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THE JOURNAL WAS FOUNDED IN 1940

PUBLISHED 6 TIMES A YEAR

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ELSEVIER Scopus

Clarivate Analytics

The scientific journal News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences has been indexed in the international abstract and citation database Scopus since 2016 and demonstrates stable bibliometric performance.

The journal is also included in the Emerging Sources Citation Index (ESCI) of the Web of Science platform (Clarivate Analytics, since 2018).

Indexing in ESCI confirms the journal's compliance with international standards of scientific peer review and editorial ethics and is considered by Clarivate Analytics as part of the evaluation process for potential inclusion in the Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI), and Arts & Humanities Citation Index (AHCI).

Indexing in Scopus and Web of Science ensures high international visibility of publications, promotes citation growth, and reflects the editorial board's commitment to publishing relevant, original, and scientifically significant research in the fields of geology and technical sciences.

«Қазақстан Республикасы Ұлттық ғылым академиясының Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналы 2016 жылдан бастап халықаралық рефеpативтік және ғылымиметриялық Scopus дерекқорында индекстеледі және тұрақты библиометриялық көрсеткіштерді көрсетіп келеді.

Сонымен қатар журнал Web of Science платформасының (Clarivate Analytics, 2018) халықаралық рефеpативтік және наукометриялық дерекқоры Emerging Sources Citation Index (ESCI) тізіміне енгізілген.

ESCI дерекқорында индекстелуі журналдың халықаралық ғылыми рецензиялау талаптары мен редакциялық этика стандарттарына сәйкестігін растайды, сондай-ақ Clarivate Analytics компаниясы тарапынан басылымды Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) және Arts & Humanities Citation Index (AHCI) дерекқорларына енгізу қарастырылуда.

Scopus және Web of Science дерекқорларында индекстелуі жарияланымдардың халықаралық деңгейде жоғары сұранысқа ие болуын қамтамасыз етеді, олардың дәйексөз алу көрсеткіштерінің артуына ықпал етеді және редакциялық алқаның геология мен техникалық ғылымдар саласындағы өзекті, бірегей және ғылыми тұрғыдан маңызды зерттеулерді жариялауға ұмтылысын айқындайды.

Научный журнал «News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences» с 2016 года индексируется в международной реферативной и наукометрической базе данных Scopus и демонстрирует стабильные библиометрические показатели.

Журнал также включён в международную реферативную и наукометрическую базу данных Emerging Sources Citation Index (ESCI) платформы Web of Science (Clarivate Analytics, 2018).

Индексирование в ESCI подтверждает соответствие журнала международным стандартам научного рецензирования и редакционной этики, а также рассматривается компанией Clarivate Analytics в рамках дальнейшего включения издания в Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) и Arts & Humanities Citation Index (AHCI).

Индексирование в Scopus и Web of Science обеспечивает высокую международную востребованность публикаций, способствует росту цитируемости и подтверждает стремление редакционной коллегии публиковать актуальные, оригинальные и научно значимые исследования в области геологии и технических наук.

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КАТАЛИН Стефан, PhD, ассоциированный профессор, Технический университет Дрезден (Дрезден, Германия), https://www.scopus.com/authid/detail.uri?authorId=35203904500; https://www.webofscience.com/wos/author/record/ 1309251

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НУРПЕИСОВА Маржан Байсановна, доктор технических наук, профессор Казахского национального исследовательского технического университета им. К.И. Сатпаева (Алматы, Казахстан), https://www.scopus.com/authid/detail.uri?authorId=57202218883; https://www.webofscience.com/wos/author/record/AAD-1173-2019

РАТОВ Боранбай Товбасарович, доктор технических наук, профессор, заведующий кафедрой «Геофизика и сейсмология», Казахский национальный исследовательский технический университет им. К.И. Сатпаева (Алматы, Казахстан), https://www.scopus.com/authid/detail.uri?authorId=55927684100; https://www.webofscience.com/wos/author/record/1993614

РОННИ Берндтссон, профессор, Директор Центра современных ближневосточных исследований, Лундский университет (Лунд, Швеция), https://www.scopus.com/authid/detail.uri?authorId=7005388716; https://www.webofscience.com/wos/author/record/1324908

МИРЛАС Владимир, PhD, профессор, Восточный научно-исследовательский центр, Университет Ариэля, (Ариэль, Израиль), https://www.scopus.com/authid/detail.uri?authorId=8610969300; https://www.webofscience.com/wos/author/record/53680261

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Kazakh National University of Water Management and Irrigation,
Taraz, Kazakhstan.
*E-mail: rollan_n@mail.ru

STATISTICAL MODEL OF MULTI-CYCLE FATIGUE OF STEEL STRUCTURAL ELEMENTS UNDER A COMPLEX NON-UNIFORM STRESS STATE

Jakiyayev Dossumbek — Candidate of Technical Sciences, Associate Professor, Kazakh National University of Water Management and Irrigation, Taraz, Kazakhstan,
E-mail: ddosumbek1957@mail.ru, https://orcid.org/0000-0001-9145-0434;
Nussipali Rollan — PhD, Acting Associate Professor, Kazakh National University of Water Management and Irrigation, Taraz, Kazakhstan,
E-mail: rollan_n@mail.ru, https://orcid.org/0000-0001-6965-0667;
Malibekov Aldabergen — Candidate of Technical Sciences, Associate Professor, Kazakh National University of Water Management and Irrigation, Taraz, Kazakhstan,
E-mail: kaf_mim206@mail.ru, https://orcid.org/0009-0000-9907-6299;
Jakiyayev Bauyrzhan — Master, Senior lecturer, Kazakh National University of Water Management and Irrigation, Taraz, Kazakhstan,
E-mail: baika_baur@mail.ru, https://orcid.org/0000-0002-2872-3820;
Zhashen Sultangali — Candidate of Technical Sciences, Associate Professor, Kazakh National University of Water Management and Irrigation, Taraz, Kazakhstan,
E-mail: sultangali54@mail.ru, https://orcid.org/0000-0002-2872-3820.

