or failure-free lifetime), $-\infty < \gamma < \infty$.

Weibull distribution is obtained from equation (1) assuming $\gamma = 0$. In turn, the one-parametric Weibull distribution is obtained when $\gamma = 0$ and $\beta = C = constant$.

Average and expected time to failure

$$\bar{T} = \gamma + \eta \, \Gamma\left(\frac{1}{\beta}+1\right), \tag{2}$$

where $G(1/\beta + 1)$ – the gamma function.

The Weibull distribution or the time to failure of 50% of the products is defined as [14]

$$T_m = \gamma + \eta \left(\ln 2\right)^{\frac{1}{\beta}}, \tag{3}$$

The Weibull distribution, or one particular failure that occurs most frequently, [14]

$$T_{moda} = \gamma + \eta \left(1-\frac{1}{\beta}\right)^{\frac{1}{\beta}}, \tag{4}$$

Standard deviation, or a measure of the dispersion of values around the mean, [14]

$$\sigma_T = \eta \sqrt{\Gamma\left(\frac{2}{\beta}+1\right) - \Gamma\left(\frac{1}{\beta}+1\right)^2}, \tag{5}$$

Weibull reliability function, [14]

$$F(t) = 1 - e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}},\tag{6}$$

The time until which a part will operate with a certain specified reliability [14]
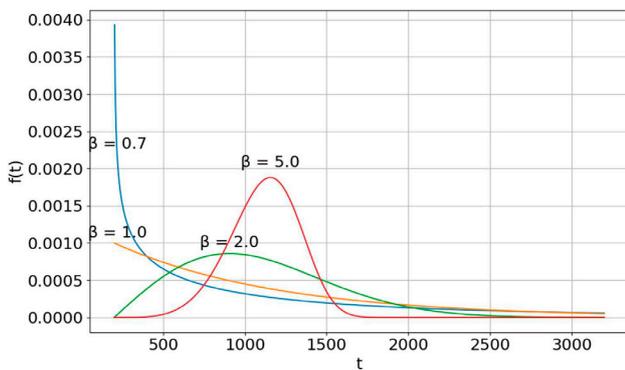
$$T_R = \gamma + \eta\left\{-\ln(R)\right\}^{\frac{1}{\beta}},\tag{7}$$
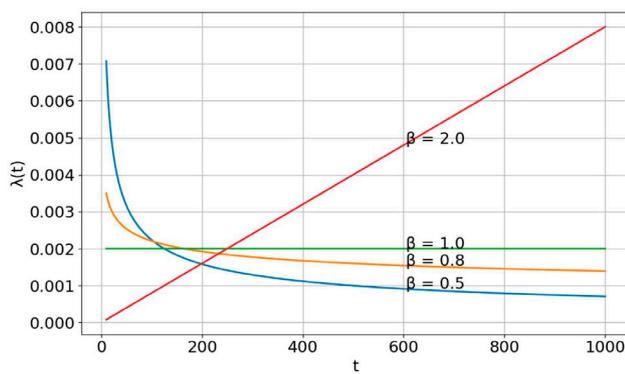
Failure intensity function [14]

$$\lambda(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1}.\tag{8}$$

The Weibull distribution was considered. So, the parameter β or the shape parameter has a noticeable effect on the behavior of the distribution. The value of this parameter determines the slope of the regression curve. With certain values of β, other shapes of the distribution can be obtained. Graph of the change in the probability density of the distribution depending on the change in β presented in Fig. 1.

From the graph in Fig. 1, a, it can be noted that for values of $\beta < 1$ the distribution curve repeats the shape of a hyperbola and the smaller the value, the steeper the curve decreases. For values of $\beta > 1$ the curve first increases, then reaches its peak, and then decreases. Additionally, it should be noted that for $\beta = 0.999$, $f(0) = \infty$, but for $\beta = 1.001$, $f(0) = 0$. This property of the distribution complicates the estimation of the maximum likelihood (MLE).

The influence of the coefficient β on the failure rate is shown in Fig. 1, b. From the graph it can be noted that at $\beta = 1$, the distribution curve is horizontal and reflects a constant failure rate. Thus, the distributions that are determined at $\beta < 1$ reflect the failure rate, which decreases over time, and at $\beta > 1$ failure rate that increases with time. Failure rates in the range $0 < \beta < 1$ may indicate early failures, i.e. problems in the production process, packaging, etc. Constant failure rate at $\beta = 1$ reflects the failure rate of units over their service life. For $\beta > 1$, the parameter $\lambda(t)$ increases and reflects the failure rate of units exhibiting wear-like damage.

The change in the scale parameter on the probability density distribution is presented in Fig. 2.
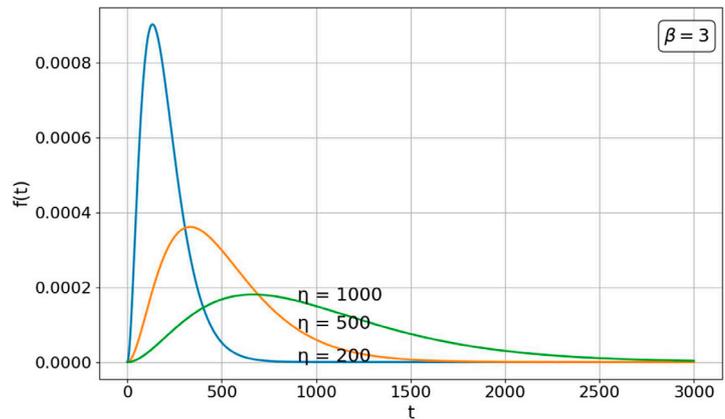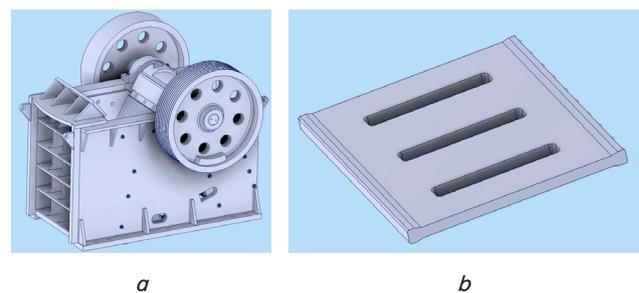

Fig. 2. Graph of the influence of the scale parameter on the change in the probability density of the distribution

Increasing the value of η at a constant value of β stretches the graph in the direction of increasing the abscissa scale, such that the peak of the probability density curve of the distribution decreases.

