Abstracts

Kharchenko V. V., Chirkov A. Yu., Kobel'skii S. V., and Kravchenko V. I. **Peculiarities of the Fracture Strength Design of the Branch Pipe Zone of the Nuclear Reactor Vessel** // Problems of Strength. – 2018. – No. 4. – P. 5–18.

The main methodological principles and the procedure of the refined calculation of the stress-strain state and fracture strength of the branch pipe zone of the reactor vessel under thermal shock have been formulated. A mixed scheme of the finite element method was taken as a basis of finite element analysis; it ensures continuous approximation both for displacements and for stresses and strains, which allows the fracture mechanics parameters to be determined with a high degree of accuracy. The paper presents the results of an elastic-plastic analysis of the fracture strength of the inlet branch pipe zone with an underpad crack in the simulation of the typical emergency core cooling conditions of a WWER-1000 reactor. The location and orientation of the postulated crack are substantiated to obtain the most conservative estimate of the fracture strength of the branch pipe. The calculations were performed with including the postulated crack in the finite element model of a fragment of the inlet branch pipe zone using the procedure of successive mesh thickening in the crack region. To determine the allowable critical temperature of brittleness of the branch pipe base metal, the tangent point, thermal crimping, and descending branch approaches were used. According to the obtained results, the elastoplastic deformation of the metal and stress history affect the calculated estimate of the fracture strength of the branch pipe zone of the reactor vessel. It has been shown that the traditional linear elastic calculation, which is used to evaluate the fracture strength of the branch pipe, does not have sufficient degree of conservatism, which results in overestimation of its strength.

Troshchenko V. T. and Khamaza L. A. **Fatigue Fracture Stages of Metals and Alloys and Stage-to-Stage Transition Criteria** // Problems of Strength. – 2018. – No. 4. – P. 19–32.

Basic mechanisms of scattered and localized fatigue damage of metals and alloys are analyzed. The methods of evaluating the criteria of scattered-to-localized fatigue damage transition are proposed and substantiated based on the analysis of short and long crack. One of the methods is based on the analysis of short fatigue crack growth kinetics evaluated by their size or growth rate against the number of load cycles propagation behavior. Crack sizes and a number of cycles, corresponding to a more intensive increase in the crack growth rate, are taken to be the transition criteria. With the scattered-to-localized fatigue damage transition at the stresses above the endurance limit, the form and parameters of the equation describing the crack size against the number of load cycles are changed. Another method is built upon the analysis of variation of the short crack propagation rate against the stress intensity factor. In this case, the stress intensity factor range and a corresponding crack size at which the stress intensity factor starts varying at a higher rate are taken as the transition criteria. The above methods are used to assess crack sizes and a number of load cycles, corresponding to the scattered to-localized fatigue damage transition, for carbon, alloy, austenitic steels and an aluminum alloy accounting for stress levels and properties of examined materials. Fatigue crack sizes on the transition at the stresses above the endurance limit are established to decrease with stresses and remain smaller than the crack sizes at the endurance limit. Main crack sizes are shown to correlate with the endurance limit of examined materials, decreasing with its increase.

Matveev V. V., Onishchenko E. A., and Boginich O. E. **Vibration-Based Diagnostics of Transverse Surface Cracks in Rods of Different Cross Section under Longitudinal Vibrations** // Problems of Strength. – 2018. – No. 4. – P. 33–51.

The paper considers the results of determining the vibrodiagnostic indicators of the presence of various mode I breathing transverse cracks in rod elements of rectangular and circular cross section with different boundary conditions under longitudinal vibrations. Relative second harmonic amplitudes in the vibration spectrum at the main and superharmonic resonance of the first eigenmode of cantilever rods without mass and with a mass at the end and rods with the ends free for longitudinal displacements under forced and kinematic vibration excitation were taken as diagnostic indicators. To determine the above indicators, analytical and numerical bending vibration methods considered before are used. In the analytical solution, the nonlinearity parameter of the vibrating system is calculated using the corresponding values of stress intensity factors. The numerical solution is obtained on the basis of light-node finite element models with the representation of a breathing crack as a mathematical cut and the treatment of a contact problem in the formulation providing mutual nonpenetration between crack faces. Plots of the values of diagnostic indicators as a function of relative crack depth, crack location, and the site of measurement of longitudinal displacements have been obtained. Comparisons of values of diagnostic indicators with the value of relative change in natural vibration frequency are presented. It has been shown that at the main resonance, the numerical solution confirmed the pronounced effect of localization of diagnostic indicators in the crack region. It has been found that at the superharmonic resonance, the value of the vibrodiagnostic indicator is two orders of magnitude higher than that of the indicators at the main resonance, but the effect of their localization near the crack does not practically manifest itself. Some localization is observed for the absolute values of the second harmonic, and only for longitudinal strain, there is a strongly pronounced effect. A comparison of the obtained values of diagnostic indicators with the data for bending vibrations is given. It is noted that in spite of basically lower indicators under longitudinal vibrations, they have an advantage in terms of the possibility to diagnose symmetric surface and internal breathing cracks.