Abstract. *Relevance.* The problems of assessing multi-cycle fatigue damage to steel structural elements and parts of mining machines under complex non-uniform stress states under conditions of stationary and non-stationary cyclic loading are the most complex and relevant. *Goal.* Construction of a statistical model of fatigue failure of a steel structural element or part, taking into account the type of stress state and the influence of non-stationary cyclic loading. *Methods.* Theoretical studies on determining the parameters of the energy equation of multi-cycle fatigue damage of a material element and their combination with the Weibull weak link theory. Experimental studies on fatigue testing of steel samples and structural elements and their statistical processing. *Results and Conclusions.* The conducted studies allow us to estimate the life distribution of a component operating under arbitrary cyclic stress conditions based on available life distribution data for laboratory specimens made of identical materials. To evaluate the effectiveness of the proposed statistical model, a comparative analysis of test results for specimens and structural elements of grade 45 steel under steady-state symmetric and asymmetric loading conditions, as well as test results under transient block loading at various stress levels and loading cycle asymmetry coefficients, was conducted. The dependence of the optimal sizes of the computational cells on the gradient of a single generalized parameter of the cyclic stress state has been established. A distinctive feature of the proposed statistical model is its consideration of the combined effect of all cyclic stress components, which can generally vary over time according to individual laws. Examples of stress states requiring consideration of the combined effect of all stress components include the problem of contact between two elastic bodies and the calculation of a flange joint. In these cases, recommendations from existing calculation methods are not applicable, while the proposed model allows for the construction of a statistical fatigue calculation.

Key words: multi-cycle fatigue, cyclic loading, durability, complex non-uniform stress state, statistical model, fatigue life prediction

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Қазақ ұлттық су шаруашылығы және ирригация университеті,
Тараз, Қазақстан.
*E-mail: rollan_n@mail.ru

ҚҮРДЕЛІ БІРТЕКТІ ЕМЕС КЕРНЕУЛІ КҮЙДЕГІ БОЛАТ КОНСТРУКЦИЯЛЫҚ ЭЛЕМЕНТТЕРІНІҢ КӨП ЦИКЛДІ ҚАЖУЫНЫҢ СТАТИСТИКАЛЫҚ МОДЕЛІ

Джакияев Досумбек — техника ғылымдарының кандидаты, қауымдастырылған профессор, Қазақ ұлттық су шаруашылығы және ирригация университеті, Тараз, Қазақстан,
E-mail: ddosumbek1957@mail.ru, https://orcid.org/0000-0001-9145-0434;
Нусіпәли Роллан — PhD, қауымдастырылған профессор м.а., Қазақ ұлттық су шаруашылығы және ирригация университеті, Тараз, Қазақстан,
E-mail: rollan_n@mail.ru, https://orcid.org/0000-0001-6965-0667;
Малибеков Алдаберген — кандидат технических наук, ассоциированный профессор, Казахский национальный университет водного хозяйства и ирригации, Тараз, Казахстан,
E-mail: kaf_mim206@mail.ru, https://orcid.org/0009-0000-9907-6299;

Джакияев Бауыржан — магистр, аға оқытушысы, Қазақ ұлттық су шаруашылығы және ирригация университеті, Тараз, Қазақстан,
E-mail: baika_baur@mail.ru, https://orcid.org/0000-0002-2872-3820;
Жашен Сұлтанғали — техника ғылымдарының кандидаты, қауымдастырылған профессор, Қазақ ұлттық су шаруашылығы және ирригация университеті, Тараз, Қазақстан,
E-mail: sultangali54@mail.ru, https://orcid.org/0000-0002-2872-3820.

Аннотация. *Өзектілігі.* Тау-кен машиналарының болат конструктивтік элементтері мен бөлшектерінің стационарлық және стационарлық емес циклдік жүктеу және күрделі біртекті емес кернеулі күй жағдайларында олардың көп циклді қажу зақымдануларын бағалау өте күрделі және өзекті мәселе. *Мақсат.* Кернеу күйінің түрін және циклдік жүктеменің тұрақсыздығының әсерін ескеретін болат құрылымдық элементтің немесе бөліктің қажу қирауының статистикалық моделін құру. *Әдістері.* Материал элементінің көп циклді қажу зақымдануларының энергетикалық теңдеуінің параметрлерін анықтау және оларды Вейбуллдың әлсіз буын теориясымен үйлестіру бойынша теориялық зерттеулер. Болат үлгілері мен құрылымдық элементтерді қажуға сынауға эксперименттік зерттеулер және оларды статистикалық өңдеу. *Нәтижелер мен қорытындылар.* Жүргізілген зерттеулер, типтес материалдардан жасалған зертханалық үлгілердің қажу қирау мерзімін дәл болжау туралы жинақталған деректері негізінде, кез келген циклдік кернеулі күй жағдайында жұмыс жасайтын машиналар бөлшектерінің ұзақтылығын бағалау мәселелерін шешуге мүмкіндік береді. Ұсынылған статистикалық модельдің тиімділігін дәлелдеу мақсатында 45 болаттың үлгілері мен конструктивтік элементтерінің жүктеудің стационарлық симметриялық және симметриялық емес режимдеріндегі, жүктеу циклінің асимметрия коэффициенттері мен кернеулерінің әртүрлі деңгейлеріндегі және стационарлық емес блоктық жүктеу кезіндегі сынақ нәтижелеріне салыстырмалы талдау жүргізілді. Есептеу ұяшықтардың оңтайлы өлшемдерінің циклдік кернеу күйінің бір жалпыланған параметрінің градиентіне тәуелділігі анықталды. Ұсынылған статистикалық модельдің ерекшелігі – циклдік кернеулердің барлық компоненттерінің бірлескен әрекетін есепке ала алатындығы, ал олардың әрқайсысы жеке заңдылықтармен өзгеруі мүмкін. Кернеулердің барлық компоненттерінің бірлескен әрекетін ескеру қажет болатын кернеулі күйінің мысалдары ретінде екі серпімді дененің жанасуы мәселесін және фланецті қосылыстарды есептеуді қарастыруға болады. Бұл жағдайларда қолданыстағы есептеу әдістерінің ұсыныстары ешқандай қолдау таппауы мүмкін, ал ұсынылған модель қажудың статистикалық есебін құруға мүмкіндік береді.

