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MODELS AND PREDICTION ALGORITHMS OF FRACTURE OF STRUCTURAL ELEMENTS FOR LOW- AND HIGH-CYCLE LOADING BASED ON FEM

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Abstract. Mathematical models, methods, algorithms and developed based on them the results of numerical simulation based on FEM, approaches mechanics of the damaged medium, processes of deformation and fracture (from the generation stage of microdefects to the propagation of the main cracks) of structural elements for low- and high-cycle loading.

1. Introduction

Modern approaches to the analysis of the structural strength of the most widely used methods of linear and nonlinear fracture mechanics, studying the final stage of destruction - propagation trunk cracks. Much less attention is given to the study of the initial period of the destruction associated with the accumulation of damage. However, the crack originates and develops in the volume of material prepared for destruction within the first, initial stage. Therefore, the modeling of real processes of destruction of structures should ensure that the description of these processes in both the early and final stages.

In the present work we study the deformation and damage accumulation in the material of constructions is carried out in the framework of the ratios of the mechanics of the damaged medium using proposed by authors the composite hierarchical model of the damaged material [1], which allows to investigate the behavior of structures with consideration of the peculiarities of the processes of destruction at the initial and final stages. The model is based on the ability to represent complex process of propagation of the interrelated effects of deformation and fracture in a series of formally independent elementary acts described by respective partial models of plasticity and damage accumulation. Calculation of mutual influence such basic acts is at the top level in the general model of the damaged material. However, the description of the interaction of different types of damage and their effect on the deformation process is based on invariant with respect to the nature of these injuries scalar measures of damage ω.

2. The model of the damaged material and methodic the numerical solution of problems of fatigue strength of structures

The overall proportions of the model of the damaged material, establish the link between changes in the reduced stresses and strains at the elementary step of external influences changes [1, 2]. They have the form of equations of elasticity with additional members, due to the effects of temperature, irreversible deformation and degradation of material properties associated with the accumulation of damage. In the framework of a general model of the damaged material implemented private models thermoplasticity with combined hardening and damage accumulation under low-cycle thermo loadings [1], and the model of fatigue damage accumulation during under high-cycle thermo loadings taking into account the dependence of limit cycles from the level of the operating temperature of the asymmetry parameter cycle implemented in a loop of the stress state, as well as measures of the accumulated damage [3].

To describe the development of damage in the material under cyclic loading is introduced function ψ, representing the normalized counterpart of hazardous energy, and scalar measure of damage ω used to describe the influence of current damage on the characteristics of the deformation process on the basis of the hypothesis about the existence of two phases of damage accumulation [1, 3, 4]. Within the first-hand phase is the emergence scattered by the volume of material damage in the vie de micropores and microcracks that does not lead to a significant impact of these injuries on the physico-mechanical characteristics of the material. In relation to the above model of the damaged material for this phase can be considered to change the measure of damage $\Delta\omega = 0$. The second phase is characterized by further development of co-interaction of defects occurring and is accompanied by the growing influence of the damage onto the physico-mechanical characteristics of the material and destabilization of the process of cyclic deformation under cyclic loading. The end of phase conforms the appearance in the material of macroscopic cracks.

Simulation of fatigue crack propagation in the construction carried out by the "shutdown" nodes when reaching the critical values of the measures of damage. The process of propagation of the crack is considered as a sequential "shutdown" of neighboring nodes during loading process [2], without modifying the original scheme of discretization and the initial topology of the investigated structures.

Numerical solution of boundary value problems of deformation and fracture of structural elements is based on the FEM using the generic isoparametric models FE, with high efficiency in the analysis of both massive and thin-walled fragments [1].

3. Algorithms of the prediction of fracture under cyclic loading

The necessity of creation of such algorithms is due to the fact that direct application scheme described above to solve the problems of modeling the behavior of structures under cyclic loading, by successive integration of the equations for a large number of cycles, it is very difficult, both because of the great complexity of the calculations, and the possibility of accumulation of numerical errors. To overcome these difficulties, the proposed prediction algorithms process of origin and propagation of fatigue cracks under cyclic loading based on the numerical simulation of these processes in the framework of the ratios of the mechanics of the damaged medium. These algorithms [4, 5] can significantly reduce the overall complexity of the numerical solution of problems of fatigue strength of structures.

On the foundation of the algorithms the possibility of extrapolating on the load cycles of the parameters characterizing the current elastic-plastic condition and damage of material in the construction nodes is based, taking into account the hypothesis of multi-stage nature of the development of damage in the material during deformation. The proposed algorithms consist of two levels of extrapolation: linear – at the first stage of damage accumulation; nonlinear in the second stage of damage accumulation.