Zinkovskii A. P. and Tokar' I. G. **Influence of Local Surface Damage on the Natural Frequencies of Higher Modes of Flexural Vibration of Cantilever Rods** // Problems of Strength. – 2018. – No. 4. – P. 52–61.

The operating life of gas turbine engines is dependent on the reliability of compressor rotor blades that are subjected to a complex set of forces of a different nature during their operation, and in particular, to mechanical damage resulting in severe accidents and material losses. The ingress of foreign objects into the air-gas channel of the engine is one of the causes giving rise to blade damage. As a consequence, various marks, dents, dimples, etc., occur on rotor blades changing the designed geometry of the blade airfoil and their natural vibration frequency spectrum and beginning to act as stress concentrators, thus reducing the vibration resistance of blades. The known investigations on the vibration of damaged mechanical systems, including compressor rotor blades, have an insufficient amount of data on the formation of the spectrum of their natural frequencies typical of their vibration modes with consideration of the influence of a combined change in the elastic and inertia characteristics. The paper deals with a computational and experimental investigation on the influence of local surface damage on the spectrum of natural flexural vibration frequencies of a cantilever rod with a constant cross section as a simplest model of the compressor rotor blade. The regularities in the variation of the natural frequencies of the first to fourth flexural vibration modes of the rods of different flexibility with the geometrical parameters of the notch simulating damage, such as the position along the length and its depth, are presented. The distribution of variations in the natural frequencies of the rods is found to correspond to the location of the nodes of their vibration mode under investigation. The reduction in the frequency of the damaged rod occurs independently of the vibration mode and the depth of the notch when it is located near the rod attachment. It is more significant with the depth of the notch and less pronounced for the higher vibration modes as compared to the first one, which is attributable to the variation in the rod stiffness. The equality of the natural vibration frequencies of the damaged and undamaged rods is observed at a certain position of the notch along the length, irrespective of the vibration mode. As the notch approaches the free end of the rod, the natural vibration frequencies become somewhat higher than those for the undamaged rod, since, in this case, they are more sensitive to the variation in the inertia properties of the rod due to the presence of damage. With the decreasing flexibility, the variation in the natural frequencies of the investigated vibration modes of the damaged rod increases for the same value of the relative damage depth. The results of the performed computations are in a good agreement with the experimental data on the rods.

Kravchuk L. V., Buiskikh K. P., Gusarova I. A., Potapov A. M., and Feofentov N. N. **Methods for the Simulation of the Aerodynamic Heating Conditions of the Structural Elements of Space Shuttles** // Problems of Strength. – 2018. – No. 4. – P. 62–73.

The paper considers the problem of creating and operating products of reusable space-rocket hardware, in particular with respect to ensuring the integrity of structural elements and safe return to