Түйін сөздер: көп циклді қажу, циклдік жүктеме, төзімділік, күрделі біртекті емес кернеулі күйі, статистикалық модель, қажу мерзімін болжау

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Казахский национальный университет водного хозяйства и ирригации,
Тараз, Казахстан.
*E-mail: rollan_n@mail.ru

СТАТИСТИЧЕСКАЯ МОДЕЛЬ МНОГОЦИКЛОВОЙ УСТАЛОСТИ СТАЛЬНЫХ КОНСТРУКЦИОННЫХ ЭЛЕМЕНТОВ ПРИ СЛОЖНОМ НЕОДНОРОДНОМ НАПРЯЖЕННОМ СОСТОЯНИИ

Джакияев Досумбек — кандидат технических наук, ассоциированный профессор, Казахский национальный университет водного хозяйства и ирригации, Тараз, Казахстан,
E-mail: ddosumbek1957@mail.ru, https://orcid.org/0000-0001-9145-0434;
Нусипали Роллан — PhD, исполняющий обязанности ассоциированного профессора, Казахский национальный университет водного хозяйства и ирригации, Тараз, Казахстан,
E-mail: rollan_n@mail.ru, https://orcid.org/0000-0001-6965-0667;
Малибеков Алдаберген — техника ғылымдарының кандидаты, қауымдастырылған профессор, Қазақ ұлттық су шаруашылығы және ирригация университеті, Тараз, Қазақстан,
E-mail: kaf_mim206@mail.ru, https://orcid.org/0009-0000-9907-6299;
Джакияев Бауыржан — магистр, старший преподаватель, Казахский национальный университет водного хозяйства и ирригации, Тараз, Казахстан,
E-mail: baika_baur@mail.ru, https://orcid.org/0000-0002-2872-3820;
Жашен Султангали — кандидат технических наук, ассоциированный профессор, Казахский национальный университет водного хозяйства и ирригации, Тараз, Казахстан,
E-mail: sultangali54@mail.ru, https://orcid.org/0000-0002-2872-3820.

Аннотация. *Актуальность.* Проблемы оценки многоцикловых усталостных повреждений стальных конструкционных элементов и деталей горных машин при сложном неоднородном напряжённом состоянии в условиях стационарного и нестационарного циклического нагружения являются одними из наиболее сложных и актуальных в инженерной практике. *Цель исследования* - построение статистической модели усталостного разрушения стального конструкционного элемента или детали с учётом вида напряжённого состояния и влияния нестационарности циклического нагружения. *Методы*. Теоретическая часть исследования основана на определении параметров энергетического уравнения многоцикловых усталостных повреждений материала с последующим их объединением с теорией слабого звена распределение Вейбулла. Экспериментальная часть включает испытания стальных образцов и конструкционных элементов на усталость с последующей статистической обработкой результатов. *Результаты и выводы*. Проведённые исследования позволяют решить задачу оценки распределения долговечности детали, работающей в условиях произвольного циклического напряжённого состояния, на основе данных о долговечности лабораторных образцов из идентичного материала. Для оценки эффективности предложенной модели выполнен сравнительный анализ результатов испытаний образцов и конструкционных элементов из стали 45 при стационарных симметричных и несимметричных режимах нагружения, а также при нестационарном блочном нагружении при различных уровнях напряжений и коэффициентах асимметрии цикла. Установлена зависимость оптимальных размеров расчётных ячеек от градиента обобщённого параметра циклического напряжённого состояния. Показано, что особенностью предложенной статистической модели является учёт совместного действия всех компонентов циклических напряжений, которые могут изменяться во времени по различным законам. В качестве примеров сложных напряжённых состояний, требующих учёта многокомпонентности, рассмотрены задачи контактного взаимодействия двух упругих тел и расчёт фланцевого соединения. В данных случаях традиционные методы расчёта оказываются ограниченными, тогда как предложенная модель позволяет выполнять корректный статистический анализ усталостной долговечности.

Ключевые слова: многоцикловая усталость, циклическое нагружение, долговечность, сложное неоднородное напряженное состояние, статистическая модель, прогноз усталостного ресурса

Introduction. The issues of assessing multi-cycle fatigue damage to structural elements and parts of mining machines under conditions of complex stress state and non-stationary loading are the most complex. Traditional fatigue calculations are based on comparing stresses at the most dangerous points of a structure with the endurance limit of the material found by testing laboratory samples. The weaknesses of this approach to assessing fatigue resistance have long been known. In areas of high stress gradients, we underestimate the resistance of a structure, and in the case of small gradients but large physical volumes (much greater than the volumes of the laboratory samples used), we overestimate it. In order to bring the calculation results closer to reality, semi-empirical methods for adjusting the calculated data were developed, associated with the introduction of effective stress concentration factors and scale factors. These methods can be used in special cases, but in the most general case of a structure operating in an arbitrary stress state, they are not applicable. Awareness of this fact led to the emergence of statistical models of fatigue failure, which, in principle, allow for the theoretical consideration of both the effect of stress gradients and the effect of the absolute dimensions of a part. One of the practically convenient variants of statistical calculation, associated primarily with the works of Kogaev V.P. (Kogaev, 1977) and some other researchers (Hanel and Wirthgen, 1979), is introduced in GOST (National Standard) 25.504-82. This method is based on the Weibull weak link model. The specified method successfully serves the calculations of rod structural elements with various stress concentrators, as well as to a large extent the calculations of plates and shells with holes operating in a momentless stress state, since in the stress concentration zone near the hole one main stress always dominates.

The underlying statistical theory of similarity and the known probabilistic methods of fatigue calculation for one-parameter and two-parameter stress states are generally associated with a number of assumptions, such as taking into account only the first principal stress when calculating the similarity criterion under complex stress conditions, independence of the form of the similarity criterion from the mechanical properties of the material of the part and samples, the possibility of separately determining the similarity criteria for normal and shear stresses in the case of simultaneous bending and torsion of the shaft, the possibility of separately determining equivalent loading modes for normal and shear stresses in the specified case of the shaft, if the loading is non-stationary. These assumptions introduce certain errors into the calculation, which manifest themselves to varying degrees depending on the type of cyclic stress state and the nature of the loading.