5. 2. Study of the reliability of the spacer plate based on the use of a combined method

a solid-state model of the jaw crusher with complex jaw movement and a pleasant hole size of 1080×1240 was adopted, Fig. 3, a. To study the operating life to failure, the crusher spacer plate was considered. The spacer plate model is presented in Fig. 3, b.

Fig. 3. Solid-state model: a — jaw crusher with complex jaw movement; b — spacer plate

a

b

Fig. 1. Graphs of dependence:
a — shape parameter on probability density of distribution;
b — shape parameter on failure rate

Ansys 2024 R 1 software package using the ncode module. DesignLife 2024. Ncode DesignLife 2024 is a software that allows to perform fatigue strength and durability analysis of machine and equipment structures. At the first stage, a static analysis of stresses and strains that may occur in the spacer plate was performed. In [15], it is noted that the load

on the spacer plate can be determined based on the dependence

$$F_{sp} = \frac{2\pi\sigma_C^2\left(D^2 - d^2\right)L}{12ES_K}\cos\left(\alpha - \frac{\beta}{2}\right),$$ (9)

where $\sigma_c = 80\,\text{MPa}$ – ultimate compressive strength; $E = 55000\,\text{MPa}$ – modulus of elasticity; $S_K = 0.028\,\text{m}$ – travel of the movable jaw; $L = 1.24\,\text{m}$ – length of the crushing chamber; $D = 0.8\,\text{m}$ – average diameter of the material entering the crushing chamber; $d = 0.21\,\text{m}$ – size of the crushed product; $\alpha = 20°$ – angle of engagement; $\beta = 19°$ – angle of installation of the spacer plate. Based on the accepted values of the calculation parameters, the force that will act on the spacer plate when crushing a material with a strength of 80 MPa will be 1580953 N. Additionally, it is necessary to take into account the force from weight of the crusher structural elements – 83517 N. Thus, the total force will be 1664470 N. The case of force action along the axis of the spacer plate was considered. As the manufacturing material it is possible to take SCh18 36 (analogous to Grey Cast Iron BS 1452 Grade 250 [16]) and 45 steel (similar to Carbon Steel SAE 1045-225-ANLD [17]). Pictures of the safety margin of different sections of the spacer plate for gray cast iron BS 1452 Grade 250 and carbon steel SAE 1045-225-ANLD are shown in Fig. 4.
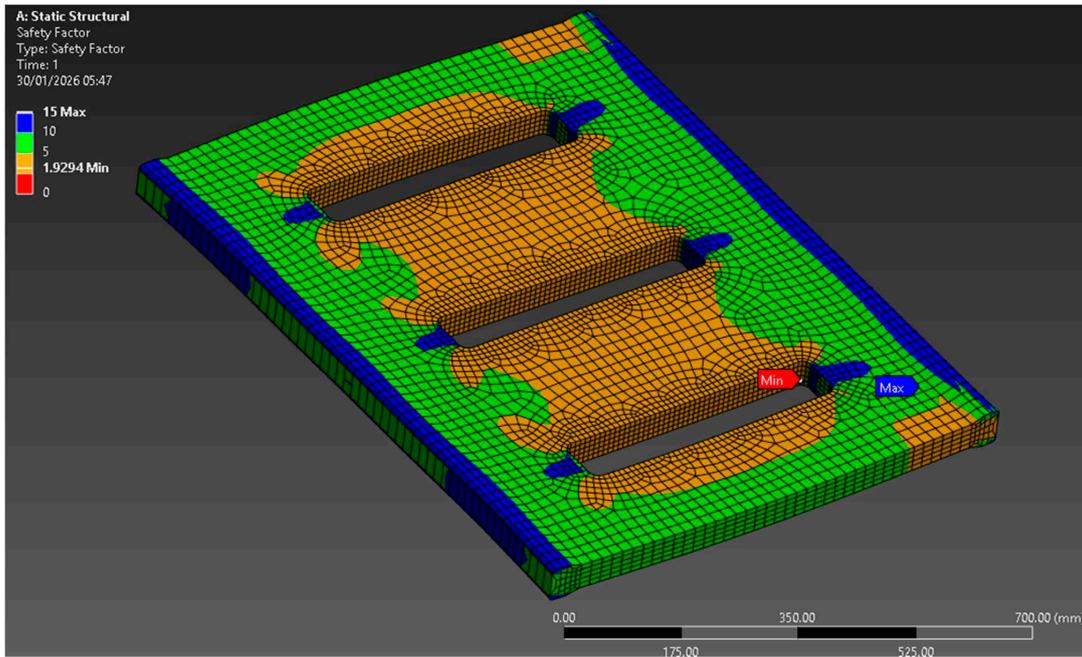
a
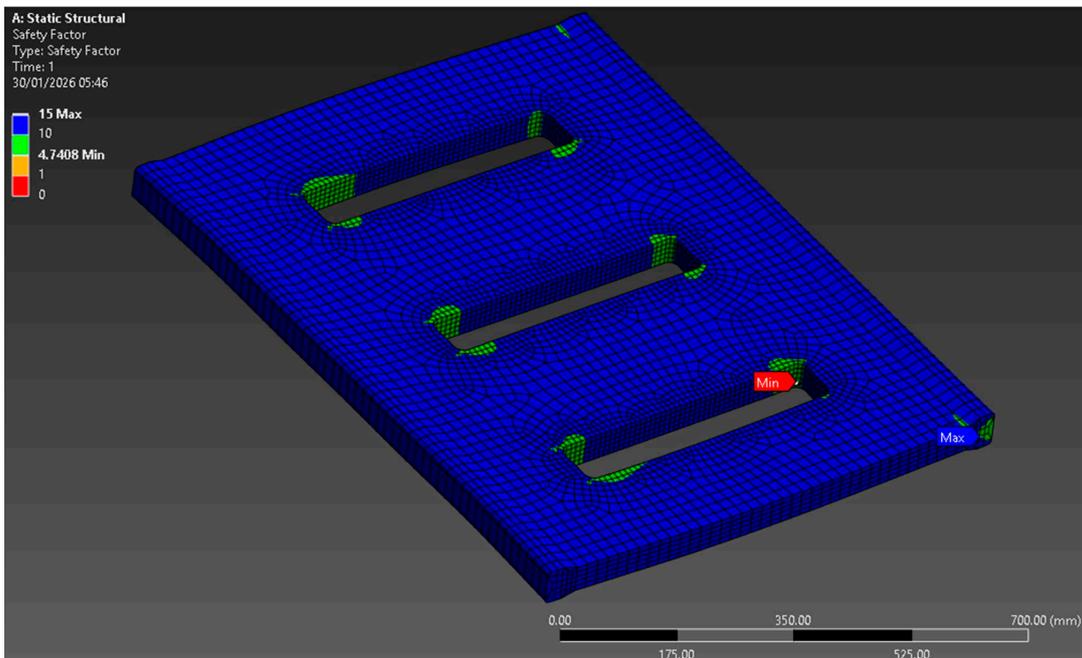
b