Earth under aerodynamic heating conditions. This problem has two aspects, which differ in specificity of the approaches to designing the elements of space shuttle systems (SSS). The first aspect is associated with ensuring the reliable functioning of the most thermally stressed elements of the re-entry glider, which are structures with large angles of attack, such as fuselage nose and leading edge, wing loading edge, elevators, and air intake edges. The second aspect mainly concerns ensuring the allowable temperature level of the spacecraft pressure shell on all flight path segments, especially during re-entry in the Earth's atmosphere. In view of this, one of the main goals in creating SSS is to develop a reliable heat shield having acceptable size and weight parameters, and cost. The successful solution of these problems is determined in many respects by the optimal choice of appropriate classes of materials' special high-temperature alloys, structural ceramics, high-melting-point metallic and polymeric composite materials. For the modern structures of SSS, the use of structural metallic materials is expedient in many respects. Rig test procedures are proposed. A complex of gas-dynamic test rigs was used as the basic equipment, whose fundamental design features and methodological solutions ensure the complete rig test cycle for the solution of problems in both directions. The methodological basis of rig tests is a set of specialized procedures for the simulation of thermally stressed states of the material and the intesity of the external action of the environment, which provide the equvalence of material damage processes and the limit state of the structural element under investigation under model and full-scale conditions. The fundamental basis of these approaches is the elassical similarity and dimensional theories, the main postulates of which have been transformed and adapted to the problems of the study of the strength of materials and damageability of structural elements under thermal cyclic loading in corrosive environments. The developed procedures and experimental means allowed the modeling of aerodynamic heating processes of the structural elements of space shuttles. It has been shown that the implemented methods enable the evaluation of functional characteristics, determination of a set of properties and refinement of the technology for the formation of structural elements of aerospace vehicles operating under the conditions of aerodynamic heating to extremely high temperatures.

Kucher N. K. and Samusenko A. A. **Mathematical Prediction of Strength of Ablating Polymer Unidirectional Composites in Transverse Direction and in Shear along and across Fibers** // Problems of Strength. – 2018. – No. 4. – P. 74–84.

The scope of the investigations of the paper includes the efficiency in the prediction of strength characteristics of the ablating polymer unidirectional carbon-fiber-reinforced plastics at elevated temperatures based on the properties of the unreinforced matrix and a bundle of fibers in the process of thermal oxidative breakdown at different types of stress state. The characteristics of elasticity and parameters of strength of the transverse-isotropic carbon-fiber-reinforced plastic, as well as of its components (epoxy matrix and carbon fibers of T700 type), have been determined in compliance with the regulatory documents of Ukraine at low heating rates with the subsequent exposure of the specimens at the fixed temperature, when the inertia effects can be neglected. It is illustrated that the variation in densities of the ablating unreinforced matrix and the bundle of fibers at elevated temperatures is properly described via the models of multiphase media employing the modified integral exponential function. The authors analyze the possibility to evaluate the critical stresses of the transverse-isotropic composite at elevated temperatures based on the mechanics of multiphase media considering the thermal and mechanical characteristics of the ablating polymer matrix and the bundle of carbon fibers. It is assumed that the task of heat and mass transfer can be solved separately from the coupled tasks of thermal mechanics of the ablating materials, since mechanical stresses have no effect on its parameters. It is found that the calculation of critical stresses using the hypothesis of the total hermetic sealing between the phases or the assumption on the low pressure in pores determines the lower and upper lines of variation of the composite strength at different types of stress state, respectively. In particular, the calculated strength of the unidirectional composite under tension in the transverse direction and in shear along and across the fibers is in good correlation with the experimental data obtained by the authors and other researches.

Rodichev Yu. M., Veer F. A., Soroka O. B., and Shabetya O. A. **Structural Strength of Heat-Strengthened Glass** // Problems of Strength. – 2018. – No. 4. – P. 85–100.

The paper considers the determining factors in the structural strength of heat-strengthened glass. The values of residual stress were obtained experimentally at different points on the surface of specimens of heat-strengthened glass and fully tempered glass using a SCALP-4 laser scanning polarimeter. The distribution of residual stresses is determined over the area of specimens. It is found that the standard methods of in-process control of the degree of strengthening that involve the determination of compressive stresses only at several points, give a fairly rough estimate of the average level of induced residual stresses in glass structural elements and do not determine their real significance near the fracture origins. The necessity of using the methods of more comprehensive in-process control of residual stresses is justified, in order to obtain data on their statistical distribution and optimize the heat strengthening modes according to special requirements to building glazing and new engineering products. As shown by the analysis of the investigations dealing with determination of the strengthening effect during heat treatment of glass, it does not exceed the level of residual stresses. Due to the statistical nature of glass strength and residual stresses, the determination of the empirical coefficient, which traditionally considers the increasing contribution of residual stresses to the strength value of heat-strengthened glass, presents great difficulties. Based on the sampling of the bending strength values for glass in the initial, as-received state and after heat strengthening using the mathematical statistics methods, the calculated distribution of stress values that characterize the strengthening effect is determined. The influence of the combination of heat strengthening and etching on the strength characteristics of glass is investigated. It is found that the enhancement of the strength of glass and glass products strengthened using combined techniques is accompanied by a significant increase in the scatter of the tensile strength values, and the influence of the combined treatment on the tensile strength of glass is not additive.