Materials and methods. This paper provides a generalization of the statistical model of multi-cycle fatigue of structural elements, which is the basis of GOST (National Standard) 25.504-82, for any complex non-uniform stress state under general conditions of non-stationary cyclic loading. To predict the distribution of the durability of a structural element operating under a complex stress state and non-stationary loading, a deterministic energy model of fatigue failure of a material element, proposed in (Pawlov, 1983), is applicable. This model is used in combination with the Weibull statistical model (Weibull, 1964). In these works, an energy equation for multi-cycle fatigue damage is constructed, which in the general case has the following form

$$\Pi(N)=\frac{\sigma_{\max}(N)}{\bar{\sigma}_p}+\sum_{k=1}^{N}\varphi(H_k,R_k), \tag{1}$$

where $\Pi(N)$ - damage accumulated by the N-th loading cycle; $\sigma_{max}(N)$ - maximum cycle stress at the time of determination Π; $\bar{\sigma}_p$ - true tear resistance; R_k - asymmetry coefficient of the k-th cycle; H_k - a dimensionless parameter that depends on the irreversible work of deformation performed in each loading cycle.

This kinetic equation is based on a hypothetical model of the material, the relationship of the parameters of which with the real material is carried out through experimental fatigue curves. From the fatigue curves of the given failure probabilities, graphs of the $\varphi(H,R)$ function can be constructed, corresponding to the same failure probabilities. According to the fatigue curves of the given failure probabilities, graphs of the function corresponding to the same failure probabilities can be constructed. This circumstance is used later in constructing a statistical model of fatigue failure (Pavlov and Dzhakiyaev,1985), based on this deterministic model of fatigue failure of a material element and the statistical theory of the "weak link" according to Weibull.

In Weibull theory, it is assumed that failures in a number of individual volumes

V_0 are independent events and the probability of failure in a volume V_i into which the entire volume of the part is divided is determined by the formula

$$P_i = 1 - (1 - P_0)^{V_i / V_0}, \tag{2}$$

where P_0 - the probability of failure of individual volume V_0. Volume V_i must be small enough to consider the stress state within its limits as uniform. Then the probability of destruction in the volume of the entire part V is found by the formula

$$P_V = 1 - \prod_{i=1}^{n} (1 - P_i), \tag{3}$$

where n - number of volumes V_i in the volume of the part.

Let us formulate the features of the statistical model of fatigue failure. In a deterministic stress state, the parameters H and R are also deterministic quantities. However, the function $\varphi(H,R)$ is not deterministic, but also depends on the given probability of failure. Damage in a unit volume is determined as a function of the given probability by formula (1). If the durability N_p is given at $\Pi = 1$, then we obtain a dependence by which we can select the probability of failure in a unit volume. The probability of failure in a conditional cell, the volume of which can be less than or greater than a unit, is found by formula (2), and the probability of failure of the entire part by formula (3). To plot the distribution curve of the durability of a structural element operating in a complex non-uniform stress state, it is first necessary to have data on the resistance of the material in a linear homogeneous stress state. These initial data are obtained by fatigue testing of smooth cylindrical specimens under tension - compression with different cycle asymmetry coefficients. The volume of material located in the destruction zone is taken as a unit. Based on these curves of equal probabilities of fatigue failure of cylindrical samples, graphs of the function are constructed, related to a unit volume of material and corresponding to the same probabilities of failure.

To construct a curve of the durability distribution of a structural element operating in a complex non-uniform stress state, it is first necessary to have data on the resistance of the material in a linear uniform stress state. These initial data are obtained by fatigue testing of smooth cylindrical specimens under tension - compression with different cycle asymmetry coefficients. The volume of material in the failure zone is taken as a unit V_0. Based on these curves of equal probabilities of fatigue failure of cylindrical specimens, graphs of the function $\varphi(H,R)$ are constructed, related to a V_0 unit volume of material and corresponding to the same failure probabilities.

The fatigue calculation algorithm for structures operating under a complex non-uniform stress state under the most general conditions of cyclic non-stationary loading is presented in the following form. The calculation begins with determining the stress state of the structure, depending on one or more load parameters changing over time according to individual cyclic laws. However, the loading mode is subject to the restriction that the entire loading mode can be divided into blocks of identical cycles.

If some method of discretization of a solid body, for example, FEM (Finite Element Model), is used to calculate stresses, then simultaneously with the stresses in each cell, the asymmetry coefficient R and the value H are found.

For the most stressed area of the structure, the gradient of the value H is determined

$$G_H = \sqrt{\left(\frac{\partial H}{\partial x}\right)^2 + \left(\frac{\partial H}{\partial y}\right)^2 + \left(\frac{\partial H}{\partial z}\right)^2}, \tag{4}$$

and the optimal (based on experimental data) dimensions used in fatigue calculations are found using this gradient. If the optimal cell dimensions found do not match the dimensions used in stress calculations, the structure is re-divided into cells of optimal dimensions. In the case where extrapolation of cell dimensions to zero is used in fatigue calculations, the selection of optimal cell dimensions is not necessary. Fatigue calculations are performed with any two cell dimensions, one of which may be the one used in the FEM calculation.

Next, the stress state is established for the center of each cell used in fatigue calculations, and the values of H and R are found for this cell at each loading stage.

Further calculations are aimed at constructing the durability distribution curve of the structure. The most stressed cell is selected, i.e. the one for which the value of H is maximum, and by setting a certain probability of destruction P_0, the value $\varphi(H,R)$ is determined at each loading stage using graphs $\varphi(H,R)$ corresponding to certain probabilities of destruction P_0 of a unit volume of material V_0, or from the expression

$$\varphi(H,R) = \left(1 - \frac{(H+2)C_2}{(1-R)\overline{\sigma}_p}\right) B^{-1} \exp\left[\frac{(H+2)^2 C_2^2 a^2 (1+R)}{8\text{в}(1-R)} + \frac{(H+2)C_2 a}{2(1-R)}\right.$$
$$\left.\sqrt{\frac{(H+2)^2 C_2^2 a^2 (1+R)^2}{16\text{в}^2} + \frac{(\ln A - \ln B)(1-R^2)}{\text{в}} + (1-R)^2}\right], \tag{5}$$

where A, B, a and в - P_0 probability-dependent parameters describing the fatigue curve for a symmetrical cycle.