Fig. 4. Picture of the safety factor for: *a* — gray cast iron BS 1452 Grade 250; *b* — carbon steel SAE 1045-225- ANLD

Next, two analyses were performed – nCode EN Constant and nCode EN TimeSeries. When using ncode DesignLife in conjunction with Ansys 2024 R 1 should be noted the presence of eight presets prepared. The first two presets nCode EN Constant and nCode EN TimeSeries are designed for fatigue calculations under constant load (Constant) or under variable load (TimeSeries). EN designation is responsible for the fact that the controlling quantity of fatigue is the deformation. In the case of presets nCode SN Constant and nCode SN TimeSeries control variable is voltage. Presets ncode SN VibrationPSD and ncode SN VibrationSweptSine are designed for fatigue analysis under vibration conditions. VibrationPSD is responsible for random vibrations specified by power spectral density. VibrationSweptSine is responsible for harmonic excitation. NCode WeldShellSeam and nCode WeldSolidSeam is designed for fatigue life analysis of welds.

The next step was to consider the preset nCode EN Constant. The modeling window looks like the one shown in Fig. 5. As follows from Fig. 5, the model consists of a set of blocks – glyphs. Here it should be noted what the main glyphs are responsible for. Glyph Simulation_Input loads the result of the part calculation from the FEA module of Ansys into the ncode module. In Simulation_Input, it is possible to display the corresponding patterns of stresses and strains that occur in the part. Bill_of_material_input allows to edit the properties of the material from which the part structure is made. StrainLife_Analysis is the main glyph that receives data from the glyphs as input. Simulation_Input and Bill_of_material_input, after which a fatigue analysis is performed by deformations or by stresses. Preset difference nCode EN TimeSeries at this calculation stage consists in the presence of an additional glyph into which experimental data are loaded and fed as input to StrainLife_Analysis. Glyph Fatigue_Results_Display displays a visual picture for fatigue and durability analysis. DataValueDisplay 1 displays a table of calculated parameters such as life cycles (Life cycles), total accumulated damage, safety factor, stress values. In general, DataValueDisplay 1 helps to track parameter values when checking the correctness of calculations.