Under low-cycle loading within the first stage can occur stabilization process of cyclic deformation occurring in the stabilization of the amplitude values of stress, strain, plastic strain. On the section of the process from the beginning of stabilization until the end of the first stage of damage accumulation, corresponding to the value $\psi = \psi_a$ (ψ_a – amplitude value function damage, specifying the moment of completion of the first phase of the development of fatigue damage in which the cumulative damage does not affect the mechanical properties of the material), the process parameters in elastic-plastic deformation is practically constant (amplitude values of stresses, full and plastic deformation), and the length of the trajectory of plastic deformation k_p (Odkwist parameter) and damage function ψ, change in law, is close to linear. Therefore, at this stage loading can, with reasonable certainty, to predict values of the above parameters by linear extrapolation on *EXT1* number of cycles forward, eliminating the corresponding part time-consuming process step-by-step integration of the equations of the original problem [4].

In the case of high-cycle loading, by results of numerical simulation of the deformation process of construction for the first loading cycle and calculating the increment of function damage $\Delta\psi$, extrapolation on *EXT1* loading cycles is, which corresponds to the completion of the first phase of damage accumulation in the most loaded physical node structure [5].

In the second stage of destruction when $\psi \geq \psi_a$, the collective interaction of the developing micropores and microcracks is in the material, leading to a significant influence of the accumulated damage on macroscopic material characteristics (modulus of elasticity, sound velocity, and so on), growth measures of damage ω, culminating in the formation of microdefects ($\omega = 1.0$).

At this stage of damage accumulation the extrapolation of the parameters of the damage of the material ψ and ω on the number of cycles *EXT2* is, given by set changing of the measure of damage $\Delta\omega^{max}$ in the most loaded node of construction, and subsequent refinement of the equilibrium structure [5]. The expression to determine the number of cycles extrapolation $EXT2$ can be obtained from the kinetic equations of fatigue damage accumulation [1, 5]. Extrapolation of the second level can be performed repeatedly until a measure of the damage in some physical node of construction ω reaches a critical value that would indicate the emergence of macroscopic cracks.

The proposed algorithms for the prediction of low- and high-cycle of destruction of structures implemented in the framework of the established and developed in the Institute of mechanics of the Nizhny Novgorod University computing complex UPAKS [6].

4. The results of numerical simulation of fatigue failure of structural elements

To assess the performance and computational efficiency of the proposed algorithms for predicting fracture and created on their basis of software tools for the numerical investigation of fatigue strength of structures in this section, we present some results of calculations of fracture construction elements for low- and high-cycle loading.

Numerical simulation of low-cycle fracture of the cylindrical sample. An example of numerical simulation of low-cycle deformation and fracture of cylindrical sample, made of stainless steel 12Kh18N10T with working part of the recess [4]. The sample is uniformly heated by volume to a temperature of T = 350 °C and is in conditions of cyclic loading by applied axial displacement on the end varying according to the law of the symmetric cycle.

It was decided two versions of the task. In the first variant numerical study of deformation and damage accumulation was carried out until the crack formation without the use of extrapolation procedures. It was found that the measure of damage in the most loaded point has reached the limit $\omega = 0.99$ of 1040 cycle. When the decision of the second variant of the problem using extrapolation procedures (20 cycle of loading was produced extrapolation 750 cycles) the predicted number of cycles to failure was 1067.

Thus, the relative error in the determination of the maximum number of cycles using extrapolation procedures for the considered tasks does not exceed 2.7 %. Using extrapolation procedures have helped to reduce the complexity of the computational process by 70 %.

Numerical simulation of high-cycle fatigue of the experimental sample. In this task was carried out numerical study of high-cycle fatigue of the experimental sample, made of steel VJ-159. The results of calculations and their comparison with experimental high-cycle fatigue curves for the symmetric and asymmetric cycles obtained for the considered material at a temperature of $T = 850$ °C given in [3].

For symmetric loading cycle, corresponding variant of the load at which the experimental sample is destroyed by 1000000 cycle of loading, the use of the developed algorithm extrapolation [5] has allowed to describe the process of damage accumulation in the second stage duration 6000 cycles by twenty extrapolations (when setting $\Delta\omega^{\max} = 0.05$). Table 1 shows the parameters of the extrapolation of the damage accumulation process until the formation of microdefects in the most loaded point of the sample.

Table 1. The sequence of extrapolations of the second level until formation of cracks.

Number of extrapolation	*N* of the cycle	*EXT*2	Number of extrapolation	*N* of the cycle	*EXT*2
1	990695	2235	11	996663	27
2	992931	1488	12	996691	18
3	994420	837	13	996710	12
4	995258	514	14	996723	8
5	995773	330	15	996732	5
6	996104	215	16	996738	3
7	996320	142	17	996742	2
8	996463	94	18	996745	1
9	996558	62	19	996747	1
10	996621	41	20	996749	1

The data presented show efficiency and high efficiency of the developed algorithms to predict processes high-cycle destruction of structural elements.

5. Conclusion

Developed models, algorithms, and software tools for the numerical investigation of the processes of fatigue failure of structural elements within the approaches of mechanics damaged medium on the basis of FEM with quasi-static thermo loading. Proven efficiency and effectiveness of the established tools for forecasting processes low- and high-cycle fatigue of structural elements is.

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