The probability of destruction in this cell is found using formula (2).

Next, for the most stressed cell, the number of cycles before destruction is calculated, and in the general case, the number of whole blocks before destruction n is first found, for which the inequality

$$\begin{aligned} &\sum_{k=1}^{n} \varphi(H_k, R_k) \cdot N_k < 1 - \sigma_{max} / \bar{\sigma}_p \\ &\sum_{k=1}^{n+1} \varphi(H_k, R_k) \cdot N_k > 1 - \sigma_{max} / \bar{\sigma}_p , \end{aligned} \tag{6}$$

and then the number of cycles before failure in the last $n+1$ block is determined

$$N_{n+1} = \frac{1 - \sigma_{max} / \bar{\sigma}_p - \sum_{k=1}^{n} \varphi(H_k, R_k) \cdot N_k}{\varphi(H_{n+1}, R_{n+1})} \tag{7}$$

In each of the remaining cells, the probability of failure is selected in such a way that, given the values H, R_r and $\varphi(H, R)$ for each loading stage, the total number of cycles to failure of each cell would be equal to the number of failure cycles found for the most stressed cell. The probability of failure of the structure given the number of cycles to failure found is determined according to (3).

To construct a durability distribution curve for a structure under a given loading regime, it is sufficient to determine the probabilities of failure for two durability values, plot the values of these probabilities and durability on a probability grid corresponding to the Weibull distribution, and connect the resulting points with a straight line.

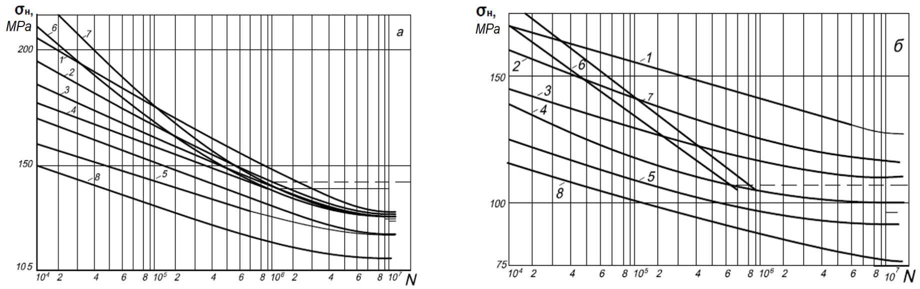
The peculiarity of the proposed statistical model is the consideration of the combined action of all components of cyclic stresses, which in the general case can change over time according to individual laws. Examples of a stress state in which it is necessary to consider the combined action of all stress components can be the problem of contact between two elastic bodies and the calculation of a flange joint. In these cases, the recommendations of existing calculation methods do not find any application, while the proposed theory allows one to construct a statistical calculation for fatigue.

Results. In order to experimentally verify the statistical model, fatigue tests were performed on plate specimens of grade 45 steel with round and elliptical holes, and fatigue tests were performed on laboratory specimens of the same steel for cyclic tension-compression. The results of the latter tests were taken as the base for determining the fatigue resistance of the material, and the results of testing the plates as structural elements operating in a complex non-uniform stress state were used to compare the theory with direct experimental data. The plate specimens were 60 mm wide, the hole was 12 mm in diameter, and the ellipse axes were 12 mm and 8 mm. The theoretical stress concentration factors in the elastic deformation region were 2.512 and 3.33, respectively, for the round and elliptical holes. These specimens were tested for cyclic tension-compression under stationary symmetric and asymmetric loading with R cycle asymmetry factors equal to –1.0 and –0.3. In this case, the durability was recorded, at which the crack that appeared at the mouth of the concentrator reached a length of 0.3-1.0 mm.

When calculating the distribution of durability of plate specimens with holes, it is necessary to know the stress state in the stress concentrator zone. Local stresses in plate specimens with round and elliptical holes tested under a symmetrical cycle did not exceed the yield strength of the material. The values of these stresses in specimens with a round hole were found from R. Gauland's solution for stretching a strip of finite width weakened by a round hole. Local stresses in specimens with an elliptical hole were determined by FEM. Under an asymmetrical loading cycle, local stresses in the concentrator zone exceeded the yield strength of the material. The precision dividing grid method was used to determine these stresses.

Calculated and experimental data on the fatigue resistance of plate specimens with holes under symmetric loading are given in (Jakiyayev and et al., 2020a). With a durability of about 10^6 cycles, the experimental and calculated data coincided if the calculation was carried out by dividing the working part of the specimens with a round hole into 0.5x0.5 mm cells, and for specimens with an elliptical hole into 0.3x0.3 mm cells.

Let us consider the calculated and experimental data on the fatigue resistance of plastic samples with holes under asymmetric loading with R= -0.3. Fig. 1 shows the calculated and experimental fatigue curves of these samples. The calculated curves correspond to the breakdown of the working force of the samples into cells of 1x1 mm (curves 1), 0.7x0.7 mm (curve 2), 0.5x0.5 mm (curve 3), and 0.3x0.3 mm (curve 4). Curve 5 was obtained by extrapolating the cell size to zero; curve 8 corresponds to the calculation for the most stressed point using direct test data for cylindrical samples.



a) b)

Figure 1. Calculated (1,2,3,4,5,8) and experimental (6,7) fatigue curves of specimens with a round (a) and an elliptical (b) hole for an asymmetric loading cycle R= -0.3.

Experimental curve 6, corresponding to the appearance of a macroscopic crack in the mouth of the concentrator with a length of 0.3-1 mm, is located somewhat steeper than the calculated curves. With a durability of about 10^6 cycles, the experimental and calculated data coincided if the calculation was carried out by dividing the working part of the samples with a round hole into 0.7x0.7 mm cells, and for samples with an elliptical hole into 0.3x0.3 mm cells.

Reducing the cell size to zero leads to lower values of the fatigue limits, which, however, are still higher than the calculated fatigue curve for the most stressed point of the structure. When analyzing these results, it should be noted, first, that the influence of the size of the conventional cells on the calculation of durability at given failure probabilities in the similarity theory adopted by GOST (National Standard) 25.504-82 is not considered. The calculation recommended there, in our opinion, assumes extrapolation of the cells to zero. On the other hand, the question may be asked: why, within the framework of the Weibull theory, the best agreement with experience is obtained at a certain finite cell size, which also depends on the stress gradient. It can be assumed that this fact is associated with the assumption of the theory that failures of individual elements of the material are independent events.