Fig. 6 shows the durability to failure patterns. The Weibull distribution was applied to the nCode calculation model EN Constant, which in this case can assess the durability of the structure based on the change in the stress-strain state. The most dangerous zones in Fig. 6, *b* are highlighted with a grid.
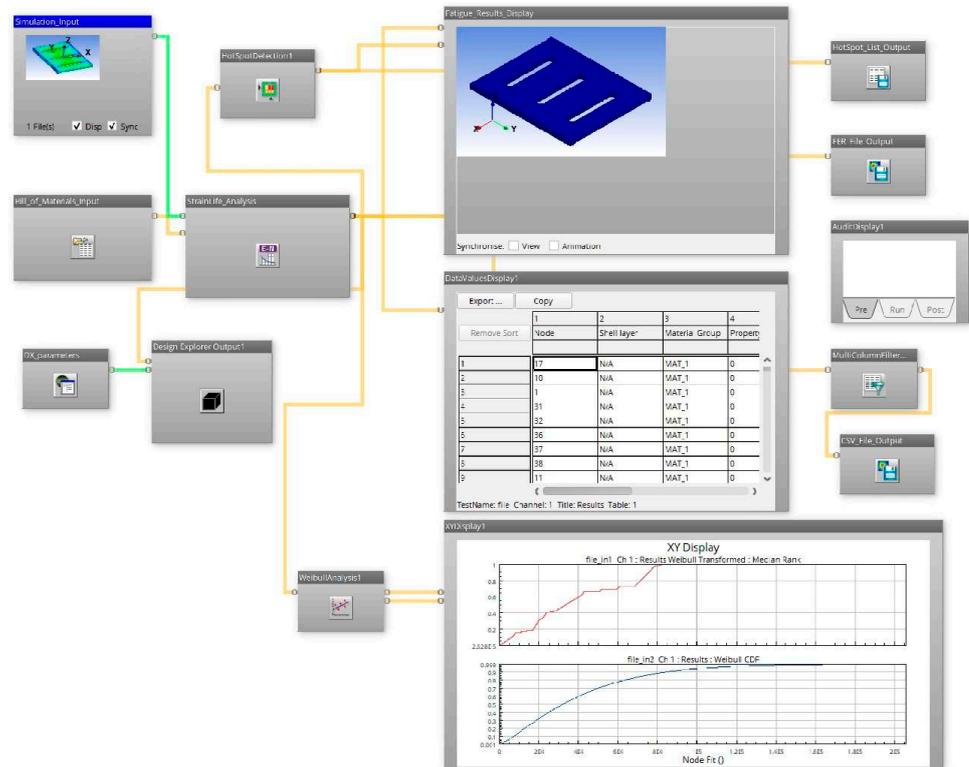

Fig. 5. Expansion plate calculation model in the nCode dialog box EN Constant

The numerical values of the simulation parameters are presented in Table 1.

When using the nCode module EN Time Series requires the presence of experimental data on the change in load over time. In the absence of such data, an approximate mathematical description of the process can be used. For example, the change in load on a structural element of the crusher can be described in some approximation by the equation

$$F_r = F_{sp}\sin(\omega t + \varphi),$$

where F_{sp} – maximum load on the spacer plate, ω – angular frequency of oscillations of the movable jaw, φ – phase shift. Another important parameter of the process is the entry of a larger amount of material into the crushing chamber or stronger pieces of material, which can cause a sharp increase in the level of load on the crusher structural elements. When crushing strong rocks or operating the machine in difficult conditions, such overloads can reach 100%. Therefore, the equation for signal generation can have a much more complex form than that presented above. It should be noted that the equation $F_r = F_{sp}\sin(\omega t + \varphi)$ builds an ideal signal shape, the use of which in calculation models gives a significant error. An important point in the formulation of the problem is that the weight force from the crusher structural elements in the process varies within fairly small limits, on the basis of which it can be assumed to be constantly acting. Then in the static calculation module, it is necessary to apply a load from the action of weight forces to the plate – 83518 N. The stress and strain patterns for steel are presented in Fig. 7. In turn, the stress and strain pattern for gray cast iron is similar.

Project window in nCode EN TimeSeries is presented in Fig. 8. The dialog box is slightly different from the standard one. Glyph removed Time Series Input, which only works well with data that has the extension .s3t. Added glyph for loading experimental data ExcelInput 1 combined with a glyph XYDisplay 1, which allows graphical display of data.

Additionally, a glyph has been added that converts data into a time series. In order to use the Weibull distribution for analysis, the WeibullAnalysis glyph has been added, as well as the corresponding display glyphs. Fig. 9 shows a graphical representation of the simulation results. The most dangerous zones in Fig. 9 are highlighted with a corresponding grid. Next to the model there is a scale, on which a red zone is marked, which reflects the minimum durability parameter.