Novikov A. I. and Tsybanev G. V. **Evaluation of Fatigue Steel Damage Stages in Stress Concentrators Considering Inelastic Strain Kinetics** // Problems of Strength. – 2018. – No. 4. – P. 101–113.

An application of the proposed model of ultimate exhaustion of cyclic plasticity is considered for the calculation of fatigue damage stages of structural elements in the elastoplastic statement and kinetics of the stress-strain state (SSS) under the conditions of stress concentration. The paper outlines the defining equations of the model of ultimate exhaustion of cyclic plasticity. The basic difference between the model solutions and the current model lies in the use of cyclic stress-strain diagrams dependent on the number of loading cycles, which is attained via the introduction of the function reflecting the variation of inelastic strains into the plastic part of the Osgood–Ramsberg equation. Based on the experimental data under symmetric tension–compression on smooth specimens, refinement of the function parameters and the introduction of ultimate values are performed. Then, these results are employed in the development of the approach to calculating the lifetime of structural elements with the presence of a stress gradient in the elastoplastic statement. The approach is used to determine the fatigue life of cylindrical specimens with stress concentrators. With this aim in view, the processes of damage to thin layers of the material with the required value of their discretization are stepwise determined by the model of ultimate exhaustion of plasticity. To define the kinetics of elastoplastic SSS within the minimal section of the specimen, a hybrid numerical-analytical scheme of calculation is proposed applying the finite elements method (FEM) at the points of support and weight functions. To consider the variations of the numerical solution depending on the change of elastoplastic properties with the increase of the number of loading cycles at various levels of stress amplitude, FEM solutions are standardized (the same as for equations of equilibrium). The solutions to these equations allow one to determine the kinetics of distribution diagrams of the elastoplastic SSS, fatigue damage to the specimens with stress concentrator and their lifetime for the material with non-stabilized cyclic deformation. The lifetime of fatigue damage to the specimens with stress concentrators is defined via the criterion of nucleation and propagation of the short crack of the specified size. The comparison of the experimental and calculated lifetimes for steels 45 and 1Kh2M demonstrates their good correlation.

Herasymchuk O. M. **Modified KT-Diagram for Stress Raiser-Involved Fatigue Strength Assessment** // Problems of Strength. – 2018. – No. 4. – P. 114–127.

The model for evaluating the fatigue strength of specimens and structure elements with sharp-edged and deep stress raisers (notches) or defects, which can be treated as initial cracks, is advanced. The model is the modification of known fracture mechanics approaches with employing the modified Kitagawa–Takahashi diagram. The model is based on the fact that cyclic loading of sharp-edged notch-containing specimens at the level of the nominal stress range, smaller than the endurance limit of smooth specimens. This results in a crack penetration to a certain size from the root of the notch, with its further arrest due to the two basic factors: descending gradient of local stresses ahead of the notch root and gradually growing effect of crack closure behind its tip. The crack size is dependent on the stress range level and notch depth. The model permits of calculating the boundary curve of threshold stress ranges and corresponding tolerable crack sizes for a sharp-edged notch of any depth, using only the characteristics of static strength and microstructure of the initial material. The model reliability was verified with experimental results taken from the literature, the calculation and experiment were in good agreement. The model needs no long-term and labor-consuming fatigue and fatigue crack resistance tests to get parameters necessary for the model implementation. The model calculations would require only the data on static strength characteristics (elastic modulus, Poisson's ratio, and proportionality limit), obtained from short-time tensile tests of standard specimens from an examined material, and microstructure characteristics (grain size, Taylor factor, and Burgers vector) determined from microstructure analysis of the initial material.

Correia J. A. F. O., *Huffman P. J.*, *De Jesus A. M. P.*, *Lesiuk G.*, *Castro J. M.*, *Calcada R. A. B.*, *and Berto F.* **Probabilistic Fatigue Crack Initiation and Propagation Fields Using the Strain Energy Density** // Problems of Strength. – 2018. – No. 4. – P. 128–145.