Since the influence of the stress state on the process of damage accumulation is estimated in the proposed theory by the parameter H, it is natural to estimate the gradients of all stress components in the calculation for fatigue by the gradient of the generalized parameter H. Based on the experiments conducted, a dependence of the optimal (in comparison with the experimental data) dimensions of the conditional cell on the stress gradient estimated by the gradient of the parameter H was established (Fig. 2). With a decrease in the gradient of H, the influence of the specified dimensions of the conditional cell on the calculated durability turns out to be quite weak. With a decrease in the gradient of H, the influence of the specified cell sizes is erased.

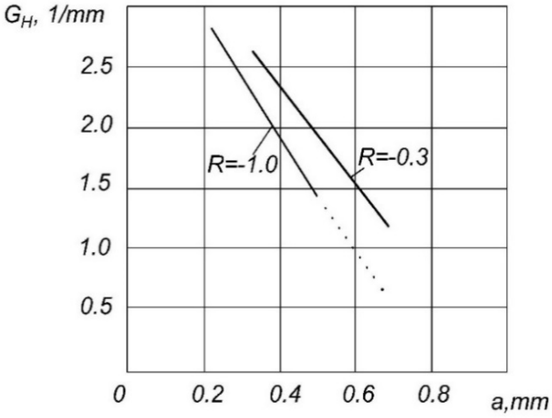


Figure 2. Graph of the change in the optimal size of the calculation cells depending on the gradient H.

The test results for plate specimens with circular holes under transient block loading are presented in Table 1. Experiment No. 1 involved two-stage cyclic loading, in which the maximum stress level outside the hole zone was varied at a constant cycle asymmetry coefficient of R = -1.0. Experiment No. 2 involved three-stage cyclic loading, in which the maximum stress level outside the hole zone and the cycle asymmetry coefficient were varied. Six plate specimens with circular holes were tested in each experiment. The specimens were brought to failure at the final loading stage, and the durability values corresponding to the appearance of a 0.3-1.0 mm long crack at the mouth of the crack concentrator were entered into the table.

Table 1. Test results of plate specimens with a round hole under non-stationary block loading.

Experiment No.	**Block No.**	$\sigma_{n\ \max}$, **MPa**	R	**Specimen No.**	**Number of cycles in a block** $N_k \cdot 10^{-6}$	**Destructive number of cycles** $N_{\exp} \cdot 10^{-6}$	**Average value of destructive number of cycles** $\overline{N}_{\exp} \cdot 10^{-6}$
1	**1**	**110,0**	**-1,0**		**0,100**		**0,209**
	2	**121,2**	**-1,0**	**1**	**0,070**	**0,170**	
				2	**0,159**	**0,259**	
				3	**0,137**	**0,237**	
				4	**0,082**	**0,182**	
				5	**0,111**	**0,211**	
				6	**0,096**	**0,196**	
2	**1**	**150,0**	**-0,3**		**0,050**		**0,302**
	2	**110,0**	**-1,0**		**0,150**		
	3	**121,2**	**-1,0**	**1**	**0,069**	**0,269**	
				2	**0,163**	**0,363**	
				3	**0,046**	**0,246**	
				4	**0,109**	**0,309**	
				5	**0,139**	**0,339**	
				6	**0,088**	**0,288**	

As a result of calculations using the proposed statistical model, the estimated durability of the specimens is determined, and ultimately, graphs are plotted showing the dependence of the estimated durability on the selected computational cell size. These curves for Experiments Nos. 1 and 2 for plate specimens with a circular hole are shown in Figure 3, where the experimental points are also plotted.

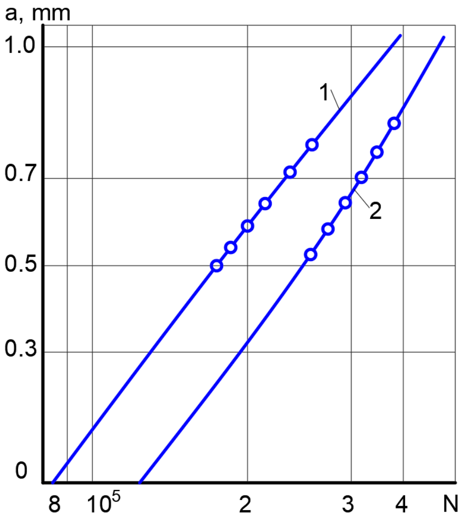


Figure 3. Graph for selecting optimal computational cell sizes for testing plate specimens with a circular hole (1 - Experiment No. 1, 2 - Experiment No. 2).

The graphs show that the best agreement between the experimental average value of the failure number of cycles and the calculated data is achieved with a cell size of approximately 0.65 x 0.65 mm. Recall that for single-stage steady loading, the optimal cell size is 0.5 mm for symmetric loading with R = -1.0 and 0.7 mm for asymmetric loading with a loading cycle asymmetry coefficient of R = -0.3.

The article (Zhashen et al., 2020) presents the results of theoretical and experimental studies of the durability of elements and machine parts made of steel 10 on the influence of loading frequency at elevated temperatures using the energy model of fatigue failure of a material element.

In (Jakiyayev et al., 2020b), an engineering calculation method is proposed based on a statistical model of fatigue failure and allows one to analytically determine the service life of a part operating under a cyclic complex non-uniform stress state. Recommendations are given for reducing the required volume of experimental information on the fatigue of the part material. This problem is solved based on the approximation of the outline of the fatigue limit lines on the Hay diagram, i.e. the diagram of limiting amplitudes in coordinates $\sigma_n - \sigma_m$.

Discussion. In subsequent works by Kogaev V.P. (Kogaev and Gadolina, 1989), devoted to probabilistic calculations of machine parts under cyclic loading, a function of the distribution of the endurance limits of a part is given, recorded taking into account all components of the main stresses. However, this relationship was not further developed, since the similarity criteria indicating the equal danger of fatigue failure, obtained on the basis of this relationship, turn out to be more complex and therefore inconvenient for practical use.