Table 2 shows the numerical values of the results of the spacer plate simulation using the nCode module. EN TimeSeries
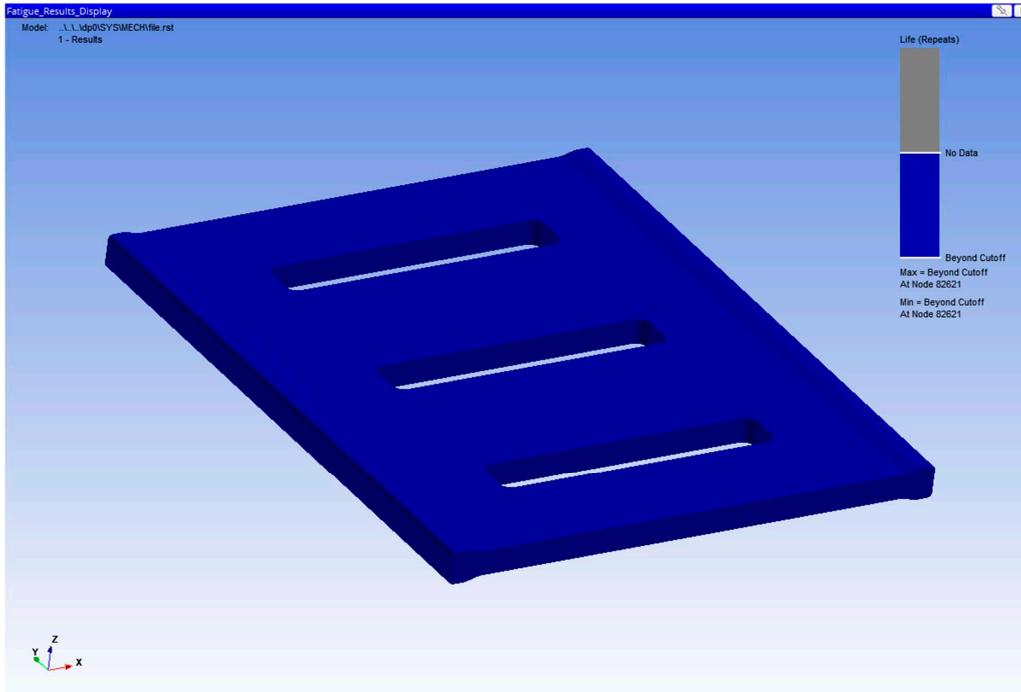
a
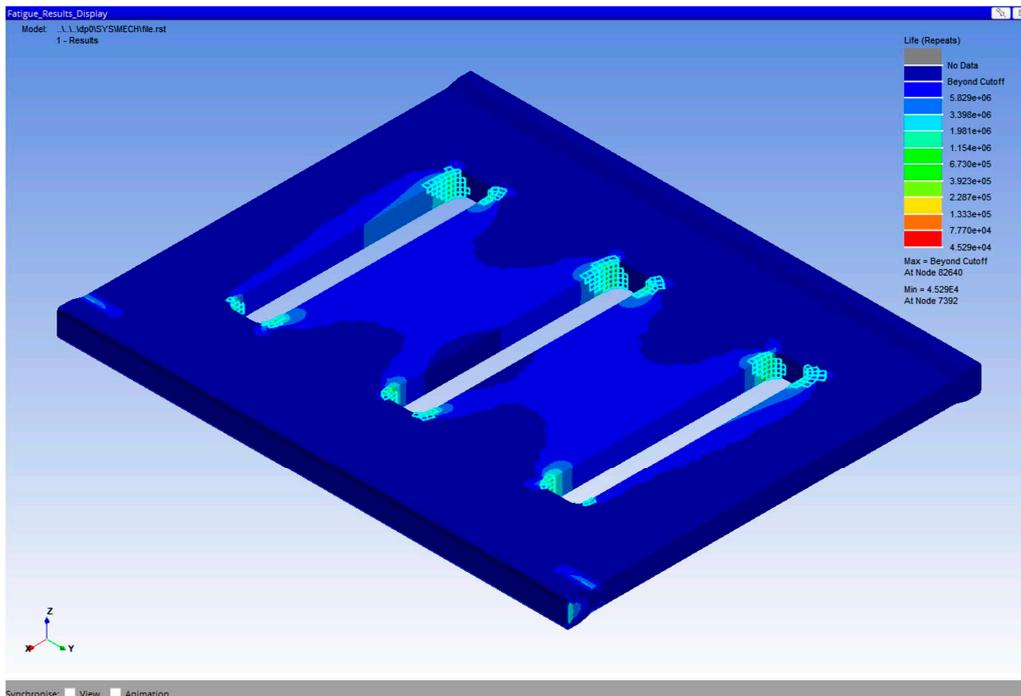
b

Fig. 6. Results of the calculation of the spacer plate for durability to failure in nCode EN Constant: *a* — SAE 1045-225-ANLD ; *b* — Gray Cast Iron BS 1452 Grade 250
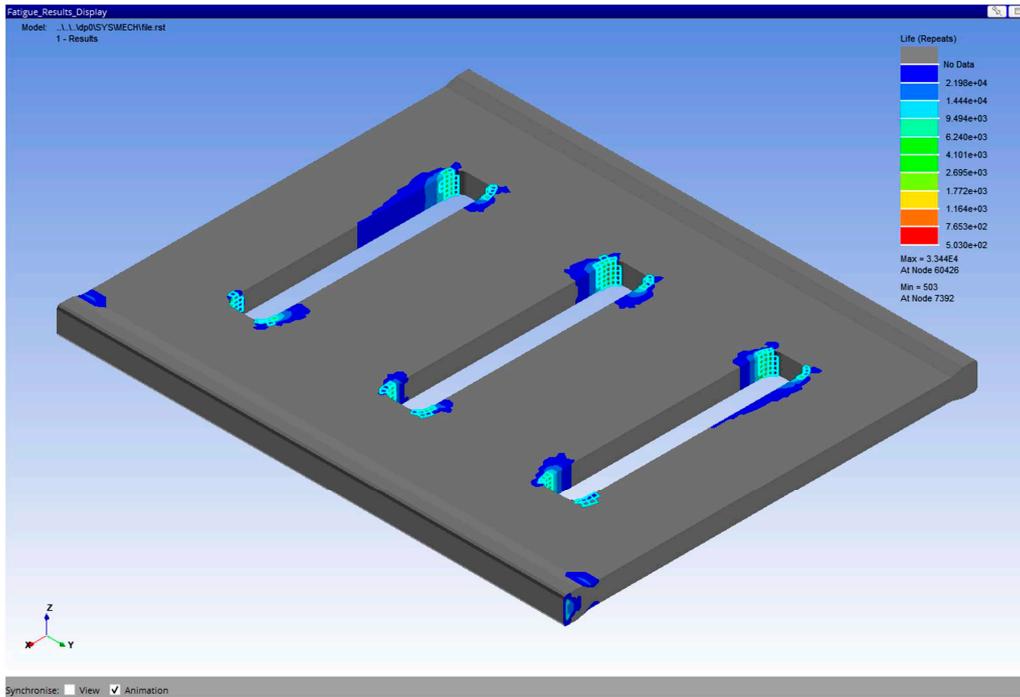
Table 1

Numerical values of the results of the spacer plate simulation in nCode EN Constant