The fatigue crack growth (FCG) has been widely studied by the scientific community. There are several proposed FCG models, the best known being the Paris relation. The fatigue crack initiation and propagation have been studied separately, however, researchers have made an effort to study the relationship between these two fatigue phenomena. In this sense, several fatigue crack growth models based on local approaches have been proposed, the UniGrow model being well-known. The fatigue crack growth process is assumed a succession of crack re-initiations considering a certain elementary material size. Recently, Huffman developed a strain energy density based on Walker-like stress life and fatigue crack growth behavior. In this paper, the Huffman model based on local strain energy density is used to predict the fatigue crack initiation and propagation for the P355NL1 pressure vessel steel. This model is combined with the generalized probabilistic fatigue model proposed by Correia aiming the generation of probabilistic fatigue crack initiation and propagation fields. In this study, the local stress and strains at the crack tip were obtained combining linear-elastic and elastoplastic analyses. The probabilistic fatigue crack growth rates fields for several stress R-ratios are estimated considering strain, SWT and equivalent stress amplitude damage parameters. A comparison between the experimental fatigue crack growth (FCG) data and the generated probabilistic FCG fields is made with very satisfactory correlations being found.

Pokrovskii V. V., *Sidyachenko V. G.*, *and Ezhov V. N.* **Fatigue Crack Growth in the Base Metal and Weld of the Combustion Chamber Casing of an Aircraft Gas-Turbine Engine** // Problems of Strength. – 2018. – No. 4. – P. 146–155.

To substantiate the serviceability of aircraft gas turbine engines on the basis of technical condition, it is necessary to have information on the rate of crack growth in the material of engine components from the initial to critical dimensions. According to normative documents, this information is used in fixing the time limits for and amount of scheduled maintenance. The rate of fatigue crack growth in the high-temperature alloy of the combustion chamber of an aircraft gas turbine engine was studied taking into account operational (temperature) and constructional (weld, thickness of the product), factors. The experiments were performed on flat rectangular specimens with an edge and a central crack by the standard procedure at test temperatures of 500 and 600℃. The fatigue crack growth rate was studied in the base metal, weld and in the heat-affected zone (HAZ) at a distance of 2–3 mm from the weld. To do this, a fatigue crack was initiated from a mechanically cut notch at the appropriate site relative to the weld: in the base metal, weld and in HAZ. A linear section of a fatigue fracture diagram has been constructed, and Paris equation coefficients have been obtained. Confidence intervals are given, which illustrate the area within which the experimental results fall with a probability of 95%. A statistical treatment of experimental data in terms of the kinetics of fatigue crack growth in HAZ and in the base metal showed them to differ only slightly, whereas the rate of fatigue crack growth in the weld increases by a factor of two or three. To estimate the change in the mechanical properties of the alloy under investigation on transition from the base metal through HAZ to the weld, Rockwell tests were carried out. The results showed a small change in hardness, which indirectly accounts for the small discrepancy (within the statistical error) between the rate of crack growth in the base metal and that in HAZ.

Borodii M. V., Adamchuk M. P., and Stryzhalo V. O. **Specification of the Parameters of an Exponential Heredity Kernel of the Endochronic Theory in Describing Ratcheting under Biaxial Loading** // Problems of Strength. – 2018. – No. 4. – P. 156–167.

A method is proposed for specifying the parameters of the exponential hereditary function kernels of the endochronic theory of plasticity to describe the ratcheting (cyclic creep) effect of metallic materials under stress-controlled complex non-proportional loading. The method involves the dependence of the difference of plastic moduli on the ratcheting rate on the steady-state portion of the cyclic stress–strain curve. The plastic moduli are determined at the points where the maximum stresses act in different half-cycles of asymmetric loading. It is assumed that the greater the difference of plastic moduli towards the mean stress in the cycle, the greater the strain increment in each cycle of loading. The statements of previously proposed approach were used to determine the rate of plastic strain accumulation at the steady-state stage of deformation under biaxial loading. This approach, based on the data of uniaxial experiments under cyclic asymmetric loading in tension–compression and reversed torsion with the known value of the cycle non-proportionality parameter, is developed to analyze the cyclic loading paths with equal mean and amplitude von Mises stress values. With some simplifications, the expression is proposed to determine the parameters of the exponential kernel of the hereditary function depending on the cyclic path geometry and the known ratcheting rate for the basic loading path. Similar values for the exponential kernel parameters of the hereditary function are obtained in terms of the difference of plastic moduli by using a simpler bilinear model of elastoplastic deformation. The obtained values of the hereditary function parameters were used to simulate the ratcheting effect under uniaxial and biaxial cyclic loading. The loading programs and data of experiments were taken from the literature. The results of simulation have shown that the parameters of the constitutive equations for cyclic plasticity obtained with this method allow one to describe satisfactorily the kinetics of the stress-state state of metallic materials subjected to biaxial non-proportional loading under cyclic creep.