Based on modern concepts of material failure, a statistical model of the fatigue failure mechanism of materials is proposed in the article (Babich and

Dorodnykh, 2018). The failure mechanism is associated with the accumulation of scattered microdamages in the material during repeated loading. The criterion for the occurrence of fatigue failure is the achievement of critical values of the density of microdamages in cyclically loaded bodies, identified with the density of microdamages formed during tearing or shear during static failure due to pure tension, compression and shear of a standard sample of the material. Low-cycle fatigue is associated with the accumulation of predominantly micro-destructive shear in the zone of plastic deformation, and high-cycle fatigue is associated with micro-destruction of tearing during elastic deformation.

The article (Igumnov et al., 2021) discusses the issue of assessing the strength and service life in relation to structures whose operational properties are characterized by multiparameter non-stationary thermomechanical effects.

The main mechanisms of degradation of structural materials (metals and their alloys) are considered. The main requirements for mathematical models describing the accumulation of fatigue damage are formulated. Within the framework of the mechanics of damaged media, a mathematical model has been developed that describes thermoplastic deformation and the accumulation of fatigue damage during combined low-cycle and high-cycle fatigue. The model consists of three interrelated parts: relations that determine the thermocyclic plastic behavior of the material taking into account its dependence on the destruction process; evolutionary equations describing the kinetics of damage accumulation; the strength criterion of the damaged material. A version of the constitutive relations of thermoplasticity is based on the concept of the yield surface and the principle of the gradient of the plastic deformation rate vector to the yield surface at the loading point. These relations describe the main effects of cyclic plastic deformation of the material under arbitrary complex loading trajectories. This version of kinetic equations of fatigue damage accumulation is based on the scalar parameter of damage and energy principles and takes into account the main effects of nucleation, growth and merging of microdefects under arbitrary complex loads. A generalized form of the evolutionary equation of fatigue damage accumulation under low-cycle and high-cycle fatigue is proposed. The critical damage value is used as a strength criterion for the damaged material. Based on the developed version of the constitutive relations of the mechanics of damaged media, the effect of the frequency of falling distillate drops on the thermocyclic fatigue life of a heated pipe is numerically analyzed. The numerical results of fatigue damage accumulation under thermal pulsation are in good agreement with the experimental data. It is shown that the proposed model of the mechanics of damaged media qualitatively, with the accuracy necessary for practical calculations, describes the experimental results and allows one to effectively estimate the accumulation of thermocyclic fatigue damage in structural alloys under combined multiaxial disproportionate thermomechanical loading.

The article (Pysarenko et al., 2022) considers the development of engineering methods for predicting the durability of structural elements and machines, which is based on the methodology for determining the degree of fatigue damage to the material of structural elements. In developing such a methodology, the work proposes to use modern optical and computer tools that allow analyzing the parameters of the deformable surface of metal structure samples and, on this basis, estimating the residual life of the metal structure. This is done by determining the limit state of damage using photometric analysis of the topography of the microdeformed surface of cyclically loaded metal structure samples. According to the analysis of the characteristics of fatigue damage to metals and alloys, an experimental information system based on the coherent optics method has been developed. Scanning of the deformed surface of metal structure samples is performed with a resolution of 0.2 μm/pixel. This made it possible to construct diagrams of the kinetics of the process of accumulation of fatigue damage of laboratory samples of steels St 45 and St 20. It is shown that the kinetics of spectrum brightness, obtained in the work by the correlation method, which corresponds to the evolution of the accumulation of fatigue damage on the surface of the studied samples of structural steel, is characterized by a nonlinear function, which is consistent with the results of experiments.

Generalization of microstructural short crack growth modeling for different loading conditions and materials is often not considered in the literature. These issues (Natkowski et al., 2022) are addressed by transferring the previously proposed model of crack initiation and transcrystalline growth of microstructural short cracks from ferritic steel to martensitic steel. The calculated fatigue lives are consistent with experimental data for martensite, as well as for the previously considered ferrite. The transferability of the model is shown for different load ratios, at which there are small deviations between the calculated and experimental data.

The article (Zavoychinskaya et al., 2021) discusses the results of numerous experimental and theoretical studies of multi-level processes of multi-cycle fatigue under complex stress conditions of metals and alloys, taking into account solid state physics, metal science and solid mechanics. Based on solid state physics, metal science and solid mechanics, the author proposes a scale-structural theory of fatigue that describes the evolution of fatigue damage and allows one to find the durability of a metal at a certain level of accumulated critical damage. The calculation of the durability of structural elements according to the proposed theory is considered, including criteria for structural reliability and technogenic safety of operation of the structure.

Operating and residual stresses are critical to the performance of metal structures, as they can cause microcracks that require emergency maintenance or lead to potential accidents. Therefore, determining real stresses is key to ensuring the performance of metal structures. In (Yu et al., 2021), the eddy current method is proposed, which is not an effective way to determine stresses. In mechanical engineering, the stress distribution is non-uniform, so in this paper, a non-destructive approach combining the eddy current method and the finite element method (FE) is proposed to predict the non-uniform stress distribution. Experimental data obtained using the eddy current method determine the relationship between the applied force and magnetic induction, while numerical modeling using the FE method provides a relationship between the magnetic flux density and the stress distribution in different directions. The authors believe that in this way it is possible to predict the distribution of non-uniform stresses in machine parts using a non-destructive method.

Probabilistic assessment of resistance to low-cycle deformation and failure of critical components of equipment used in the power, mechanical engineering, metallurgy, chemical, shipbuilding and other industries is of primary importance from the point of view of their safe operation, in particular, taking into account the high level of cyclic loads acting on the equipment during its operation. The paper (Bazaras and Lukoševičius, 2022) provides a rationale for using probabilistic calculation in the low-cycle area by systematic probabilistic assessment of cyclic elastic-plastic deformation and strength diagrams of materials representing the main types of cyclic properties (hardening, softening, stabilization) and studying the correlation links between mechanical properties and parameters of cyclic deformation and failure. An experimental technique for constructing calculated probabilistic fatigue curves was also developed, and the curves were compared with the experimental results. For their probabilistic assessment, the probabilistic values of mechanical characteristics were determined and low-cycle fatigue curves corresponding to different failure probabilities were calculated. Comparison of low-cycle fatigue curves showed that strength curves constructed for some materials using analytical expressions are not accurate. According to the analysis of relative values of experimental probabilities of low-cycle fatigue curves, the use of analytical expressions to construct curves can lead to a significant error. The obtained results allow us to reconsider the bearing capacity and service life of structural elements subject to cyclic elastic-plastic loading, taking into account the possible spread of mechanical properties and parameters of resistance to low-cycle deformations and failures. In addition, the obtained results allow us to determine tolerances for scattering depending on the criticality of a part or structure.