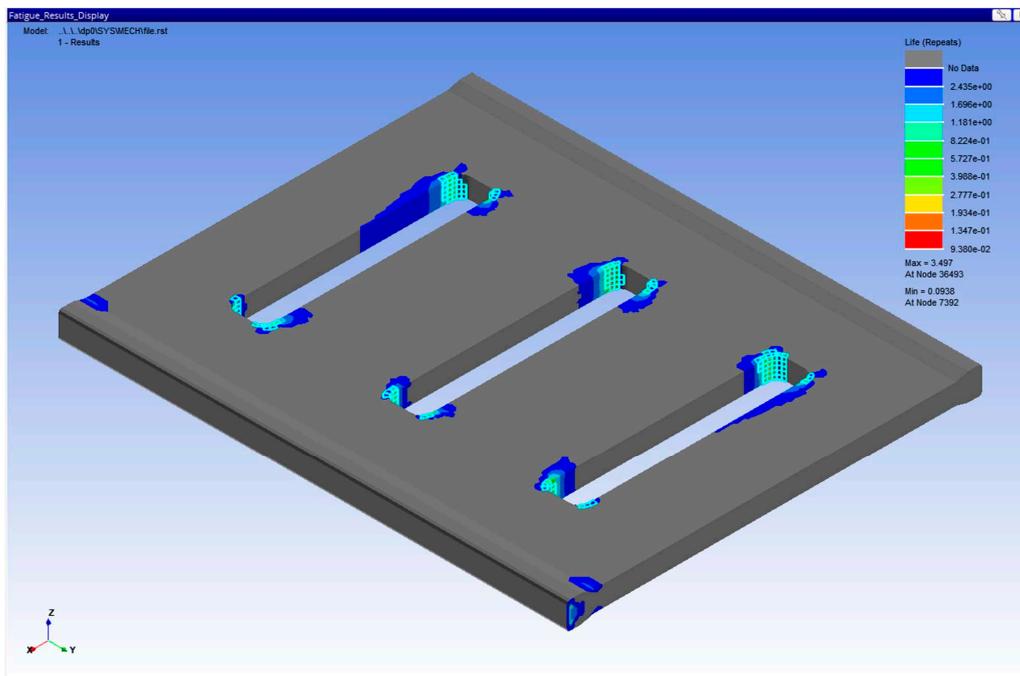| No.	Maximum stress, MPa	Maximum deformation, mm/mm	Damage parameter	Life parameter	Material
1	4.95E+07	2.50E-04	Outside the cutoff	Outside the cutoff	SAE1045 steel
2	5.90E+07	2.78E-04			
3	3.12E+07	1.59E-04			
4	4.17E+07	2.03E-04			
5	2.72E+07	1.35E-04			
6	2.55E+07	1.27E-04			
7	4.52E+07	2.19E-04			
8	4.52E+07	2.17E-04			
9	1.35E+07	5.92E-05			
10	4.95E+07	2.50E-04			
11	1.12E+08	8.82E-04	2.21E-05	4.53E+04	Cast iron BS1452
12	1.12E+08	8.82E-04	2.21E-05	4.53E+04	
13	1.13E+08	8.78E-04	2.15E-05	4.65E+04	
14	1.13E+08	8.78E-04	2.15E-05	4.65E+04	
15	1.13E+08	8.77E-04	2.14E-05	4.67E+04	
16	1.12E+08	8.77E-04	2.13E-05	4.69E+04	
17	1.12E+08	8.77E-04	2.13E-05	4.69E+04	
18	1.09E+08	8.60E-04	1.90E-05	5.25E+04	
19	1.09E+08	8.60E-04	1.90E-05	5.25E+04	
20	1.10E+08	8.56E-04	1.85E-05	5.40E+04	

Table 2

Numerical values of the results of the spacer plate simulation using the nCode module EN TimeSeries

No.	Maximum stress, MPa	Maximum deformation, mm/mm	Damage parameter	Life parameter	Material
1	5.773E8	0.01082	0.001988	503	SAE1045 steel
2	5.773E8	0.01082	0.001988	503	
3	5.788E8	0.01063	0.0019	526.2	
4	5.788E8	0.01063	0.0019	526.2	
5	5.812E8	0.01059	0.001883	531.2	
6	5.812E8	0.01059	0.001883	531.2	
7	5.81E8	0.01057	0.001875	533.3	
8	5.71E8	0.01042	0.001788	559.3	
9	5.71E8	0.01042	0.001788	559.3	
10	5.638E8	0.01032	0.001727	578.9	
11	4.21E+08	0.02443	10.66	0.0938	Cast iron BS1452
12	4.21E+08	0.02443	10.66	0.09381	
13	4.22E+08	0.02396	10.2	0.09805	
14	4.22E+08	0.02396	10.2	0.09805	
15	4.23E+08	0.02384	10.09	0.09913	
16	4.23E+08	0.02384	10.09	0.09913	
17	4.23E+08	0.0238	10.05	0.09949	
18	4.17E+08	0.0235	9.682	0.1033	
19	4.17E+08	0.0235	9.682	0.1033	
20	4.13E+08	0.02329	9.423	0.1061	

a

b

Fig. 7. The result of the calculation of the spacer plate from the action of the weight forces of the crusher structural elements:
a — stress pattern; *b* — deformation pattern

Fig. 8. Expansion plate calculation model in the nCode dialog box EN TimeSeries

a

b

Fig. 9. Results of the calculation of the spacer plate for durability to failure in nCode EN TimeSeries:
a — SAE 1045-225-ANLD; *b* — Gray Cast Iron BS 1452 Grade 250

In the glyph WeibullAnalysis, the analysis parameters were adjusted accordingly. It should be noted that only the two-parameter distribution is available for analysis in this case. The distribution curves are presented in Fig. 10.