Maslei V. N., Krishchuk N. G., and Tsybenko A. S. **Analysis of the Amplitude-Frequency Characteristics of the Composite Honeycomb Panel for Spacecraft Scanner under Harmonic Vibration** // Problems of Strength. – 2018. – No. 4. – P. 168–178.

The coordinate and frequency distributions of the values of displacement and acceleration amplitudes, the vibration acceleration amplification factors, and the equivalent von Mises stresses are obtained from the data on the simulation modeling of harmonic vibration of the composite honeycomb panel for spacecraft scanner and its related operational equipment (a scanner, magnetometer, optical devices, etc.) mounted on it. A dynamic simulation model of the composite honeycomb panel was developed using modern finite element analysis tools, such as ANSYS APDL. Carbon fiber reinforced plastic plates with an aluminum foil honeycomb core in the form of regularly shaped hexagonal cells that make up the honeycomb panel are approximated by multilayer plate finite elements. The related operational equipment, such as optical devices, a scanner and magnetometer, are represented in the model by lumped masses rigidly attached to the panel. The spectrum of natural frequencies and vibration modes of the spacecraft scanner honeycomb panel is determined using the developed simulation model. The resonant displacement and acceleration amplitudes, the vibration acceleration amplification factors as well as the distributions of the amplitudes of the equivalent von Mises stresses are obtained in the operating frequency range of the investigated harmonic vibration mode of the spacecraft scanner honeycomb panel.

He T., Liu H., Shi X., Huo Y., Li M., and Pan T. **Effect of Si and Mn on Microstructure and Mechanical Properties of Vacuum Suction Casting Al–4.5Cu Alloy** // Problems of Strength. – 2018. – No. 4. – P. 179–188.

The high performance of alloys is dependent on microstructure, while alloying elements have significant influence on microstructure. In order to study the effect of Si and Mn elements on the microstructure and mechanical properties, different content of alloying elements, Si and Mn, are added into the matrix Al–4.5Cu alloy. The compounded alloys (CA) are prepared by vacuum suction casting. The microstructure of CA is investigated by a scanning electron microscope (SEM). The mechanical properties are tested by a universal testing machine and a microhardness tester. Analysis is conducted by comparing experimental results of CA with different content of Si and Mn. It is found that the irregular lamellar structure of the CA appears with the increase of Si and Mn content. The solid solution coexists with the irregular lamellar laminated structure when both Si and Mn contents are 3 wt.%. The tensile strength of CA is the highest when the content of both Si and Mn is 1 wt.%. Its ultimate tensile stress reaches 205.87 MPa, the elongation reaches 34.97% and the microhardness reaches 74.6 HV. When both Si and Mn contents are 2 wt.%, the tensile strength of CA is the weakest. Its ultimate tensile stress reaches 146.65 MPa, the elongation reaches 24.15% and the microhardness reaches 60.2 HV. The elongation of the CA decreases with the increase of Si and Mn contents.

Ismail Ali A. and Al-Habardi K. **Optimum Plans of Step-Stress Life Tests Using Failure-Censored Data Form Burr Type-XII Distribution** // Problems of Strength. – 2018. – No. 4. – P. 189–202.

In this paper, optimum test plans of step-stress partially accelerated life tests are developed using failure-censored data from Burr type-XII distribution. The maximum likelihood approach is applied to obtain the estimates of the acceleration factor and the parameters of the distribution. The minimization of the generalized asymptotic variance of the maximum likelihood estimators of the model parameters is used as an optimality criterion to develop optimum plans of the step-stress PALTs. For illustrative purposes, simulation studies are presented.