The fatigue properties of multiphase steels, which are an important factor in the automotive industry, are considered in (Hilditch et al., 2009). The different microstructural phases present in these steels can affect the service life under various cyclic loading conditions due to the way in which these phases accommodate the applied cyclic strain. Low-cycle fatigue testing with fully reverse strain monitoring was used to characterize the mechanical fatigue properties of dual-phase steel, using transmission electron microscopy to study the deformed microstructures. It was shown that the higher service life under low-cycle strain can be attributed to the increased yield strength of the material.

In (Shi et al., 2012), the test results of a series of Q460D steel specimens under various loading conditions were investigated to evaluate the stress-strain relationship, hysteretic behavior, and energy dissipation capacity. Based on the experimental results, a constitutive model for high-strength structural steel under uniaxial cyclic loading was developed, describing the monotonic loading curve, the skeletal hysteresis curve, and the hysteresis criterion. This constitutive model was then implemented in the ABAQUS finite element analysis software using the UMAT user interface. It was shown that the model proposed in this study agrees well with experimental data both at the material level under various loading conditions and at the structural level under uniaxial cyclic loading.

The paper (Papuga, 2011) presents a comprehensive review of the main currently published fatigue prediction models for multiaxial fatigue limit estimation. The set of criteria analyzed includes 17 different methods, which are validated using a series of 407 experiments. The methods are briefly described and general trends in their prediction capabilities are commented on, including some properties common to certain groups of criteria. The set of experiments is from the publicly available FatLim database. The calculation results were obtained using the free PragTic fatigue solver. Some possible avenues for further improvement of the methods are proposed.

This work (Dantas et al., 2021) aims to evaluate and compare the ability of various multiaxial fatigue models to evaluate and represent the fatigue behavior of S355 steel under high-cycle fatigue. Experimental data are used to evaluate the performance of the selected multiaxial fatigue models. Finally, the most suitable multiaxial fatigue models are selected for evaluating fatigue damage observed in S355 steel. Since this paper focuses on proportional loading with constant amplitude, material behavior mechanisms associated with more complex loading, such as non-proportional or variable amplitude, are not mentioned or studied.

Let us compare the results of calculating the effective stress concentration factors, as well as the data on the optimal cell sizes with the theoretical and experimental-theoretical recommendations of various authors (Table 2).

The data on the optimal cell sizes can be compared with the recommendations for the sizes of the structural parameters introduced by some authors. The values of the structural parameter obtained using the formulas of Leonov M.D. and Novozhilov V.V. turn out to be significantly larger than the optimal cell sizes established based on our calculations and experiments. The values of the effective stress concentration factors K_σ calculated using the recommendations of Neuber G., Kuhn P., Peterson R., Heywood R. and Kogayev V.P. do not differ from each other very much. Thus, for samples with a round hole, the smallest value of K_σ according to Heywood differs from the largest according to Peterson by approximately 20%, and for samples with an elliptical hole – by 28%. The discrepancies with our experimental and calculated values of K_σ are also not very large. Thus, in the case of a concentrator in the form of a hole, all of the above recommendations are confirmed by experience.

Table 2. Values of the effective stress concentration factor and the structural parameter of the material, determined according to the recommendations of various authors.

Recommendation authors	Round hole specimens				Elliptical hole specimens			
	R = - 1,0		R = - 0,3		R = - 1,0		R = - 0,3	
	K_σ	Structural-related parameter, mm	K_σ	Structural-related parameter, mm	K_σ	Structural-related parameter, mm	K_σ	Structural-related parameter, mm
G. Neuber	2,180*	0,480	-	-	2,630*	0,480	-	-
P. Kuhn	2,320*	0,130	-	-	2,910*	0,130	-	-
R. Peterson	2,460*	0,210	-	-	3,160*	0,210	-	-
R. Heywood	2,200* 2,040	0,082	-	-	2,670* 2,470	0,082	-	-
M.Ya. Leonov	2,020**	1,260*	1,950**	1,380*	-	-	-	-
V.V. Novozhilov	2,020**	1,350*	1,950**	1,650*	2,560**	0,830*	2,520**	0,900*
V.P. Kogayev	2,200*	-	-	-	2,740*	-	-	-
Our data on optimal cell size determining	2,020**	0,5*	1,950**	0,7*	2,560**	0,3*	2,520**	0,3*
Our calculation when extrapolating cell size to zero	2,110*	-	2,200*	-	2,640*	-	2,760*	-

Note: 1. The asterisks (*) mark the values that were determined by calculation in accordance with the recommendations of various authors.

2. Two asterisks (**) mark our experimental values of the effective stress concentration factor.

However, it should be borne in mind that the above recommendations apply to the case of taking into account local stresses in the zone of the structural concentrator, where one principal stress always dominates, but do not apply to the general case of a non-uniform stress state. We also note that the listed recommendations of various authors do not take into account the effect of the asymmetry of the loading cycle.

Conclusion. A statistical model of multi-cycle fatigue failure has been developed, allowing one to determine the service life of structural elements and machine parts under cyclic complex non-uniform stress state.

The results of testing samples and parts of steel 45 are presented to assess the effectiveness of the statistical model of fatigue failure.

The dependence of the size of the calculation cell on the gradient of the value H, describing the influence of the type of stress state on the process of accumulation of fatigue damage, is obtained.

Thus, the condition of similarity of the distributions of the durability of two structural elements operating in different stress states turns out to be generally dependent on the mechanical properties of the material. The distribution of the durability of a structural element can be constructed according to the proposed model and in the general case of multi-component non-stationary cyclic loading. For this general case, no recommendations are contained in the known literature.

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