The first output of the Weibull analysis glyph in Fig. 10, *b* displays the data in ascending order along with the corresponding median rank. The median rank is calculated using the Benard function. The second output provides values that represent the cumulative distribution function (CFD). The distribution is fitted to the median ranks. The range of output values is determined by the CurveNumPoints, CurveYMin, and CurveYMax properties. The two-parameter distribution forms a straight line on the Weibull axes and tends to the minimum life. The CDF function can be used to estimate the probability of failure. The service lives N 1, N 10 and N 50 are automatically calculated and displayed in the metadata.
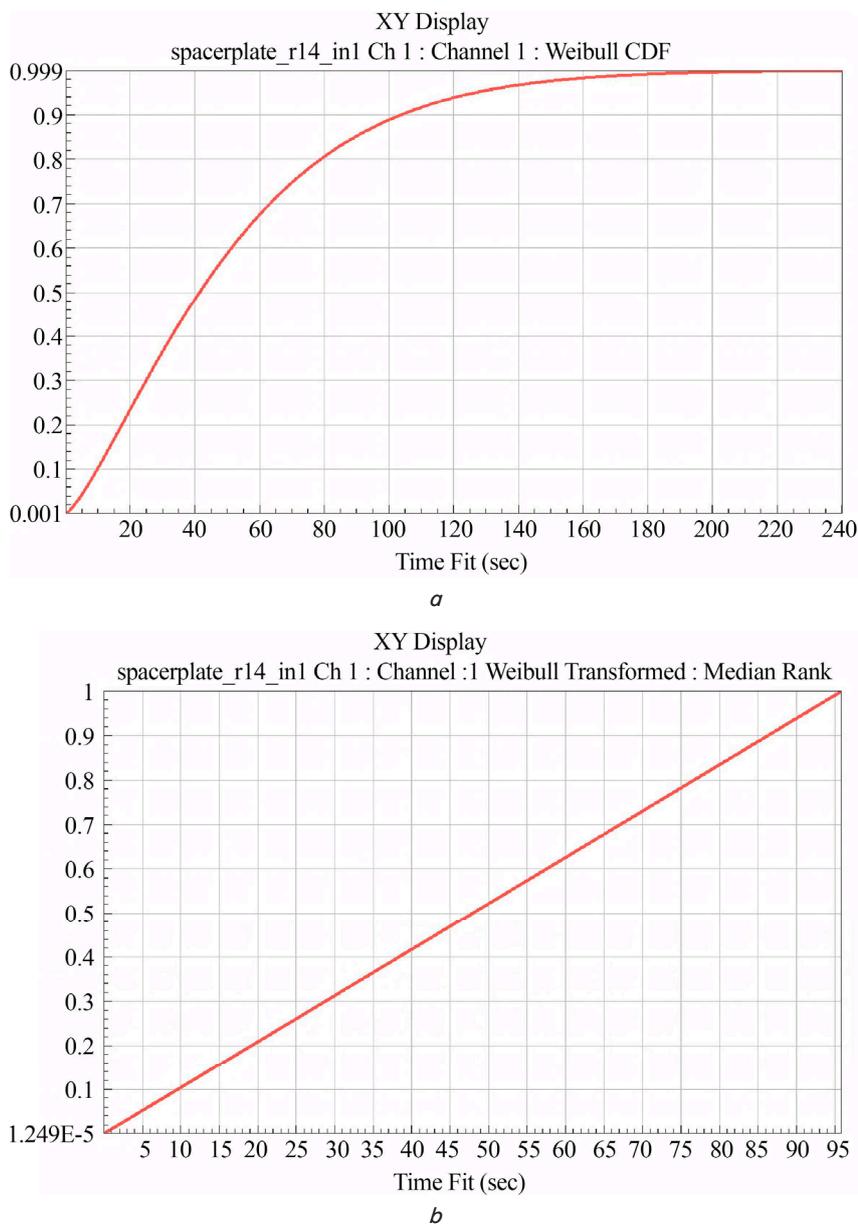
XY Display
spacerplate_r14_in1 Ch 1 : Channel 1 : Weibull CDF

a

XY Display
spacerplate_r14_in1 Ch 1 : Channel :1 Weibull Transformed : Median Rank

b

Fig. 10. Weibull distribution results: *a* — approximated data; *b* — experimental data with median rank

6. Discussion of the results of determining the reliability parameters of the jaw crusher spacer plate

Based on the analysis of the reliability parameters specified in Section 5. 1, it is possible to determine that the parameter β is in the vicinity of 2, and the parameter η will have a similar picture to Fig. 2.

The proposed model for calculating the spacer plate in the dialog box (Fig. 8) allowed to determine the fatigue life patterns (Fig. 9). This result is one of the practical recommendations for determining the reliability of structural elements of a similar class of machines, and is implemented for specific materials. The following patterns have been established:

1) the minimum value of the Life parameter for SAE 1045-225-ANLD steel is 503, while for cast iron Grey Cast Iron BS 1452 Grade 250 this parameter is within zero according to the results shown in Fig. 9;

2) for a long service life of the spacer plate and under conditions of crushing materials, which compressive strength may exceed 80 MPa, it is better to use SAE 1045-225- ANLD steel as the spacer plate material, which follows from the previous paragraph;

3) it was determined that the most dangerous zones are the tops of technological holes, according to the results obtained in Fig. 6, 9.

Thus, using a preset nCode EN Constant and nCode EN TimeSeries allows to estimate the durability of the structure taking into account the change in the stress-strain state, which makes it possible to analyze parts that operate under constant and variable loads in time. The proposed method of combining finite element analysis of the part with the linear damage accumulation algorithm and the Weibull functional distribution method is proposed as recommendations for scientific and practical use. The importance of this research method lies in the possibility of taking into account the physical and mechanical properties of the material, formula (9), which is being crushed.

As a result of the studies carried out on the failure reliability of the jaw crusher spacer plate using the nCode model EN Constant reflect its significant resource (Fig. 9). In [3], an analysis of the reliability of numerically controlled machine tools is presented, where data between the failure times of machines are described by a two-parameter Weibull distribution. In this work, there is no analysis of operational factors, which reduces the use of the results for implementation for use in other studies. In [5], mixed Weibull models were also used, but without taking into account the stress-strain state of the structure. In this method and in the results of these studies, the stress-strain state was taken into account by combining finite element analysis of the part with by the Weibull distribution method, while also taking into account the algorithm of linear accumulation of damage and physical and mechanical parameters of the material being crushed (9). Such a model allowed for a comprehensive assessment of the reliability of machine parts. Analyzing the simulation results using experimental data in the form of time series (nCode module EN Time Series) it is possible to note a small range of cycles of the parameter Life, Fig. 9. From the picture of stresses and durability to failure it was found that the most critical area of the spacer plate is the tops of the technological holes. For example, by removing the technological holes, the service life of the plate made of cast iron Grey Cast Iron BS 1452 Grade 250 will increase to 3497 cycles.

For SAE 1045 steel, the minimum safety factor is significant – 4.74, Fig. 4.

From Fig. 6 it can be noted that for steel the above-mentioned load in time will not lead to fatigue. For cast iron the minimum number of cycles will be 45290.

Analyzing the fatigue life pictures in Fig. 9, it can be noted that the most dangerous zones are the tops of technological holes. The minimum value of the Life parameter for SAE 1045-225 -ANLD steel is equal to 503, while for cast iron Grey Cast Iron BS 1452 Grade 250 this parameter is within zero.

The studies performed have the following limitations:

1) using a preset nCode EN Constant, Fig. 6 is possible when solving statics problems. For dynamic problems, the result obtained may reflect deviations, which will lead to overspending of material;

2) using a preset nCode EN Time Series requires experimental data and works poorly with theoretically calculated machine operating curves, Fig. 8;

3) the proposed dependence (9) for determining the force applied to the spacer plate based on the physical and mechanical properties of the material does not take into account the dissipative component of the process, friction and thermal effects, which in combination affect the force value;

4) the determination of reliability parameters is based on the assumption that only axial load is applied to the spacer plate, Fig. 4, 7, however, in the real process the plate is alternately subjected to axial and off-axis load.

The main drawback of this work is the lack of consideration of the structure of the material, which will be implemented in further research.

The development of this study involves the use of a three-parameter Weibull distribution with the connection of MatLab (MathWorks, Inc., USA) or Python (Python) libraries. Software Foundation, Netherlands – USA). The proposed research method, the obtained analytical dependencies can be used in the calculation and creation of machines, the parts and assemblies of which operate in a variable stressed-deformed state.

7. Conclusions

1. An analysis of the influence of changes in the main parameters of the Weibull distribution on reliability is performed. From the graph of the influence of the parameter β on the probability density of the distribution, it is determined that the limit of its change from 2 and above is appropriate. At β values within 1, the maximum likelihood estimation (MLE) becomes more complicated. The optimal shape of the curve when determining the influence of the coefficient β on the failure rate is a value that does not significantly exceed 1.

2. Studies of the reliability parameters of the spacer plate of a jaw crusher were carried out in order to reduce the probability of its premature failure and to evaluate methods for increasing its service life, which will ensure a reduction in the cost of component materials. For this purpose, a combined model was used, including finite element analysis of the part, a linear damage accumulation algorithm, a functional Weibull distribution method and parameters of the crushed medium. Based on the modeling, the corresponding failure durability patterns were obtained, separately for constant and time-varying load application to the plate. By taking into account the physical and mechanical properties of the medium, it becomes possible to estimate the machine resource at the early stages of construction materials production.

When analyzing the reliability of a jaw crusher spacer plate using the nCode module EN Constant has the following parameter values set for the gray cast iron material BS 1452 Grade 250:

1) maxLife = 4.53 E+04;
2) maxDamage = 2.21 E-05;
3) maxStrain = 8.82 E-04 mm/mm;
4) maxStress = 1.12E+08 MPa.

For steel, the Life and Damage parameters are above the shear limit, which is additionally confirmed by the corresponding safety factor. The maximum stresses and strains for SAE 1045 steel are:

1) maxStrain = 2.50 E-04 mm/mm;
2) maxStress = 4.95E+07 MPa.

That is, it is possible to note a greater durability of the plate when it is made of SAE 1045 steel under static load conditions.

Reliability analysis of the jaw crusher spacer plate using the nCode module EN Time Series showed a slightly different picture of durability. So for steel and for cast iron the cut-off value of the parameter is low. For SAE 1045 steel there is the following list of parameters:

1) maxLife = 503;
2) maxDamage = 0.001988;
3) maxStrain = 0.01082 mm/mm;
4) maxStress = 5.773E8 MPa.

For cast iron BS 1452 Grade 250:

1) maxLife = 0.0938;
2) maxDamage = 10.66;
3) maxStrain = 0.02443 mm/mm;
4) maxStress = 4.21E+08 MPa.

Conflict of interest

The authors declare that they have no conflict of interest regarding this study, including financial, personal, authorship, or other, that could influence the study and its results presented in this article.

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The study was conducted without financial support.

Data availability

The manuscript has no associated data.

Using artificial intelligence tools

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

Authors' contributions

Ivan Nazarenko: Conceptualization, Methodology, Writing -reviewing and editing, Supervision, Funding acquisition; **Yevhen Mishchuk**: Software, Writing – original draft, Visualization; **Viktor Nechyporuk**: Validation, Formal analysis; **Dmytro Albeshchenko**: investigation, resources; **Ivan Pereginets**: data curation, project administration.

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